# ABSTRACT

MOHSENIN, SEYEDEHMAHSAN. Assessing Daylight Performance in Atrium Buildings by Using Climate-Based Daylight Modeling. (Under the direction of Dr. Jianxin Hu).

This research focuses on daylight and energy assessments in office buildings with different atrium proportions and roof aperture designs. The goal is to assess and optimize atrium roof aperture design and proportion to improve daylighting performance and energy efficiency of atrium buildings. This study investigates daylight and thermal performance metrics in central and attached atrium types with different proportions and roof aperture designs, such as monitor and horizontal skylight. This research measures daylight performance of an atrium based on its proportion defined by the Well Index (WI). Climate-based daylight modeling (CBDM) is applied as the assessment strategy in Raleigh, NC. Spatial Daylight Autonomy (sDA) and Annual Solar Exposure (ASE) are adopted as the dynamic daylight metrics. This study also validates DIVA for Rhino as the simulation tool by comparing daylight results of the computer simulation with the physical scale-model results.

This study then employs DIVA simulation tool to assess daylight performance based on the Well Index. The results demonstrate that the Well Index is an effective indicator to characterize atrium proportion when the climate-based daylight modeling (CBDM) method is adopted. Considering the impact of other design parameters, such as climate, building depth, material reflectance, material transmittance, furniture and monitor roof glazing height, the study provides architects with an atrium design database for U.S climate zone 3. An online interface has been developed to allow for designers to access the database to inform their atrium designs in early project phases.

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# Assessing Daylight Performance in Atrium Buildings by Using Climate-Based Daylight Modeling

by
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# BIOGRAPHY

Mahsan received a Master of Science in Architectural Studies from the Massachusetts Institute of Technology in 2011. She began her PhD in Design at North Carolina State University in 2012, while working as a research assistant at the Building Systems Integration Lab. Her research focuses on daylighting assessment and optimization in atrium buildings, supervised by Dr. Jianxin Hu. Her interests also include daylight modeling and simulation, environmental technology and healthy built environments.

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# Chapter 1 INTRODUCTION

## 1.1 Research Goal

Buildings account for 41% of U.S. primary energy consumption and 74% of total U.S. electricity consumption (Department Of Energy, 2011). The growing need to lessen the use of energy in buildings calls for innovative ways to optimize the use of natural light in buildings. Augmenting the use of natural light not only helps with sustainable solutions, but also reduces energy costs. Conversely, to use natural light in buildings, architects often offer large expanses of glass for light, which often brings in too much heat if the light is not successfully controlled, forcing engineers to increase the cooling tonnage. As a result, there is a need to optimize the use of daylight in buildings and to provide an easy-to-use design tool for architects.

An atrium is a common architectural component in commercial buildings to introduce daylight to the core of buildings. Previous studies demonstrated evidence of increased retail sale (Heschong, Wright, & Okura, 2002), increased office rental values (Boyce, Lloyd, Eklund, & Brandston, 1996), and enhanced worker health (Heschong Mahone Group, 2003) in daylit spaces. While atria can be used as a source of natural light, they can cause excessive energy consumption if not properly designed. The goal of this project is to optimize the choice of atrium type and its design proportion to improve the energy efficiency of atrium buildings.

It is often complex to predict and optimize daylight in atrium buildings. In order to increase the desirable solar gain in buildings, this research proposes to investigate how an atrium building augments the amount of light entering the building and optimizes its energy consumption. This premise assumes atria within buildings act as urban courtyards, reflecting daylight performance at an urban scale. Therefore, the main research question is: *what dimensional attributes of an atrium increase the desirable solar gain and optimize its energy consumption?*

The goal of this dissertation is to provide architects with a daylight database to assist them with more energy-efficient design of atrium buildings. This research is therefore to achieve an atrium database to reduce energy consumption in the office building sector without using detailed energy calculations for designers.

## 1.2 Definition of Key Terms

This section clarifies the terms used in the literature of daylighting in atrium buildings.

*Illuminance*

According to Reinhart, illuminance is “the total luminance flux incident on a surface and is measured in lumen per unit area or lux.” (Reinhart, 2014; 79) Light flux is basically the amount of visible light perceived by human eye, measured in lumens.

### *Daylight Factor (DF)*

Daylight Factor is a static daylight metric that quantifies the amount of diffuse daylight using a ratio of the interior illuminance and the outside illuminance (New Buildings Institute, 2015).

### *Climate-Based Daylight Modelling (CBDM)*

CBDM is a daylight prediction model which defines various luminous quantities using sun and sky conditions derived from meteorological datasets. CBDM includes spatial daylight autonomy, annual sunlight exposure and useful daylight illuminance (Beckers, 2012).

### *Daylight Autonomy (DA)*

Daylight Autonomy demonstrates the percentage of the *occupied* times of the year when the minimum illuminance requirement at the daylight sensor is met by daylight alone (Reinhart, Mardaljevic, & Rogers, 2006).

### *Useful Daylight Illuminance (UDI)*

Useful Daylight Illuminance represents the annual illumination distribution for a space to reach a preordained illumination goal in a range of 100 lux-2000 lux (New Buildings Institute, 2015).

### *Spatial Daylight Autonomy (sDA)*

Spatial Daylight Autonomy (sDA) has been developed to test the sufficiency of daylight illuminance, using the percentage of the floor area that meets certain illuminance level for a specified number of annual hours. For instance, sDA $_{(300,\ 50\%)}$ represents the percentage of space in which the illuminance level is greater than 300 lux for 50% of the occupied hours (Illuminating Engineering Society, 2012).

### *Annual Sunlight Exposure (ASE)*

Annual Sunlight Exposure (ASE) is a metric describing the potential for excessive sunlight exposure by calculating the percentage of the space that exceeds a certain illuminance level more than a specified number of annual hours (Illuminating Engineering Society, 2012). For instance, ASE $_{(1000,\ 250)}$ represents the percentage of space in which the illuminance level is more than 1000 lux for 250 annual occupied hours.

### *Atrium Well Index (WI)*

The daylight performance of an atrium depends on its geometry. Well Index is a quantifier that describes the three-dimensional proportion of an atrium. Equation 1 defines the Well Index according to Calcagni & Paroncini (Calcagni & Paroncini, 2004):

$$\mathrm{WI} = \frac{\mathrm{height\ (width+length)}}{2 \times \mathrm{width} \times \mathrm{length}} \qquad \text{Eq. (1)}$$

Based on this equation, the Well Index (WI) of a square-shaped atrium is measured as height divided by width, as the width of the atrium equals its length.

The next chapter reviews the literature on daylight performance metrics, daylight prediction methods, atria factors and thermal analysis of atrium buildings. When discussing energy performance in atrium buildings, we describe the problems that have been addressed in the past. The Well Index (WI) was used as a quantifier of the atrium proportion, although it was not studied as a cohesive method to address daylight metrics and thermal loads. Chapter three first introduces the framework of this study based on the Well Index, then provides details about computer simulation methodology. Chapter four will finally turn to the results of this study, enumerating lighting and energy assessment in atrium buildings. This chapter will conclude with the methodological and technical improvements that this study provides.

# Chapter 2 LITERATURE REVIEW

## 2.1 Daylighting Rules of Thumb

A strong body of knowledge describes the rules of thumb for daylighting design in general and daylighting in atrium buildings in particular. While studies of the former design provide concepts and equations to calculate the amount of light that a space receives, the latter approach centers on atrium sizing rules in the context of overcast sky conditions. A large body of literature on atrium daylighting has utilized the Cartwright Sizing Rule. Cartwright indicated that the average Daylight Factor (DF) in adjoining spaces varies based on the ratio of height to length of an atrium (Cole, 1990). Another study based on this sizing rule was Mark DeKay's research on urban atria. It provided daylighting performance data, expressed in DF, for various atrium proportions (DeKay, 2010). Although this research provided valuable findings in urban daylit buildings, the use of DF, which does not account for climate and building orientation, limited the scope of the study. Another limitation of DeKay's research was that the study was based on atrium dimensions instead of atrium proportions, providing DF based on different building thicknesses and heights.

### *2.1.1 Daylight Feasibility Test*

The concept of having the minimum light flux entering a sidelit space was introduced in 1989 “Daylighting Manual” by Public Works and Government Services Canada (Reinhart, 2014). The light flux is a function of Window to Wall Ratio (WWR), visual transmission of the glazing unit $\tau_{vis}$, and obstructions from neighboring buildings (Figure 1). Reinhart and Lo Verso defined the concept of a daylight feasibility test, stating that the minimum sky angle θ × WWR > 2000 (Reinhart & LoVerso, 2010). In this formula, WWR is measured in percentage, meaning that the minimum WWR for θ = 90 degrees that is an unobstructed façade is around 22% (2000 / 90 ~ 22 degrees). On the other end, a fully glazed façade (WWR = 80%) requires a sky angle of at least θ = 2000 / 80 = 25 degrees to be daylit.

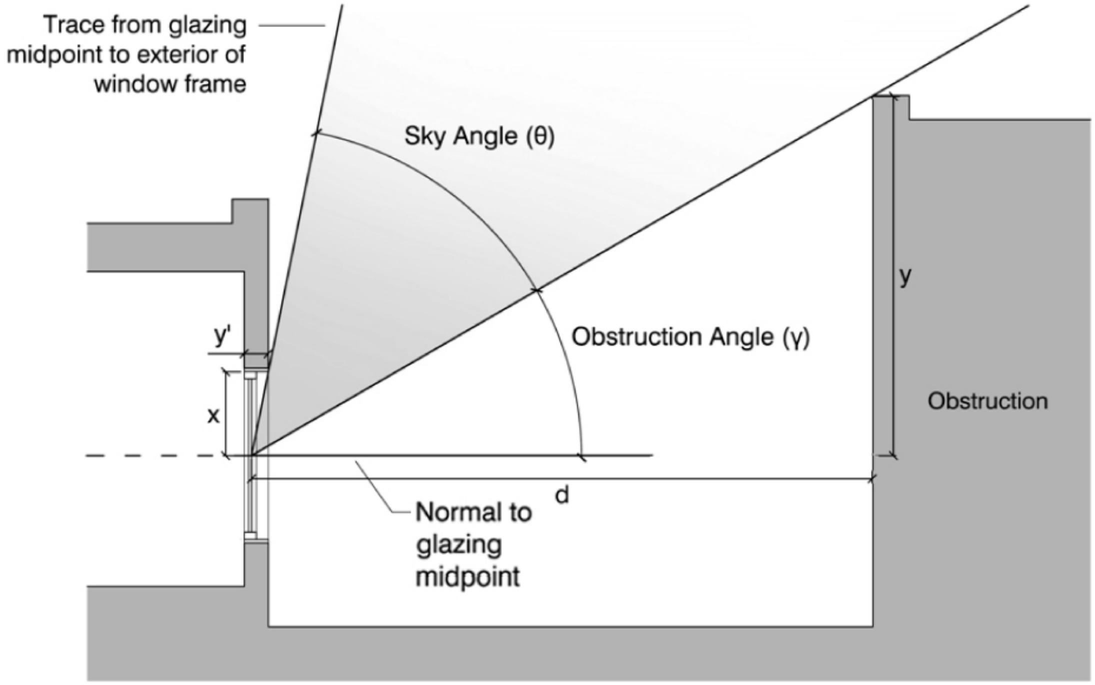


Figure 1. Sky Angle = Sky angle (θ) = 90º – arctan(y’/x) – arctan(y/d) (Otis & Reinhart, 2009; 6)

Atrium rule of thumb, derived from the feasibility test, suggests that the ratio of height to width of an atrium should not exceed tan (22) ~ 2.5. This example implies that in a square shape atrium of 30 ft, the number of stories should not exceed five levels to have the ground level properly daylit (assuming floor to ceiling height is 10 ft and the height of ceiling interstitial space is 5 ft)

### *2.1.2 Limiting Depth*

The next daylighting rule of thumb is the limiting depth for daylit spaces. There are three estimating methods:

A) Daylight Uniformity — defined by the following formula:

$$\text{Limiting depth} = \frac{2}{1-R_{mean}} \Big/ \frac{1}{w} + \frac{1}{h_{window\text{-}head\text{-}height}}$$

where:

$R_{mean}$: mean surface reflectance

w: room width in meters (Otis & Reinhart, 2009).

B) No skyline depth — the depth at which the sky is no longer visible = ($h_{window\text{-}head\text{-}height}$ – work plane height) × tan (θ). (Ibid)

C) Depth of daylight — calculated through 2.5 × $h_{window\text{-}head\text{-}height}$ (with no shading device) and 2.0 × $h_{window\text{-}head\text{-}height}$ (with shading device). (Ibid)

According to Otis & Reinhart, the greatest room depth that can be used for daylighting is “the smallest of the three values prescribed by the daylight uniformity, no sky line depth and the depth of daylight equations.” (Ibid; slide 18)

### *2.1.3 How much light is enough*

While meeting a code of practice does not necessarily result in well-lit spaces, many standards have provided minimum lighting requirements (USGBC, 2013). For example, the Illuminating Engineering Society recommended 300 lux for general task lighting (Illuminating Engineering Society, 2012). Innes discussed that “the perception of brightness can sometimes be far more important than the actual measured light level” (Innes, 2012; 88). The Illuminating Engineering Society (IES) and the Leadership for Energy and Environmental Design (LEED) made an effort to develop dynamic metrics such as sDA and ASE to more adequately assess well-lit spaces. For instance, LEED v.4 recommended that at least 50% of the space should meet a minimum daylight level of 300 lux for 50% of the occupancy hours (USGBC, 2013). The present study adopts these dynamic metrics and attempts to provide designers with the percentage of space meeting certain levels of illuminance with the considerations on glare and excessive brightness.

### *2.1.4 How much light is excessive*

This section is focused on the upper threshold for daylight to prevent the excessive light, called glare. According to Jakubiec, in order to avoid discomfort within the field of view, “the most frequently quoted rule is to avoid luminance ratios larger than 1:3 and 3:1 between the work surface and the near visual field and 1:10 and 10:1 in the far visual field, which is not based on human subject studies” (Jakubiec, 2012; 150). IES and USGBC recommended using upper thresholds for Annual Sunlight Exposure (ASE) to control for excessive daylight. As such, LEED v.4 suggested that the percentage of space with daylight levels greater than 1000 lux for more than 250 occupancy hours in a year should not exceed 10% (USGBC, 2013).

## 2.2 Daylighting Performance Metrics

A subset of the literature seeks to understand daylight performance metrics in atria. Static daylight metrics, such as Daylight Factor, are based on individual sky conditions (i.e., overcast sky condition), while dynamic daylight metrics are defined with regard to a time series of illuminance or luminance over the whole calendar year. Reinhart et al. (2006) offered several examples indicating the benefits of making design decisions based on dynamic performance metrics rather than on static indicators.

Reinhart et al. (2006) and Leslie et al. (2012) explored the limitations of static daylight performance metrics, which are based on overcast sky conditions. The most common static metric used to measure daylighting performance is Daylight Factor. Dynamic daylight metrics, on the contrary, are achieved by climate-based daylight modeling (CBDM). CBDM predicts various luminous quantities by using solar and sky conditions that are derived from meteorological datasets (Mardaljevic, Heschong, & Lee, 2009). Dynamic daylight metrics, such as Daylight Autonomy (DA) and Useful Daylight Illuminance (UDI), are therefore dependent upon both locale and orientation. As a result, using dynamic daylight metrics will significantly enhance the validity of daylighting assessments.

Point-in-time simulation is another daylight assessment method that provides tangible results for the illumination level in lux values rather than percentages of hours. Point-in-time daylight metrics represent illuminance lux values for a specific time (e.g., 9:00 a.m. on

September 21) under a specific sky condition (clear sky or CIE overcast sky). This present research has adopted both the annual daylighting metrics and the point-in-time daylight method.

## 2.3 Daylighting Prediction Methods

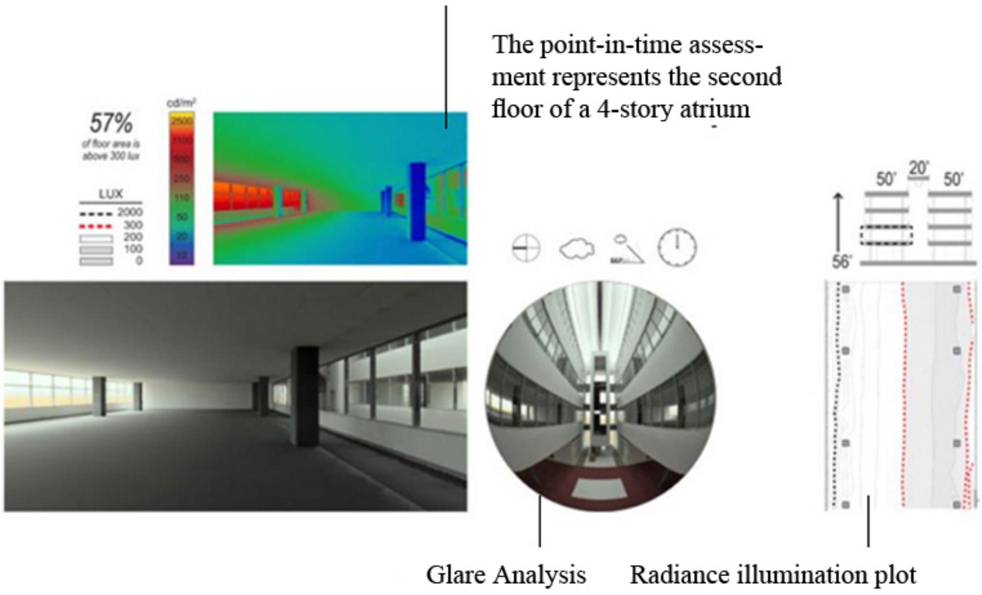
Ander (2006) reviewed daylighting analysis tools including hand calculation, computer simulation, and physical modeling. Calcagni and Paroncini (2004) and Al-Turki and Schiler (1997) described daylight prediction methods for atrium buildings based on physical models by using the Daylight Factor. Littlefair (2002) examined analytical formulae as a technique to evaluate the average Daylight Factor in atria. Currently, a trend existing involving the application of computer tools to simulate and assess daylighting performance. Daylight algorithms adopted in these computer tools vary in how light paths are traced. For instance, the radiosity method accounts for diffuse light, whereas ray-tracing traces the light path through objects and measures the impact of its encounters in the scene (Radiance, 2014). Using an optimized computer simulation tool provides researchers with the ability to obtain daylight results for various cases in a timely manner and under controlled conditions. Although a physical model has been tested to validate the results of the computer simulation, the present study primarily uses DIVA-for-Rhino, a climate-based daylight modeling tool.

Created by the NREL's Electric Systems Center, DIVA-for-Rhino employs the National Solar Radiation Database to simulate weather/solar conditions for different climatic locations. The National Solar Radiation Database provides a typical meteorological directory, which contains the typical meteorological year (TMY3) data sets derived from the periods of

1961-1990 and 1991-2000 (NREL, 2015). The standard file format for annual weather data is the Energy Plus Weather (EPW) file.

### *2.3.1 Existing Expert Systems*

Since simulation tools require investment in time and professional skills, so-called “expert systems” have been developed to assess the impact of design on energy performance. *Daylighting Pattern Guide*, developed by the New Buildings Institute, in partnership with the University of Idaho and University of Washington, represents an example that provides daylighting performance for buildings, including atria (Figure 2). This expert system provides daylighting data that are based on point-in-time analysis for limited design options. Compared to this expert system, the present study is intended to further explore the balance between daylighting and energy consumption and to cover diverse design alternatives by using the Well Index as the way to quantify atrium proportion. Another improvement is the annual assessment of the whole building rather than a focus on a certain orientation or building level.



The point-in-time assessment represents the second floor of a 4-story atrium

Glare Analysis

Radiance illumination plot

Figure 2. Daylighting Pattern Guide Interface (New Buildings Institute, 2015)

## 2.4 Daylighting in Atrium Buildings

### *2.4.1 Why Atrium Buildings?*

According to Sharples & Lash, the atrium “has become one of the most popular architectural forms of the last 40 years” (Sharples & Lash, 2007; 301). An atrium is potentially a source of daylight in deep buildings. Because people spend up to 90% of their time in indoor spaces, access to daylight can improve their physiological health and psychological well-being (Heschong Mahone Group, 2003). The benefits of daylight in buildings and the significance of studies on atrium buildings exceed the aesthetics of architectural design. Atria also provide the building with a gathering and social space, connecting outdoor and interior environments.

### *2.4.2 Atrium Buildings Case Studies*

The following cases represent successful examples of the use of atria in buildings (Figures 3-7).

Figure 3. Atrium at the U.S. EPA Regional Headquarters, KS
The atrium design provides most of the office space with natural light. The atrium's glass has a low emissive coating, receiving daylight while reflecting large percentages of the infrared spectrum, which controls heat gain (Whole Building Design Guide, 2005).

Figure 4. Center for Advanced Energy Studies, Idaho Falls, ID, GSBS Architects (New Buildings Institute, 2015)

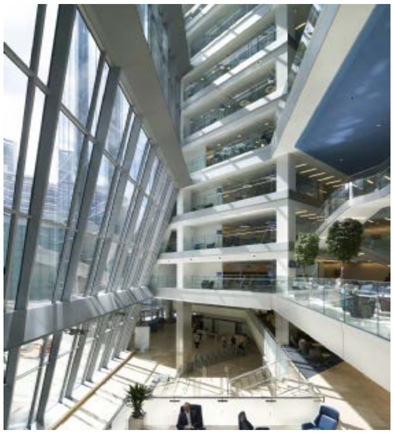


Figure 5. KPMG European Headquarters, London, UK

Architect: KPF

British Council for Offices National Urban Workplace Award (2011) (KPF)

Figure 6. James R. Thompson Center, Chicago, IL (A view on cities, 2015)

Figure 7. Smithsonian American Art Museum, Washington, D.C. (Foster + Partners, 2015)

### *2.4.3 Atria Factors Influencing Daylighting*

Daylighting studies on atria often face the challenge of quantifying the relationship between daylighting performance and atrium attributes. Liu et al. (1991) presented the relationship between the shape index of an atrium and daylight quantity. Szerman (1992) reviewed the impact of atrium design parameters on the average Daylight Factor (DF) inside the adjoining spaces. He investigated the relation between atrium Well Index (WI) and the mean DF, providing a nomograph based on artificial sky measurements (Szerman, 1992). This subject was further studied by DeKay, who explored different building latitudes, using the aspect ratio of an atrium $(L \times W) / H^2$ (DeKay, 2010). His study examined the relationship between DF and the street proportion between buildings.

Calcagni and Paroncini (2004) pointed out important atrium attributes that influenced daylight performance, including shape, roof aperture transmittance, and surface reflectance. Liu et al. (1991), Baker et al. (1993), and Kim and Boyer (1986) defined the shape of an atrium with WI (Calcagni & Paroncini, 2004). Littlefair (2002) probed for the correlations among geometrical properties of an atrium. Samant and Yang (2007) indicated that quadrangular atria had the highest daylight performance among other geometries.

According to Samant and Yang (2007), the reflectance of wall surfaces had limited or no effect on daylight distribution across the atrium floor. The results of the investigation carried out on the impact of atrium floor reflectivity on DF demonstrated that atria with more reflective floors have higher DF (Cole, 1990). Based on ASHRAE (2009), this study assumed 50% for wall reflectance, 80% for ceiling reflectance, and 20% for the floor reflectance in all cases.

Cole (1990) reproduced data to support the relation between the mean DF and the aspect ratio of an atrium (Well Index, Eq. 1) established by Cartwright.

## 2.5 Thermal Analysis and prediction methods

The thermal performance of atrium spaces has been examined by researchers such as Göçer (2006), by using computer simulation tools. This research found higher heating energy consumption than cooling in a central atrium in a warm temperate climate. It also found greenhouse effect on thermal performance of the atrium space, while the adjoining spaces were not investigated (Göçer, Tavil, & Özkan, 2006).

Efforts have been made in the present study to explore both heating and cooling loads in adjoining spaces in relationship to the atrium WI. To evaluate the impact of an atrium on building performances, there is a need to analyze energy performance besides daylighting. This research uses DesignBuilder, an energy simulation tool based on EnergyPlus, to perform thermal analysis to assess the energy performance of atrium designs. In addition to computer simulation, this section provides an analytical procedure to understand building load calculations, including heating and cooling loads. To calculate heating loads, we consider heat loss through a building's surfaces and heat loss through infiltration and ventilation.

Peak heating and cooling loads are usually calculated to estimate HVAC equipment / duct size. In addition, annual heating and cooling loads are significant tools for measuring the operating cost of a building. While this research employs DesignBuilder to calculate annual heating and cooling loads, the peak heating and cooling loads are confirmed, by comparing the results of peak cooling loads with hand calculations.

Heating load through conduction is calculated based on $Q = UA \times \Delta T$ where *U-value* is the material conductivity, *A* represents the area of the building surface and $\Delta T$ is the temperature difference between indoor and outdoor. Heating load through ventilation follows the same formula replacing UA with $1.08 \times CFM$, where cubic feet per minute (CFM) represents the volume of outdoor air that needs to be heated. To calculate the difference between the inside and outside temperature, we use heating degree-hours (HDH) which reflects the difference in temperature for annual hours based on the ASHRAE typical year data. Peak cooling loads are often more complicated to measure, because of the time dependent heat transfer due to solar radiation through the thermal mass. The following are common methods to calculate cooling loads through simplified equations (Terry, 2015):

- Transfer Function Method
- Finite Difference Method
- Bin Method
- Cooling Load Temperature Difference (CLTD) Method

### *2.5.1 Building Load Calculations with Cooling Load Temperature Difference (CLTD)*

Since cooling load depends on both thermal mass and solar radiation, it is calculated based on ASHRAE’s cooling load temperature difference method (CLTD). CLTD provides engineers with corrected cooling temperature differences for each building component calculated for a specific time and day of a year. The following formula can be used to compute cooling load.

$$Q_{\text{cooling load}} = Q_{\text{walls \& roof}} + Q_{\text{fenestration}} + Q_{\text{ventilation}} + Q_{\text{people \& equipment}}$$

Eq. (2)

Heat transfer through the wall and roof are computed using the CLTD method.

$$Q_{\text{walls \& roof}} = U.A.\ CLTD_{\text{correction}}$$

where

Eq. (3)

$$CLTD_{correction} = (CLTD_{base} + LM) + (78-T_i) + (T_o-85)$$

Eq. (4)

CLTD $_{base}$ is looked up using tables provided by ASHRAE (1985 Fundamentals Handbook). CLTD $_{base}$ for roof and walls is provided in Tables 5 and 7 respectively in Chapter 26 of the ASHRAE 1985 Fundamentals Handbook. See (Table 1) and (Table 2) CLTD $_{base}$ for walls are categorized based on the construction group.

Table 1
Cooling Load Temperature Differences for Calculating Cooling Load from Flat Roofs (ASHRAE, 1985; 26.8)

With Suspended Ceiling

| Roof No | Description of construction | Weight | U-value | Solar Time |
|---|---|---|---|---|
| | | | | 14 |
| 3 | 4-in.1.w.concrete | 20 | 0.134 | 48 |

Table 2
Cooling Load Temperature Differences for Calculating Cooling Load from Sunlit Group C Walls (ASHRAE, 1985; 26.10)

| | Solar Time |
|---|---|
| Wall facing | 14 |
| N | 9 |
| NE | 20 |
| E | 27 |
| SE | 24 |
| S | 14 |
| SW | 13 |
| W | 13 |
| NW | 11 |

LM: Latitude month correction

LM is derived for Raleigh's latitude: 35.8° N based on the orientation of the surface from Table 9 in Chapter 26 of the ASHRAE 1985 Fundamentals Handbook. See (Table 3)

Table 3
CLTD Correction for Latitude and Month Applied to Walls and Roofs, North Latitudes (ASHRAE, 1985; 26.12)

| Lat. | Month | N | NNE<br>NNW | NE<br>NW | ENE<br>WNW | E<br>W | SSE<br>WSW | SE<br>SW | SSE<br>SSW | S | HOR |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 32 | May/Jul | 1 | 1 | 1 | 0 | 0 | -1 | -1 | -3 | -3 | 1 |
| 40 | May/Jul | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |

In Equation 4, $T_i$: Temperature Inside

$T_o$: Average Temperature Outside

For windows, there are two factors to be considered. The first is a conduction/ convection effect like a wall. The second is radiation that is transmitted through the glass.

$$Q_{\text{fenestration}} = U.A.\ CLTD_{window} + A \times SC \times SHGF \times CLF \qquad \text{Eq. (5)}$$

CLTD $_{window}$ can be looked up in Table 10 on Page 26.14 of the ASHRAE 1985 Fundamentals Handbook.

SC: shading coefficient depends on shading type and fenestration material (can be looked up in tables 34-37, pages 27. 34-35 ASHRAE 1985 Fundamentals Handbook)

This study uses SC=0.88 Btu/hr.ft$^2$.F for insulating glass with 1/8 inch thickness.

SHGF: solar heat gain factor varies based on the orientation at certain latitude (can be looked up in pages 26. 15-16) See (Table 4)

Table 4
Maximum Solar Heat Gain Factor, Btu/h.ft2 for Sunlit Glass, North Latitudes (ASHRAE, 1985; 26.15)

| | 36° N | | | |
|---|---|---|---|---|
| | N (shade) | E/W | S | HOR |
| July | 39 | 216 | 90 | 268 |

CLF: cooling load factor converts radiation to heat and depends on thermal mass, time and interior shading (can be looked up in pages 26. 17-18 1985 Fundamentals Handbook)

This study uses CLF for glass without interior shading at solar time 14:00 and assumes medium construction. Table 5 describes related details.

Table 5
Cooling Load Factors for Glass Without Interior Shading, North Latitudes ASHRAE, 1985; 26.17)

| Fenestration facing | N | E | W | HOR |
|---|---|---|---|---|
| CLF | 0.75 | 0.31 | 0.29 | 0.67 |

To complete equation 2, we need to calculate Q $_{ventilation}$

Q $_{ventilation}$ = CFM×ΔW

In order to better understand the computation, we calculate annual heating and cooling loads for July 9 at 14:00 for a central atrium building with skylight aperture orientation. Heating load for the central atrium building with a WI of 0.5 in Raleigh with given dimensions is as follows:

- $(UA)_{Wall} = 0.062\times(2\times15\times(90+146))$ Btu/hr-F
- $(UA)_{Roof} = 0.044\times((90\times146)-(30\times86))$ Btu/hr-F
- $(UA)_{Floor} =$ F-factor×Perimeter $= 0.35\times2\times(146+90)$ Btu/hr-F
- $(UA)_{Glazing} = 0.345\times(86\times30)$ Btu/hr-F
- $(UA)_{Infiltration} = 1.08\times$CFM $=1.08\times$(5 cfm/people×45 people) + (0.06 cfm/$ft^2$×13140 $ft^2$) = 1094.47 (based on ASHRAE, 2009)

$Q_{\text{Annual heating}} = UA_{\text{total}}\times$ Heating Degree-Hours (35160) = **107.35** kBtu×$10^{\wedge3}$

Table 6
CLTD Cooling Loads for a Central Atrium Building with WI=0.5 using the Skylight Roof in Raleigh

**$Q_{\text{cooling-July 9 at 14:00}}$**

| ***1. ENVELOPE*** | **British Units** | **Results** |
|---|---|---|
| ***OPAQUE EXTERIOR WALLS*** | | |
| Area | [ft2] | 7080 |
| U-value | [Btu/h-ft2-oF] | 0.062 |
| CLTD $_{correction}$ | [oF] | 11.7 |
| *Wall heat gain* | [Btu/h] | 5136 |
| ***Roof Horizontal Glazing*** | | |
| Area | [ft2] | 2580 |

Table 6 Continued

| | | |
|---|---|---|
| U-value | [Btu/h-ft2-oF] | 0.345 |
| *Aperture heat gain* | [Btu/h] | 419,244 |
| ***Roof Opaque Area*** | | |
| Area | [ft2] | 10560 |
| U-value | [Btu/h-ft2-oF] | 0.044 |
| CLTD $_{\text{correction}}$ | | 46.7 |
| *Roof heat gain* | [Btu/h] | 21699 |
| ***2. VENTILATION*** | | |
| ventilation requirements | [cfm/person] | 10 |
| ventilation requirements | [cfm/ft2] | 0.12 |
| total ventilation needed | [cfm] | 2880 |
| ΔW | [lbmwater/lbmdry air] | 10 |
| *total ventilation heat gain* | [Btu/h] | 126131 |
| ***3. INTERNAL GAINS*** | | |
| ***PEOPLE*** | | |
| sensible heat gain per person | [Btu/h] | 250 |
| latent heat gain per person | [Btu/h] | 200 |
| total heat gain per person | [Btu/h] | 450 |
| *total people heat gain - sensible* | [Btu/h] | 11250 |
| *total people heat gain - latent* | [Btu/h] | 9000 |

Table 6 Continued

| | | |
|---|---|---|
| *total people heat gain* | [Btu/h] | 20250 |
| ***EQUIPMENT*** | | |
| number of computers & monitors | [#] | 45 |
| computer & monitor heat gain | [W] | 150 |
| *total equipment heat gain* | [Btu/h] | 23018 |
| ***total cooling load*** | ***[kBtu/h]*** | ***615*** |

Comparing computer heating loads for an atrium with WI=0.5 using a skylight roof (98.08 kBtu×10^3) with the hand calculation result (107.35 kBtu×10^3) demonstrates a valid 9% difference. This study has also simulated cooling loads for July 9 at 14:00, resulting in 616.26 kBtu. The comparison between the computer simulation and CLTD hand calculation (615 kBtu) verifies the validity of cooling load computation.

## 2.6 LEED Requirements for Daylighting

Leadership in Energy & Environmental Design (LEED) is a green building certificate program that introduces energy efficient building strategies and practices. There are different levels of LEED certification that could be achieved through fulfilling certain prerequisites (USGBC, 2013). LEED is made up of a combination of categories, such as integrative process, location and transportation, materials and resources, water efficiency, energy and atmosphere, sustainable sites, indoor environmental quality, innovation, and regional priority credit. LEED has four levels of certification, determined by the number of points a project achieves. For instance, a project is LEED-certified if it earns 40-49 points, based on a scale of silver (50-59 points), gold (60-79 points), and platinum (80+ points). In 2009, LEED developed EQc8.1 for daylighting, through which a project could earn up to 2 points. This study considers LEED version 4 requirements to assess the atrium buildings. LEED v.4 suggests using sDA and ASE to evaluate buildings, by using three different options (Appendix A).

## 2.7 Literature Synthesis

Figure 8 summarizes outcomes of this literature review. This list of studies generally summarizes what has been covered by the efforts of previous researchers. It also introduces some important issues and limitations to be addressed by future research:

- Daylight Factor was used in the previous studies as a performance metric to assess daylight quantity. Daylight Factor is a static daylight metric that quantifies the amount of diffuse daylight under an overcast sky condition (New Buildings Institute, 2015). Because the luminance distribution of an overcast sky is symmetrical about the vertical axis going through the zenith and the sun component is excluded from the scenario, this method has two disadvantages. First, it is insensitive to the building orientation because of the symmetrical sky luminance distribution, and, secondly, it is insensitive to the location, hence the climate, of the building. Consequently, it would be more practical to assess daylighting systems by a climate-based method, in which case various types of sky conditions (e.g., clear sky or intermediate sky) are all taken into consideration.

- Climate-based daylight modeling is a daylight prediction model that defines various luminous quantities using sun and sky conditions derived from meteorological datasets. CBDM uses Daylight Autonomy and Useful Daylight Illuminance as performance metrics (Mardaljevic, Heschong, & Lee, 2009). As a tool to conduct CBDM, DIVA-for-Rhino was developed by the Graduate School of Design at Harvard University. “It is a highly optimized daylighting and energy modeling plug-in for the Rhinoceros NURBS modeler” (Solemma LLC, 2014). Compared to the conventional Daylight Factor approach that only involves overcast sky condition, DIVA uses TMY3 weather data to calculate climate-based results. However, including climate as a factor can make the results less broadly applicable, because they are climate-specific. For example, the daylighting results assessed in a building located in rainy Seattle cannot be applied to the same building design located in sunny Phoenix. As the starting point of developing the database, this present study focuses on climate zone 3 based on U.S. climate zones. However, replicating computer simulations for all eight climate zones in the United States (based on Department of Energy’s classification) will complete the data set.
- The previous studies tend to address the averaged daylight quantities across all adjoining floors by using Mean Daylight Factor. However, the daylight performances at individual floors (e.g., top, bottom, and middle floors) were not studied separately.
- The impact of atrium roof aperture has not been a focus of the previous studies, in which atria were examined as “courtyards” regardless of their aperture type.

- Limitations of previous expert systems for designers.

To address the above issues, this dissertation is intended to apply the CBDM approach in the assessment of atrium buildings in terms of daylight quantity. Specifically, the objectives are:

- To use the climate-based daylight modeling (CBDM) approach to assess atrium and adjoining spaces by using the WI (Equation 1) as the method of characterizing atrium proportions;
- To examine the impact of atrium aperture type — central, attached and semi-enclosed atria;
- To examine the impact of atrium roof aperture type on daylight performance;
- To examine the impact of furniture layout on daylight metrics; and
- To provide architects with a database to assist them with evaluating the performance of atrium buildings without conducting complex computer simulations.

To simplify the research and limit the number of parameters, the following assumptions are established:

- The atrium shape is assumed to be quadrangular with the focus on north- and south-facing spaces due to the undesirable eastern and western daylight exposures.
- Roof glazing transmittance and surface reflectance are set to be constant across different options.

This research is focused on daylight at the interior envelope of the building (the facades between atrium and adjoining spaces), rather than dealing with the urban façades (facades facing the streets) (Beckers, 2012). Therefore, the atrium’s contribution is considered the sole source of daylight to its adjoining spaces in instances in which a 30-foot depth is assumed from the boundary between the atrium and the adjoining spaces.

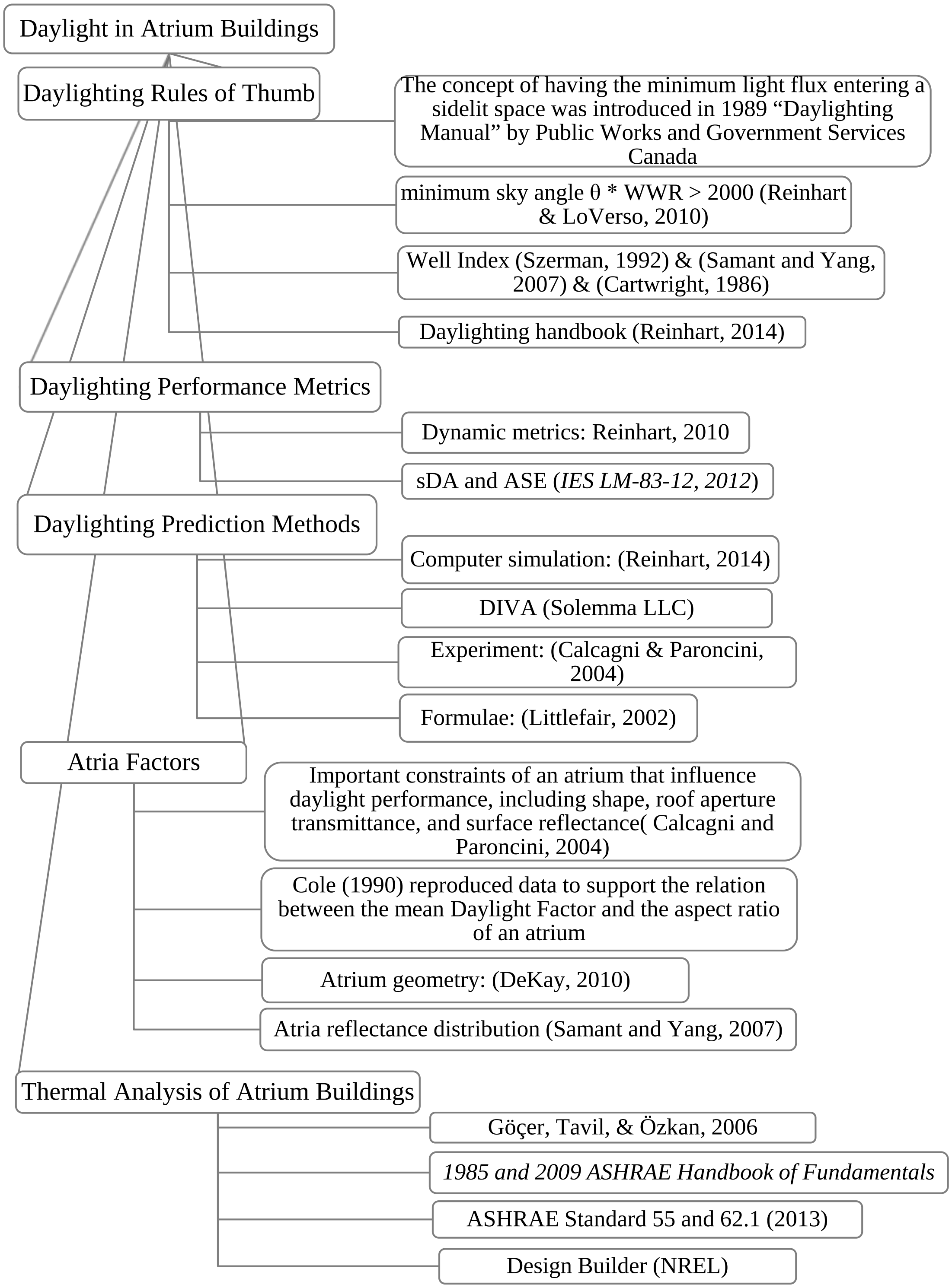


Figure 8. Summary of the literature review map

# Chapter 3 RESEARCH METHODOLOGY

## 3.1 Conceptual Framework

One of the objectives of this research is to provide architects with a design database to assist them in evaluating the performance of atrium buildings without investing a substantial amount of time in energy analysis. To build such a database for atrium buildings, this project focuses on daylighting and thermal performances (output) based on the climate in Raleigh, NC. Daylight performance is assessed by spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE), and thermal evaluation is based on annual heating and cooling loads. Atrium factors that are considered in the study consist of atrium type, proportion (Well Index), and roof aperture type as the primary independent variables (input). In all simulations in this study, daylight is measured in two areas that measure 30 ft×30 ft adjacent to north and south of the atrium.

### *3.1.1 Atrium Types*

Figure 9 represents common atrium types. This study examines central and attached atria. The daylight results in atria have the potential to be applied in urban settings, assuming

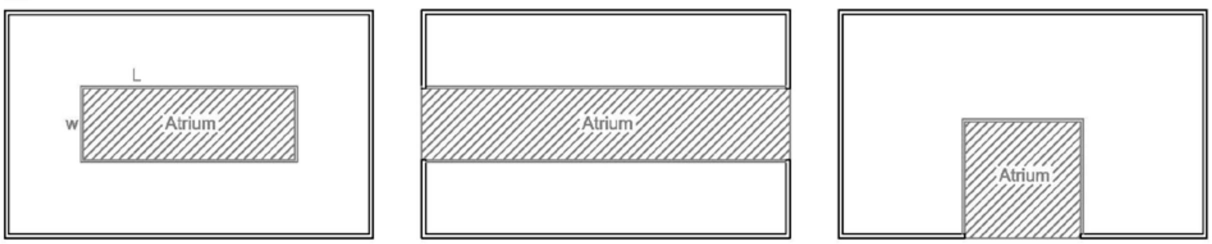


Figure 9. Atrium types plan view (left to right): central, attached and semi-enclosed (Huang, 2003)

an atrium as an open urban space.

### 3.1.2 Roof Aperture Types

This research considers monitor and horizontal skylight aperture types, because of their prevalent use in buildings (

Figure 10). Monitor roof apertures have the advantage of providing the space primarily with diffuse light, while horizontal skylights tend to introduce direct sun beams that cause glare.

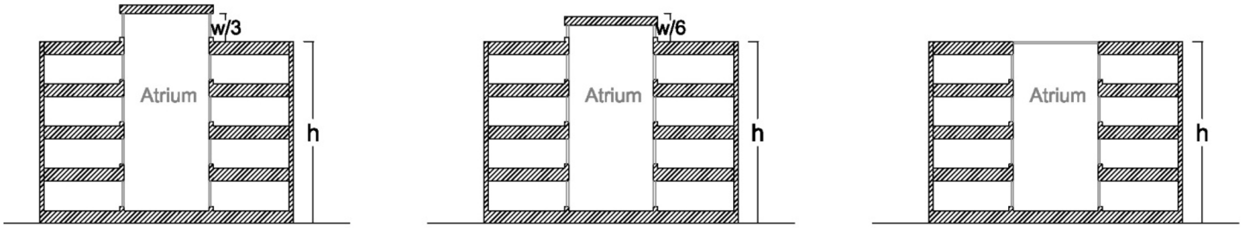


Figure 10. Aperture types (left to right) monitor w/3, monitor w/6, and horizontal skylight

To assess the effect of monitor glazing height, this research examined daylight metrics for atria with the same Well Index but different glazing height equal to one third and one sixth of atrium width (w). This hypothesis is tested in atrium buildings with glazing heights smaller than one sixth of the atrium's width. Though assuming a glazing height of one half the atrium's width demonstrates higher spatial Daylight Autonomy, it potentially causes glare and may not be architecturally feasible. For instance, a two-story building with an atrium 30 ft wide does not need a monitor roof height of 15 ft. The results, shown in

Figure 11, are tested for an atrium with a Well Index of 1. The same study is repeated for atria with WI=0.5 and WI=2, resulting in the same findings.

Figure 11 illustrates the increase in sDA and ASE based on the increase in monitor glazing height. The results demonstrate that $sDA_{300,\ 50\%}$ is greater than 50% when the monitor glazing height exceeds one sixth of atrium width, while smaller heights do not have a great impact on sDA and ASE. It is therefore empirically concluded to control monitor glazing height by running simulations for monitor glazing height equal to one third and one sixth of atrium width.

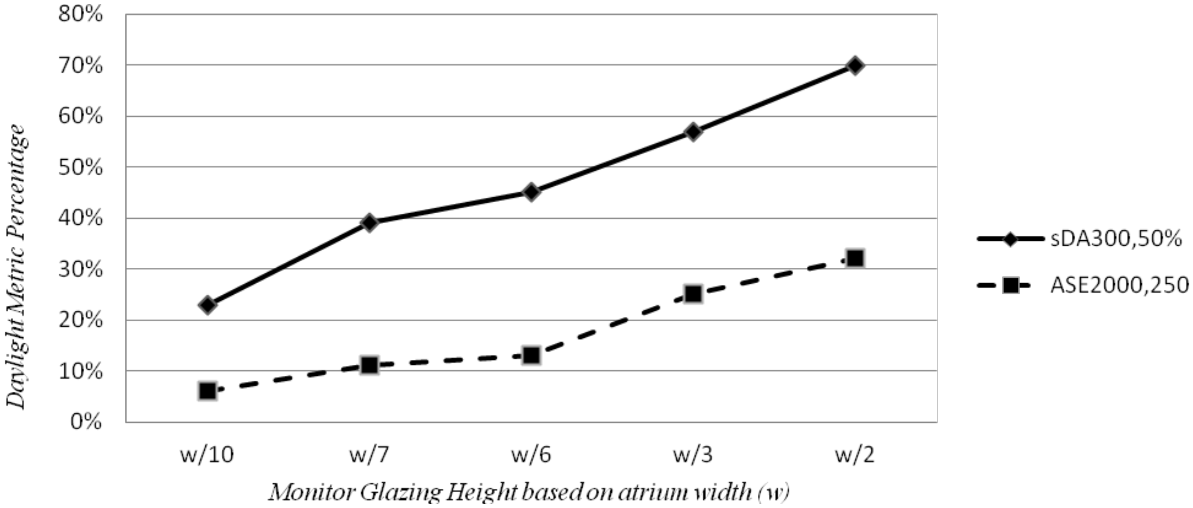


Figure 11. Monitor roof glazing height

### *3.1.3 Well Index and its Validity*

As it was mentioned, Well Index (WI) is used to characterize and measure the obstructive effects in atrium buildings.

$$\mathrm{WI} = \frac{\mathrm{height\ (width + length)}}{2 \times \mathrm{width} \times \mathrm{length}}$$

Eq. (1)

It has been demonstrated that Well Index is an effective indicator for characterizing atrium proportions in studies based on Daylight Factor (Calcagni & Paroncini, 2004; DeKay, 2010). In this section, we are investigating the validity of the Well Index for characterizing atrium proportion when dynamic daylighting approach (CBDM) is adopted. Specifically, the questions are:

- Will atria with the same Well Index result in the same averaged dynamic daylight metrics, across all floors?
- Will atria with the same Well Index result in the same dynamic daylight metrics at the bottom floor?

For instance, the following two atria have the same Well Index (WI=1).

- 60 ft×60 ft central atrium in a four-story building (building height = 15 ft×4= 60 ft)
- 45 ft×225 ft central atrium in a five-story building (building height = 15 ft×5= 75 ft)

Results from computer simulations show that the average sDA and ASE of the adjoining spaces in both atria listed above are the same. Table 7 shows the results from testing other Well Indices in different atrium types and roof aperture designs. The results have confirmed that no significant difference exists between the average dynamic daylight metrics among atria with the same Well Index. The results in Table 7 also demonstrate no significant difference in terms of heating and cooling loads per cubic feet among atria with the same Well Index. These findings are significant in that atrium proportion can be characterized by Well Index rather than by actual dimensions. This can also drastically streamline the creation of the proposed atrium design database, because it is not practically feasible to list performance data for all possible atrium dimensions.

Table 7
Well Index Validity

| Roof type | Height | Atrium width | Atrium depth | Avg $sDA_{300, 50\%}$ | Avg $ASE_{1000, 250}$ | Bottom $sDA_{300, 50\%}$ | Bottom $ASE_{1000, 250}$ | Cooling/ft$^3$ | Heating/ft$^3$ |
|---|---|---|---|---|---|---|---|---|---|
| Central Atrium WI=1 | | | | | | | | | |
| skylight | 4×15 | 60 | 60 | 0.63 | 0.51 | 0.29 | 0.33 | 2.73 | 0.59 |
| skylight | 5×15 | 75 | 75 | 0.63 | 0.51 | 0.25 | 0.33 | 3.59 | 0.55 |
| skylight | 5×15 | 45 | 225 | 0.63 | 0.46 | 0.25 | 0.33 | 3.49 | 0.55 |
| monitor w/3 | 4×15 | 60 | 60 | 0.5 | 0.29 | 0.17 | 0.08 | 1.65 | 1.22 |
| monitor w/3 | 5×15 | 75 | 75 | 0.55 | 0.32 | 0.17 | 0.08 | 1.23 | 1.11 |
| Central Atrium WI=0.5 | | | | | | | | | |
| skylight | 3×15 | 90 | 90 | 0.81 | 0.67 | 0.59 | 0.58 | 3.50 | 0.61 |
| skylight | 5×15 | 100 | 300 | 0.85 | 0.67 | 0.65 | 0.58 | 2.15 | 0.66 |
| Attached Atrium WI=0.5 | | | | | | | | | |
| skylight | 4×15 | 120 | 120 | 1 | 0.8 | 1 | 0.77 | 3.50 | 0.61 |
| skylight | 5×15 | 100 | 300 | 0.97 | 0.75 | 0.94 | 0.67 | 2.15 | 0.66 |
| Central Atrium WI=2 | | | | | | | | | |
| skylight | 4×15 | 30 | 30 | 0.33 | 0.24 | 0 | 0 | 2.68 | 0.52 |
| skylight | 5×15 | 37.5 | 37.5 | 0.31 | 0.22 | 0 | 0 | 2.20 | 0.56 |
| skylight | 5×15 | 25 | 75 | 0.32 | 0.24 | 0 | 0 | 2.20 | 0.56 |

This research has also tested whether the daylight level remains the same in individual floors in atria with the same Well Index. This study assumes the same atrium type and roof designs in all comparisons in addition to their Well Index. The results in Table 7 indicate that sDA and ASE remain the same for the bottom floor in different atrium buildings with the same Well Index. To predict the daylight level at any other adjoining floor of an atrium, one can imagine the atrium floor is “sliding” up to become flush with the floor of interest, which will result in a new atrium proportion and a new Well Index. Now the floor of interest has been transformed into the bottom floor of a new atrium building and its performance can be predicted by using the bottom floor performance data obtained from an atrium with the same Well Index. For example, Figure 12 shows this thought process for assessing the top floor in a 60 ft×60 ft four-story building as the one in a 45 ft×225 ft five-story building, with both having a Well Index = 1.00. Comparing the two cases, researchers realized that individual floors have the same performance if the Well Index of that individual floor is the same. To be more specific, every single floor could be treated as a building with a Well Index characterization and this Well Index will give the same energy modeling results no matter which floor number it has.

For instance, the WI $_{\text{third floor}}$ in a 30 ft×30 ft four-story atrium is 1.00 and its daylight and energy performance are the same as the ones in the first floor of a two-story building with an atrium of 30 ft×30 ft. Figure 12 illustrates the idea that by “sliding” individual floors,

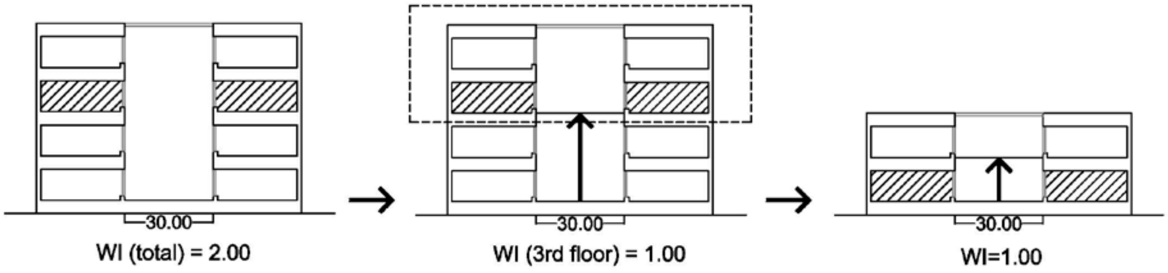


Figure 12. “Sliding” concept of individual floors in atria to calculate Well Index in individual levels

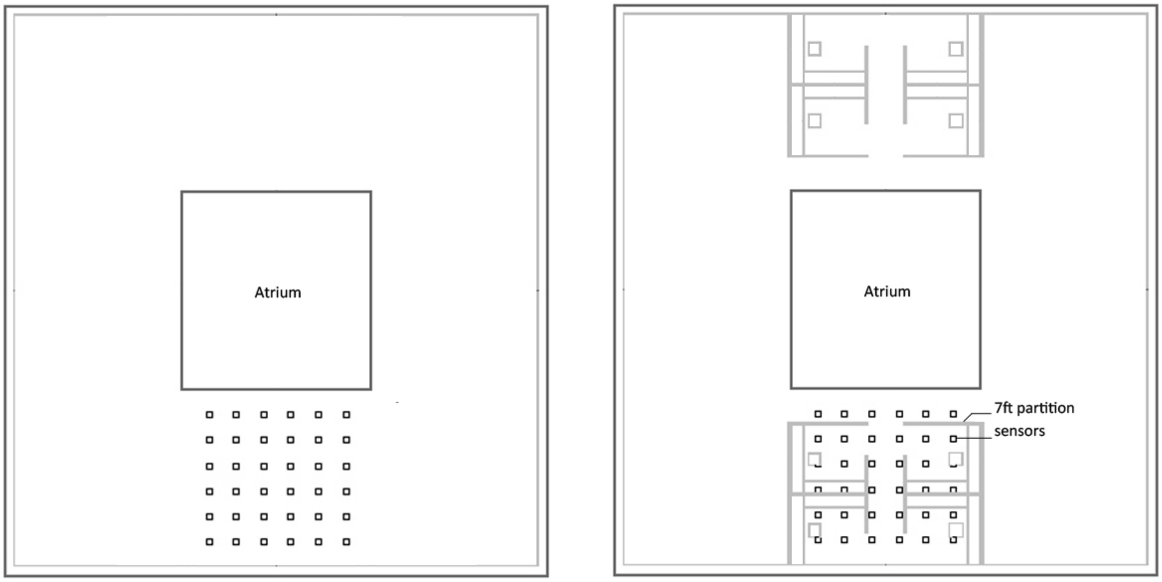
we can calculate the WI of that specific floor, which gives the same energy performance in atria with the same Well Index but with different building proportions.

Heating and cooling per the cubic feet of the atrium itself has been calculated and confirmed that they remain the same among atrium with the same Well Index under the same conditions. As mentioned before, conditions include the climate, atrium type, roof aperture design and material properties, which are controlled in this study. This finding provides researchers with the fact that the Well Index not only provides them with the average dynamic daylight metric, but it gives information for every individual floor. The reason behind this is explained by the sky angle, which changes based on the height and width of the atrium. Therefore, this research concluded to calculate dynamic daylight metrics and energy performance of atria for 0.1 intervals of atrium Well Index atrium to cover more dimension variations.

### *3.1.4 Furniture*

The IES (LM-83-12) standard suggests that furniture be modeled within 6 inches of accuracy and with 25-45% reflectance (Illuminating Engineering Society, 2012). This recommendation is consistent with the Analysis of Daylighting Requirements recommended by Pacific Northwest National Lab (Athalye, Xie, & Liu, 2013) in ASHRAE Standard 90.1. Dubois (2001), however, simulated spaces without furniture, arguing that this method provided an average light distribution in a space. The results indicated that the difference between an unfurnished and furnished space is dependent on the sun angle, distance from the window, and the furniture layout (Dubois, 2001). Dubois performed point-in-time assessment rather than simulated annual results. Since furniture arrangements result in diverse illuminance distributions under different sky and solar conditions, this study suggests that the impact of furniture be assessed by computer simulation.

The simulation is conducted in a 30 ft×30 ft space to the south of a central atrium with a skylight roof and WI= 0.5 in Raleigh, NC. An unfurnished open space serves as the base case. Case 1 includes a combination of 7 ft and 3.6 ft-high office partitions. These models are simulated in DIVA for Rhino, assuming furniture reflectance value of 45% (recommended by IES, 2012). The results show a 27% decrease from the base case (unfurnished) to case 1 (furnished), with a 6% difference in $ASE_{1000, 250}$ (Figure 13).



| | Base case | Case 1 |
|---|---|---|
| $sDA_{300, 50\%}$ | 0.94 | 0.67 |
| $ASE_{1000, 250}$ | 0.50 | 0.44 |
| $ASE_{3000, 250}$ | 0.17 | 0.17 |

Figure 13. The impact of furniture on daylight using skylight aperture with WI= 0.5

Based on these assessments, this research suggests that partitions be included in simulations (Figure 14). Since different reflectance values did not considerably change the results, future simulations will be done using 45-50% as the furniture reflectance.

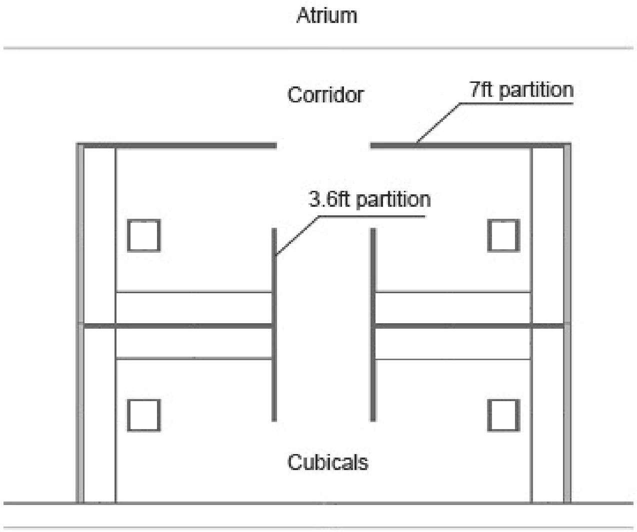


Figure 14. Plan view of the furniture layout in a typical office

## 3.2 Research Method

This study applies a two-stage research design including *Scale-Model Experiment for Validating computer simulation* and *Computer-based Simulation* as the primary tool for assessing daylighting models.

### *3.1.5 Validating Computer Simulation by Scale-Model Experiment*

DIVA for Rhino is an optimized daylight and energy analysis tool based on radiance for daylight analysis. In order to verify the accuracy of computer-simulation results, a validation study is conducted to compare results collected from a physical scale-model with an atrium and computer simulation with the same building. Both physical and computer simulation models measure at 140 ft ×140 ft (four floors) with a central atrium of 36 ft ×36 ft. In both physical and computer models, four sensors are placed on each floor at the center of the adjoining spaces surrounding the atrium (north wing, south wing, west wing and east wing), which are labeled from A1 to A16 starting from the top floor. The atrium wall surfaces in the scale model are painted at 80% reflectance for ceilings, 58% for walls and 38% for floor levels. The physical model was monitored at North Carolina State University Daylight Lab in Raleigh, NC and hourly illuminance measurements are collected for six months. The data was collected by Campbell Scientific CR1000 logger and LI-COR 210 photometric sensors, and compared with DIVA version 2.1.0.3 simulation results. Figure 15 illustrates the scale model constructed at a scale of 1:6.

Useful Daylight Illuminance (UDI - 100-2000 lux) between scale-model data and computer simulation is compared in this study, because it addresses both lower and upper thresholds. UDI is defined as the percentage of hours that fall between 100-2000 lux for a point of interest in a space. Another reason to use UDI, instead of sDA, is because only one sensor is placed at each adjoining space, while sDA and ASE measurements require a grid of

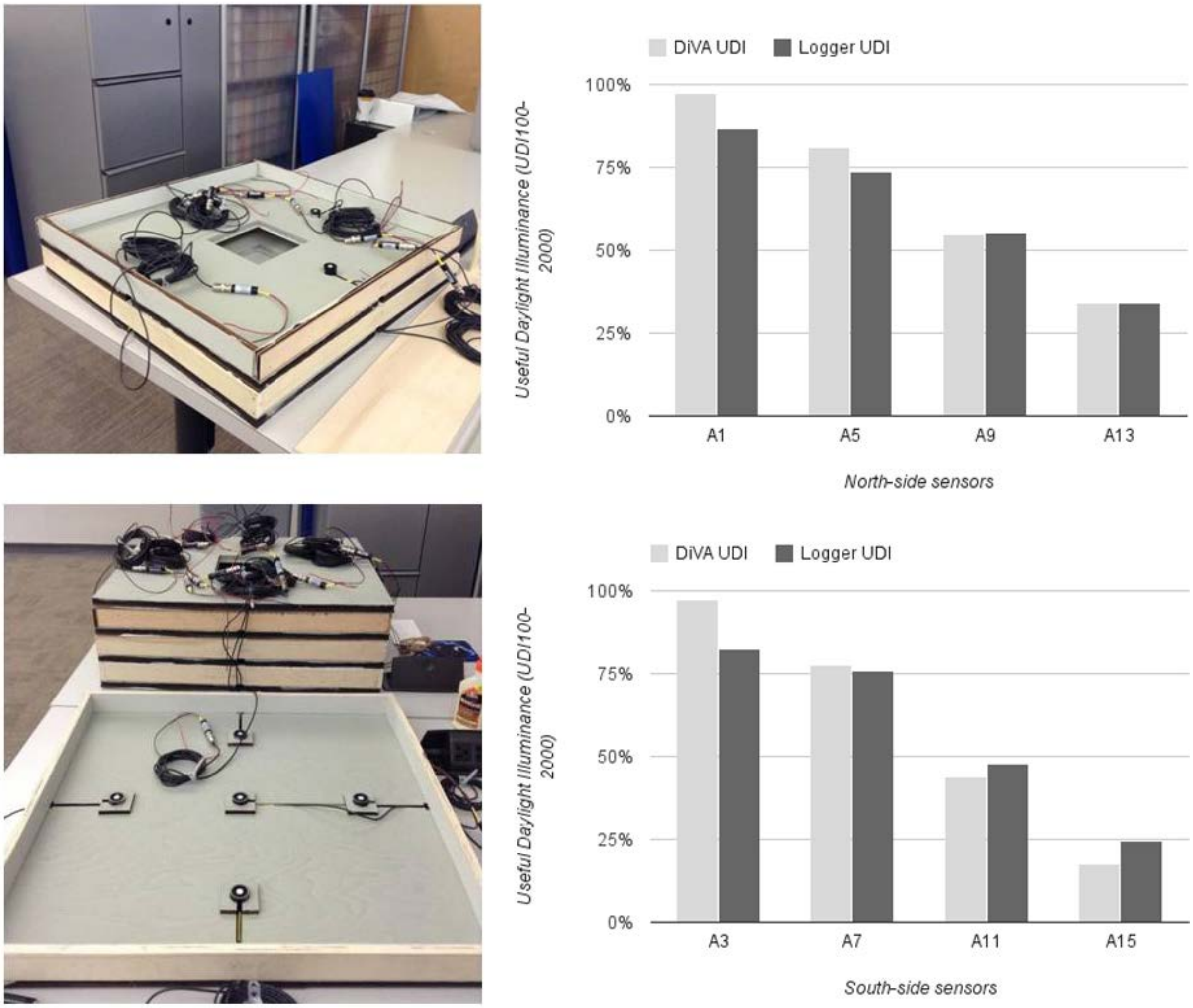


Figure 15. Scale-model validation of DIVA for Rhino through 6-month data

sensors to provide the percentage of space that meets a certain level of daylight.

Figure 15 shows the comparison between computer simulation and physical scale model testing results for all north-wing sensors (A1, A5, A9, A13) and south-wing sensors (A3, A7, A11, A15). The results show that performance data UDIs obtained from physical model testing and computer simulation are reasonably close.

### *3.1.6 Computer-Model Simulation*

Atrium sizes are estimated based on the average size for small office parcels in Raleigh, NC (ASHRAE, Advanced Energy Design Guide for Small Office Buildings: 30% Energy Savings, 2011). Based on the maximum potential depth for daylight penetration, the depth of the adjoining spaces is assumed to be 30 ft, and floor-to-ceiling height is 10 ft, and the height of ceiling interstitial space is 5 ft. This study assumes generic materials with typical surface reflectance for the floor at 20%, the ceiling at 80%, the wall at 50% and double-pane low-E glass at 65% transmittance for roof glazing. The atrium partition (the wall between atrium and adjoining space) is defined as a single-pane glazing with 88% transmittance.

This research expands its database by exploring more Well Index cases starting from 0.1 to 2. The following shows specification of the explored cases (Table 8).

Table 8
Specification of Explored Atrium Cases

| WI | Atrium dimensions (ft) | Height |
|---|---|---|
| 0.1 | 150×150 | 1×15 |
| 0.2 | 90×90 | 1×15 |
| 0.3 | 90×30 | 1×15 |
| 0.4 | 25×75 | 1×15 |
| 0.5 | 90×90 | 3×15 |
| 1 | 90×30 | 3×15 |
| 1.5 | 40×40 | 4×15 |
| 2 | 25×75 | 5×15 |

#### 3.1.6.1 Daylight Simulation Settings

Illuminance values are simulated in a 30×30 ft area adjacent to the north and south side of an atrium, where light sensors are placed on a 3.5×3.5 ft grid (Figure 16).

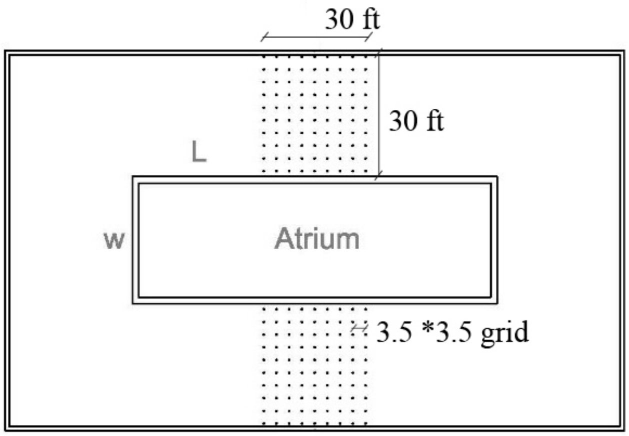


Figure 16. Daylight sensor grids used in computer simulations

Radiance uses a series of parameters to simulate a daylit space: Ambient bounces (ab) represent the number of reflections between the surfaces, which, along with ambient division, can have a significant impact on the accuracy of daylight output. Ambient division (ad) and super-samples set the number of samples sent. Ambient resolution (ar) specifies the maximum error, scene dimension, and the sampling cutoff point. Table 9 summarizes the minimum, accurate, and maximum radiance ambient parameters, on which this study is based (Ward, 2014).

Table 9
Radiance Ambient Parameters

| Parameters | Description | Min | Fast | Accurate | Current Research | Max |
|---|---|---|---|---|---|---|
| ab | ambient bounces | 0 | 0 | 2 | 6 | 8 |
| aa | ambient accuracy | .5 | .2 | .15 | .1 | 0 * |
| ar | ambient resolution | 8 | 32 | 128 | 300 | 0 * |
| ad | ambient divisions | 0 | 32 | 512 | 1000 | 4096 |
| as | ambient super-samples | 0 | 32 | 256 | 256 | 1024 |

* Maximum value disables optimization and can be very expensive

#### 3.1.6.2 Thermal Simulation Settings

The atrium is modeled in Design Builder with adiabatic walls between atrium and adjoining spaces. Cloning each story of the building on top of the other automatically converts floors to adiabatic, through which there is no heat transfer. Table 10 shows material thermal conductance used in this study and Table 11 shows the climatic data of Raleigh, NC.

Table 10
U-value for Different Materials Used in This Study

| Building material | U-value |
|---|---|
| Roof: Asphalt+Air gap+Plasterboard | 0.044 |
| Wall: Brickwork+XPS extruded polystyrene+Concrete block | 0.062 |
| Ground floor: UF foam+Cast concrete+screed+Wooden flooring | 0.35 |
| Roof glazing: Double-pane Low-E 65% | 0.345 |

Table 11
Climate Data for Raleigh, NC

| *Climate data for Raleigh, ASHRAE* ***Cooling 0.4% Data*** | |
|---|---|
| Cooling dry bulb Temperature [$^{o}$F] | *94.1* |
| Humidity ratio [lbs moisture/lb dry air] | *0.016* |
| Summer occupied setpoint [$^{o}$F] | *76* |
| Summer occupied humidity ratio [lbs moisture/lb dry air] | *0.0096* |
| Total Solar Radiation - Horizontal [Btu/ft2/day] | *75* |
| Average Outside temperature in July 9th | *80.7* |
| *CLIMATE DATA, ASHRAE* ***Heating 99.6% Data*** | |
| Heating dry bulb Temperature [$^{o}$F] | *16* |
| Winter occupied setpoint [$^{o}$F] | *68* |

# Chapter 4 RESEARCH FINDINGS AND CONCLUSION

This study has investigated the effects of atrium proportion (characterized by Well Index), roof aperture design (skylight and monitor) and atrium type (central and attached) on daylighting and energy performances. While Well Index was used in previous studies to assess daylit atria in terms of Daylight Factor, this study has evaluated the validity of Well Index for characterizing atrium proportion by using climate-based metrics and concluded that atria sharing the same Well Index will have lighting and energy performances that are significantly close. This finding implies that one can simulate a series of atria with distinct Well Index values (e.g., from WI= 0.1 to WI= 2 with 0.1 intervals). The lighting and energy performance data associated with each of the WI values can form a database. This will allow designers to calculate the Well Index of their own specific atrium design, and use the calculated WI value to look up its performance in the database. In addition, different roof aperture design and atrium type are added as additional design parameters for each Well Index value in the database.

Research findings in this study are discussed here in terms of the lighting and energy assessments. The last section of the research findings focuses on the user interface (UI) design of an online tool, which is based on the database created in this project. This tool aims to provide designers a user-friendly interface for accessing daylighting and energy data for atrium designs in early design phases.

## 4.1 Lighting Assessment

Table 12 summarizes daylight results for central, attached and semi-enclosed atria with monitor and skylight as roof apertures, based on a Well Index of 0.5, 1 and 2. With other parameters, such as the climate, adjoining space depth, material reflectance, material transmittance, furniture and monitor roof glazing height, the results potentially provide architects with a preliminary atrium design database for Raleigh, NC.

Table 12
Daylight Metrics for Monitor and Skylight Roof in Central, Attached and Semi-Enclosed Atria

| Atrium Type | WI | Roof Type | $sDA_{300, 50\%}$ | $ASE_{1000, 250}$ | $ASE_{3000, 250}$ |
|---|---|---|---|---|---|
| Central | 0.5 | monitor w/3 | 0.59 | 0.38 | 0.20 |
| | 0.5 | monitor w/6 | 0.44 | 0.25 | 0.14 |
| | 0.5 | skylight | 0.64 | 0.52 | 0.31 |
| | 1 | monitor w/3 | 0.38 | 0.25 | 0.13 |
| | 1 | monitor w/6 | 0.22 | 0.11 | 0.04 |
| | 1 | skylight | 0.45 | 0.40 | 0.24 |
| | 2 | monitor w/3 | 0.25 | 0.20 | 0.09 |
| | 2 | monitor w/6 | 0.10 | 0.05 | 0.04 |
| | 2 | skylight | 0.27 | 0.24 | 0.04 |
| Attached | 0.5 | monitor w/3 | 0.92 | 0.59 | 0.30 |
| | 0.5 | monitor w/6 | 0.87 | 0.51 | 0.19 |
| | 0.5 | skylight | 0.95 | 0.61 | 0.31 |
| | 1 | monitor w/3 | 0.58 | 0.38 | 0.13 |
| | 1 | monitor w/6 | 0.55 | 0.25 | 0.09 |
| | 1 | skylight | 0.60 | 0.40 | 0.19 |
| | 2 | monitor w/3 | 0.54 | 0.39 | 0.15 |
| | 2 | monitor w/6 | 0.53 | 0.33 | 0.09 |
| | 2 | skylight | 0.63 | 0.49 | 0.21 |
| Semi-enclosed | 0.5 | monitor w/3 | 0.73 | 0.67 | 0.41 |
| | 0.5 | monitor w/6 | 0.67 | 0.59 | 0.26 |
| | 0.5 | skylight | 0.77 | 0.67 | 0.44 |
| | 1 | monitor w/3 | 0.93 | 0.69 | 0.43 |
| | 1 | monitor w/6 | 0.89 | 0.70 | 0.37 |
| | 1 | skylight | 1.00 | 0.70 | 0.48 |
| | 2 | monitor w/3 | 0.87 | 0.69 | 0.45 |
| | 2 | monitor w/6 | 0.86 | 0.70 | 0.39 |
| | 2 | skylight | 0.94 | 0.70 | 0.47 |

### 4.1.1 *Climate-Based Metrics*

More simulations have been conducted to cover more WIs with denser intervals (Table 13 and Table 14). Certain data are constructed by using the linear interpolation method. Interpolation is a method to generate new data within a discrete set of known data points, using the following equation:

$$\frac{y - y_a}{x - x_a} = \frac{y_b - y_a}{x_b - x_a} \qquad \text{Eq. (6)}$$

Using CBDM has limited the results to a certain climate zone such as the one in which Raleigh is located (zone 3). The current project is intended to develop a methodology for this type of research. The database certainly needs more entries to cover more climate conditions beyond Raleigh, NC.

Table 13
Energy Performance of Central Atria Based on Well Index

| WI | Roof | Avg sDA | Avg ASE$_{1000}$ | Avg ASE$_{3000}$ | sDA | ASE$_{1000}$ | ASE$_{3000}$ | Cooling | Heating |
|---|---|---|---|---|---|---|---|---|---|
| 0.1 | monitor w/3 | 0.9 | 0.53 | 0.19 | 0.9 | 0.53 | 0.19 | 1.68 | 1.09 |
| 0.1 | monitor w/6 | 0.58 | 0.26 | 0.08 | 0.58 | 0.26 | 0.08 | 1.92 | 0.89 |
| 0.1 | skylight | 0.86 | 0.65 | 0.31 | 0.86 | 0.65 | 0.31 | 9.49 | 0.70 |
| 0.2 | monitor w/3 | 0.69 | 0.44 | 0.19 | 0.69 | 0.44 | 0.19 | 2.26 | 1.11 |
| 0.2 | monitor w/6 | 0.56 | 0.32 | 0.1 | 0.56 | 0.32 | 0.1 | 2.41 | 0.83 |
| 0.2 | skylight | 0.72 | 0.56 | 0.31 | 0.72 | 0.56 | 0.31 | 9.22 | 0.66 |
| 0.3 | monitor w/3 | 0.63 | 0.42 | 0.19 | 0.63 | 0.42 | 0.19 | 3.41 | 1.23 |
| 0.3 | monitor w/6 | 0.35 | 0.11 | 0 | 0.35 | 0.11 | 0 | 3.17 | 0.99 |
| 0.3 | skylight | 0.67 | 0.58 | 0.31 | 0.67 | 0.58 | 0.31 | 10.55 | 1.18 |
| 0.4 | monitor w/3 | 0.6 | 0.42 | 0.19 | 0.6 | 0.42 | 0.19 | 3.27 | 1.03 |
| 0.4 | monitor w/6 | 0.29 | 0.14 | 0.08 | 0.29 | 0.14 | 0.08 | 2.89 | 0.78 |
| 0.4 | skylight | 0.42 | 0.31 | 0.08 | 0.42 | 0.31 | 0.08 | 9.93 | 0.62 |
| 0.5 | monitor w/3 | 0.59 | 0.38 | 0.2 | 0.43 | 0.33 | 0.22 | 1.40 | 0.98 |
| 0.5 | monitor w/6 | 0.44 | 0.25 | 0.14 | 0.33 | 0.19 | 0.17 | 1.25 | 0.65 |
| 0.5 | skylight | 0.64 | 0.52 | 0.31 | 0.6 | 0.47 | 0.31 | 2.15 | 0.66 |
| 0.6 | monitor w/3 | 0.55 | 0.36 | 0.18 | 0.38 | 0.28 | 0.20 | 1.45 | 1.03 |
| 0.6 | monitor w/6 | 0.40 | 0.22 | 0.12 | 0.28 | 0.17 | 0.14 | 1.23 | 0.67 |
| 0.6 | skylight | 0.60 | 0.50 | 0.29 | 0.53 | 0.43 | 0.29 | 2.27 | 0.65 |

Table 13 Continued

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 0.7 | monitor w/3 | 0.51 | 0.33 | 0.17 | 0.33 | 0.23 | 0.17 | 1.50 | 1.08 |
| 0.7 | monitor w/6 | 0.35 | 0.19 | 0.10 | 0.23 | 0.15 | 0.11 | 1.22 | 0.69 |
| 0.7 | skylight | 0.57 | 0.48 | 0.28 | 0.46 | 0.38 | 0.28 | 2.38 | 0.64 |
| 0.8 | monitor w/3 | 0.47 | 0.30 | 0.16 | 0.28 | 0.18 | 0.14 | 1.55 | 1.13 |
| 0.8 | monitor w/6 | 0.31 | 0.16 | 0.08 | 0.20 | 0.13 | 0.10 | 1.20 | 0.71 |
| 0.8 | skylight | 0.53 | 0.46 | 0.27 | 0.39 | 0.34 | 0.24 | 2.50 | 0.62 |
| 0.9 | monitor w/3 | 0.42 | 0.28 | 0.14 | 0.22 | 0.13 | 0.11 | 1.60 | 1.17 |
| 0.9 | monitor w/6 | 0.26 | 0.12 | 0.06 | 0.16 | 0.10 | 0.09 | 1.18 | 0.74 |
| 0.9 | skylight | 0.50 | 0.43 | 0.25 | 0.32 | 0.29 | 0.21 | 2.61 | 0.61 |
| 1 | monitor w/3 | 0.38 | 0.25 | 0.13 | 0.17 | 0.08 | 0.08 | 1.65 | 1.22 |
| 1 | monitor w/6 | 0.22 | 0.09 | 0.04 | 0.13 | 0.08 | 0.08 | 1.16 | 0.76 |
| 1 | skylight | 0.46 | 0.41 | 0.24 | 0.25 | 0.25 | 0.17 | 2.73 | 0.59 |
| 1.1 | monitor w/3 | 0.33 | 0.21 | 0.11 | 0.16 | 0.08 | 0.08 | 1.58 | 1.15 |
| 1.1 | monitor w/6 | 0.18 | 0.07 | 0.03 | 0.09 | 0.06 | 0.06 | 1.14 | 0.77 |
| 1.1 | skylight | 0.40 | 0.36 | 0.21 | 0.23 | 0.23 | 0.17 | 2.73 | 0.58 |
| 1.2 | monitor w/3 | 0.28 | 0.18 | 0.08 | 0.15 | 0.08 | 0.07 | 1.51 | 1.08 |
| 1.2 | monitor w/6 | 0.13 | 0.05 | 0.02 | 0.06 | 0.05 | 0.03 | 1.11 | 0.78 |
| 1.2 | skylight | 0.35 | 0.31 | 0.18 | 0.22 | 0.22 | 0.16 | 2.72 | 0.57 |
| 1.3 | monitor w/3 | 0.22 | 0.14 | 0.05 | 0.14 | 0.08 | 0.05 | 1.44 | 1.01 |
| 1.3 | monitor w/6 | 0.09 | 0.03 | 0.01 | 0.04 | 0.03 | 0.02 | 1.08 | 0.79 |
| 1.3 | skylight | 0.29 | 0.26 | 0.15 | 0.20 | 0.20 | 0.13 | 2.72 | 0.56 |
| 1.4 | monitor w/3 | 0.17 | 0.11 | 0.03 | 0.13 | 0.08 | 0.03 | 1.37 | 0.95 |
| 1.4 | monitor w/6 | 0.05 | 0.02 | 0.01 | 0.02 | 0.02 | 0.01 | 1.06 | 0.80 |
| 1.4 | skylight | 0.23 | 0.22 | 0.12 | 0.19 | 0.19 | 0.11 | 2.72 | 0.56 |
| 1.5 | monitor w/3 | 0.11 | 0.07 | 0 | 0.11 | 0.07 | 0 | 1.29 | 0.88 |
| 1.5 | monitor w/6 | 0 | 0 | 0 | 0 | 0 | 0 | 1.03 | 0.80 |
| 1.5 | skylight | 0.17 | 0.17 | 0.08 | 0.17 | 0.17 | 0.08 | 2.72 | 0.55 |
| 1.6 | monitor w/3 | 0.15 | 0.10 | 0.02 | 0.09 | 0.06 | 0.00 | 1.22 | 0.88 |
| 1.6 | monitor w/6 | 0.03 | 0.02 | 0.01 | 0.00 | 0.00 | 0.00 | 0.97 | 0.80 |
| 1.6 | skylight | 0.19 | 0.18 | 0.07 | 0.15 | 0.15 | 0.06 | 2.71 | 0.54 |
| 1.7 | monitor w/3 | 0.19 | 0.13 | 0.03 | 0.07 | 0.05 | 0.00 | 1.15 | 0.87 |
| 1.7 | monitor w/6 | 0.06 | 0.03 | 0.02 | 0.00 | 0.00 | 0.00 | 0.92 | 0.81 |
| 1.7 | skylight | 0.21 | 0.19 | 0.06 | 0.13 | 0.13 | 0.05 | 2.70 | 0.53 |
| 1.8 | monitor w/3 | 0.23 | 0.15 | 0.05 | 0.05 | 0.03 | 0.00 | 1.08 | 0.87 |
| 1.8 | monitor w/6 | 0.09 | 0.05 | 0.02 | 0.00 | 0.00 | 0.00 | 0.86 | 0.81 |
| 1.8 | skylight | 0.23 | 0.21 | 0.06 | 0.12 | 0.12 | 0.03 | 2.70 | 0.53 |
| 1.9 | monitor w/3 | 0.26 | 0.18 | 0.07 | 0.02 | 0.02 | 0.00 | 1.01 | 0.86 |
| 1.9 | monitor w/6 | 0.13 | 0.06 | 0.03 | 0.00 | 0.00 | 0.00 | 0.79 | 0.82 |
| 1.9 | skylight | 0.25 | 0.22 | 0.05 | 0.10 | 0.10 | 0.02 | 2.69 | 0.52 |
| 2 | monitor w/3 | 0.3 | 0.21 | 0.09 | 0 | 0 | 0 | 0.94 | 0.86 |
| 2 | monitor w/6 | 0.15 | 0.07 | 0.04 | 0 | 0 | 0 | 0.74 | 0.83 |
| 2 | skylight | 0.27 | 0.24 | 0.04 | 0.08 | 0.08 | 0 | 2.68 | 0.52 |

Table 14
Energy Performance of Attached Atria Based on Well Index

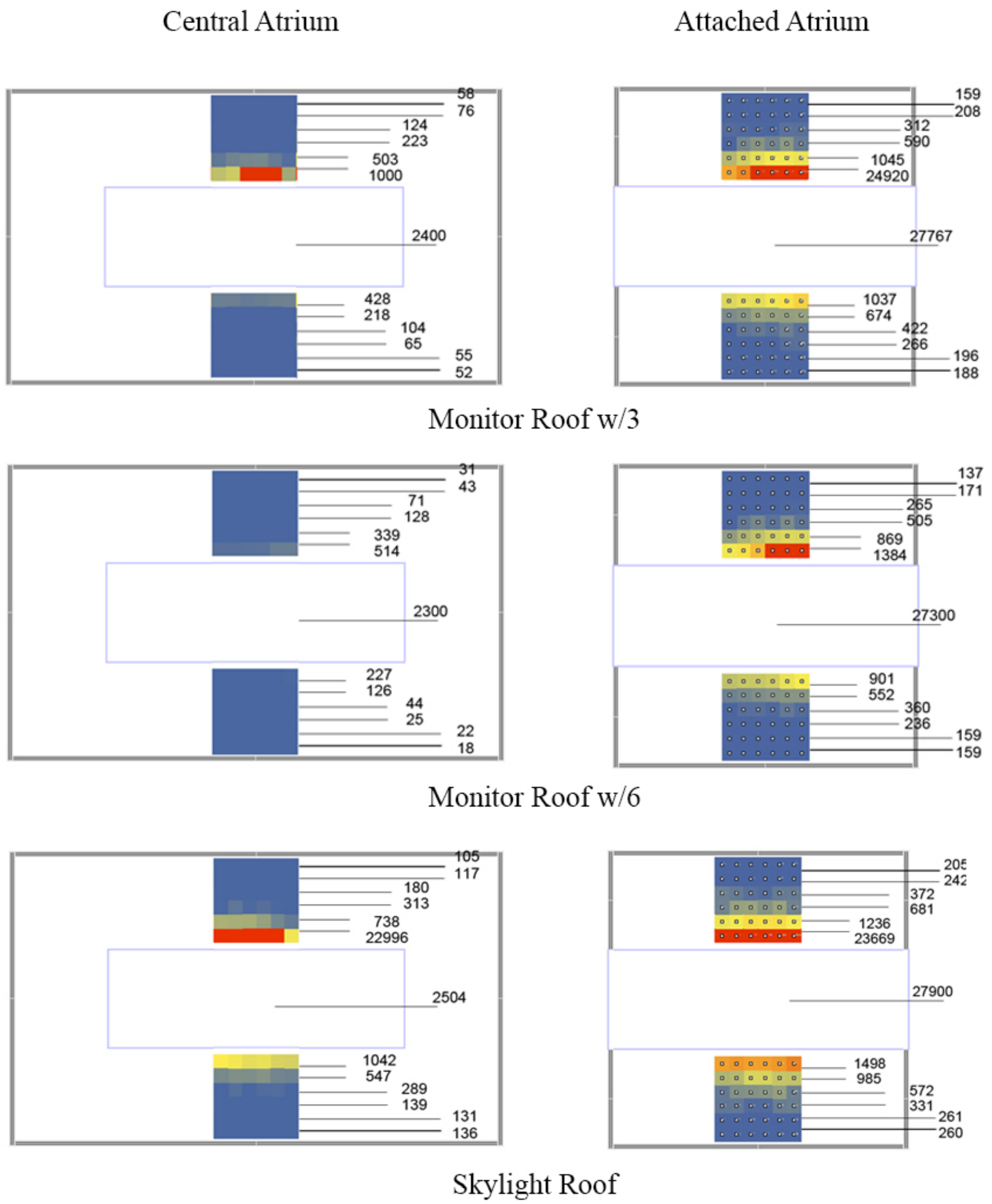
| WI | Roof | Avg sDA | Avg ASE$_{1000}$ | Avg ASE$_{3000}$ | sDA | ASE$_{1000}$ | ASE$_{3000}$ | Cooling | Heating |
|---|---|---|---|---|---|---|---|---|---|
| 0.1 | monitor w/3 | 1 | 0.69 | 0.19 | 1 | 0.69 | 0.19 | 1.68 | 1.09 |
| 0.1 | monitor w/6 | 1 | 0.47 | 0.1 | 1 | 0.47 | 0.1 | 1.92 | 0.89 |
| 0.1 | skylight | 1 | 0.83 | 0.31 | 1 | 0.83 | 0.31 | 9.49 | 0.70 |
| 0.2 | monitor w/3 | 1.00 | 0.61 | 0.28 | 1.00 | 0.61 | 0.28 | 2.26 | 1.11 |
| 0.2 | monitor w/6 | 0.94 | 0.47 | 0.1 | 0.94 | 0.47 | 0.1 | 2.41 | 0.83 |
| 0.2 | skylight | 1.00 | 0.64 | 0.31 | 1.00 | 0.64 | 0.31 | 9.22 | 0.66 |
| 0.3 | monitor w/3 | 0.67 | 0.42 | 0.16 | 0.67 | 0.42 | 0.16 | 3.41 | 1.23 |
| 0.3 | monitor w/6 | 0.49 | 0.25 | 0.08 | 0.49 | 0.25 | 0.08 | 3.17 | 0.99 |
| 0.3 | skylight | 0.69 | 0.61 | 0.31 | 0.69 | 0.61 | 0.31 | 10.55 | 1.18 |
| 0.4 | monitor w/3 | 0.67 | 0.53 | 0.19 | 0.67 | 0.53 | 0.19 | 3.27 | 1.03 |
| 0.4 | monitor w/6 | 0.64 | 0.36 | 0.08 | 0.64 | 0.36 | 0.08 | 2.89 | 0.78 |
| 0.4 | skylight | 0.78 | 0.61 | 0.31 | 0.78 | 0.61 | 0.31 | 9.93 | 0.62 |
| 0.5 | monitor w/3 | 0.92 | 0.59 | 0.30 | 0.83 | 0.56 | 0.31 | 1.40 | 0.98 |
| 0.5 | monitor w/6 | 0.87 | 0.51 | 0.19 | 0.79 | 0.54 | 0.28 | 1.25 | 0.65 |
| 0.5 | skylight | 0.95 | 0.61 | 0.31 | 0.89 | 0.57 | 0.31 | 2.15 | 0.66 |
| 0.6 | monitor w/3 | 0.85 | 0.55 | 0.26 | 0.75 | 0.50 | 0.27 | 1.45 | 1.03 |
| 0.6 | monitor w/6 | 0.80 | 0.46 | 0.17 | 0.72 | 0.48 | 0.25 | 1.23 | 0.67 |
| 0.6 | skylight | 0.88 | 0.57 | 0.29 | 0.81 | 0.52 | 0.27 | 2.27 | 0.65 |
| 0.7 | monitor w/3 | 0.78 | 0.50 | 0.23 | 0.68 | 0.44 | 0.23 | 1.50 | 1.08 |
| 0.7 | monitor w/6 | 0.73 | 0.41 | 0.15 | 0.65 | 0.43 | 0.22 | 1.22 | 0.69 |
| 0.7 | skylight | 0.81 | 0.52 | 0.26 | 0.73 | 0.47 | 0.23 | 2.38 | 0.64 |
| 0.8 | monitor w/3 | 0.71 | 0.46 | 0.20 | 0.60 | 0.38 | 0.19 | 1.55 | 1.13 |
| 0.8 | monitor w/6 | 0.67 | 0.36 | 0.13 | 0.57 | 0.37 | 0.18 | 1.20 | 0.71 |
| 0.8 | skylight | 0.74 | 0.48 | 0.24 | 0.65 | 0.42 | 0.19 | 2.50 | 0.62 |
| 0.9 | monitor w/3 | 0.65 | 0.42 | 0.17 | 0.52 | 0.32 | 0.15 | 1.60 | 1.18 |
| 0.9 | monitor w/6 | 0.61 | 0.31 | 0.11 | 0.50 | 0.31 | 0.15 | 1.18 | 0.74 |
| 0.9 | skylight | 0.67 | 0.44 | 0.22 | 0.57 | 0.38 | 0.15 | 2.62 | 0.61 |
| 1 | monitor w/3 | 0.58 | 0.38 | 0.13 | 0.44 | 0.25 | 0.11 | 1.65 | 1.22 |
| 1 | monitor w/6 | 0.55 | 0.25 | 0.09 | 0.42 | 0.25 | 0.11 | 1.16 | 0.76 |
| 1 | skylight | 0.60 | 0.40 | 0.19 | 0.49 | 0.33 | 0.11 | 2.73 | 0.59 |
| 1.1 | monitor w/3 | 0.61 | 0.40 | 0.17 | 0.48 | 0.29 | 0.15 | 1.58 | 1.15 |
| 1.1 | monitor w/6 | 0.58 | 0.29 | 0.13 | 0.46 | 0.28 | 0.15 | 1.14 | 0.77 |
| 1.1 | skylight | 0.63 | 0.42 | 0.22 | 0.53 | 0.36 | 0.15 | 2.73 | 0.58 |
| 1.2 | monitor w/3 | 0.64 | 0.42 | 0.20 | 0.52 | 0.32 | 0.19 | 1.51 | 1.08 |
| 1.2 | monitor w/6 | 0.61 | 0.32 | 0.17 | 0.50 | 0.31 | 0.19 | 1.11 | 0.78 |
| 1.2 | skylight | 0.66 | 0.44 | 0.24 | 0.57 | 0.39 | 0.19 | 2.72 | 0.57 |
| 1.3 | monitor w/3 | 0.67 | 0.44 | 0.24 | 0.56 | 0.36 | 0.23 | 1.44 | 1.01 |
| 1.3 | monitor w/6 | 0.64 | 0.36 | 0.21 | 0.54 | 0.35 | 0.23 | 1.08 | 0.79 |
| 1.3 | skylight | 0.69 | 0.46 | 0.27 | 0.61 | 0.42 | 0.23 | 2.72 | 0.56 |
| 1.4 | monitor w/3 | 0.70 | 0.46 | 0.28 | 0.61 | 0.40 | 0.27 | 1.37 | 0.95 |
| 1.4 | monitor w/6 | 0.68 | 0.40 | 0.25 | 0.59 | 0.39 | 0.27 | 1.06 | 0.80 |
| 1.4 | skylight | 0.73 | 0.49 | 0.30 | 0.65 | 0.46 | 0.27 | 2.72 | 0.56 |
| 1.5 | monitor w/3 | 0.73 | 0.48 | 0.31 | 0.65 | 0.43 | 0.31 | 1.29 | 0.88 |
| 1.5 | monitor w/6 | 0.71 | 0.43 | 0.28 | 0.63 | 0.42 | 0.31 | 1.03 | 0.80 |

Table 14 Continued

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1.5 | skylight | 0.76 | 0.51 | 0.32 | 0.69 | 0.49 | 0.31 | 2.72 | 0.55 |
| 1.6 | monitor w/3 | 0.69 | 0.46 | 0.28 | 0.60 | 0.40 | 0.27 | 1.22 | 0.88 |
| 1.6 | monitor w/6 | 0.67 | 0.41 | 0.24 | 0.59 | 0.40 | 0.27 | 0.97 | 0.80 |
| 1.6 | skylight | 0.74 | 0.51 | 0.30 | 0.65 | 0.47 | 0.27 | 2.71 | 0.54 |
| 1.7 | monitor w/3 | 0.65 | 0.44 | 0.25 | 0.56 | 0.37 | 0.23 | 1.15 | 0.88 |
| 1.7 | monitor w/6 | 0.64 | 0.39 | 0.21 | 0.55 | 0.38 | 0.23 | 0.92 | 0.81 |
| 1.7 | skylight | 0.72 | 0.51 | 0.28 | 0.61 | 0.45 | 0.23 | 2.71 | 0.54 |
| 1.8 | monitor w/3 | 0.61 | 0.42 | 0.21 | 0.51 | 0.34 | 0.19 | 1.08 | 0.87 |
| 1.8 | monitor w/6 | 0.60 | 0.37 | 0.17 | 0.51 | 0.35 | 0.19 | 0.86 | 0.81 |
| 1.8 | skylight | 0.69 | 0.50 | 0.26 | 0.56 | 0.42 | 0.19 | 2.70 | 0.53 |
| 1.9 | monitor w/3 | 0.58 | 0.41 | 0.18 | 0.46 | 0.31 | 0.15 | 1.01 | 0.86 |
| 1.9 | monitor w/6 | 0.57 | 0.35 | 0.13 | 0.47 | 0.32 | 0.15 | 0.80 | 0.82 |
| 1.9 | skylight | 0.66 | 0.49 | 0.23 | 0.51 | 0.39 | 0.15 | 2.69 | 0.52 |
| 2 | monitor w/3 | 0.54 | 0.39 | 0.15 | 0.42 | 0.28 | 0.11 | 0.94 | 0.86 |
| 2 | monitor w/6 | 0.53 | 0.33 | 0.09 | 0.43 | 0.29 | 0.11 | 0.74 | 0.83 |
| 2 | skylight | 0.63 | 0.49 | 0.21 | 0.47 | 0.36 | 0.11 | 2.68 | 0.52 |

### *4.1.2 Point-in-Time Metrics*

Point-in-time simulations for central and attached atria have also been conducted to provide illuminance values in adjoining spaces of an atrium (Figure 17). Illuminance values are measured in lux, illustrated with colors representing a scale of 300 lux to 2000 lux in a range of colors from blue to red, respectively. Point-in-time analysis in this study also provides the illuminance values for the atrium space, in addition to the adjoining spaces of atria.



Central Atrium

Attached Atrium

Monitor Roof w/3

Monitor Roof w/6

Skylight Roof

Figure 17. Point-in-time analysis of atrium buildings for WI=1 on Dec 21st at 9:00 a.m. under clear sky with sun

### *4.1.3 On LEED Daylighting Credit*

LEED v.4 Daylight Credit provides two options for earning the points. In option 1, buildings can earn 2-3 points (1-2 points in the Healthcare category) if at least 50% of the space meets $sDA_{300, 50\%}$ and $ASE_{1000, 250}$ should not exceed 10% of the space (Illuminating Engineering Society, 2012). There have been debates about the practical aspects of LEED v.4 requirements, since the threshold – 1000 lux for assessing glare (ASE) — is considered too low by some researchers (Hu, Place, & Malekafzali, 2014), and it is likely to result in a dim space if designers adhere to this requirement. There have been studies in the literature in which higher thresholds were used for assessing glare. For example, Useful Daylight Index (UDI) uses 2000 lux as the upper threshold for glare (New Buildings Institute, 2015). Continuous Daylight Autonomy uses 10 times the lower threshold as the glare threshold (New Buildings Institute, 2015). For example, if an office space requires 300 lux as the minimum light level, the upper threshold for glare assessment will be 3000 lux. To account for these recommendations, $ASE_{3000, 250}$ has also been used as the threshold to calculate another set of ASE percentages in the present study. Table 13 and Table 14 highlight atria that meet LEED option 1 requirements. For instance, a central atrium with a Well Index of 0.1 and 0.2 using a monitor roof with glazing height equal to one sixth of its width gains 2 points (Appendix A).

Buildings can earn 1-2 points by using LEED Daylight Credit option 2 through point-in-time computer modeling. Option 2 provides 2 points when 75% of the space meets illuminance levels between 300 lux and 3,000 lux for 9:00 and 15:00, both on a clear-sky day at the equinox (for buildings in the categories of New Construction, Core and Shell, Schools, Retail, Data Centers, Warehouses & Distribution Centers, CI, Hospitality) (USGBC, 2013). Table 15 shows the percentage of space that meets LEED option 2 requirement using the point-in-time simulation. Highlighted rows indicate atrium cases that meet LEED option 2 requirements.

Table 15
Exploration of Atrium Buildings Based on WI Through Point-in-Time Illuminance Values

| WI | Roof | point-in-time clsky@9 (300-3000 lux) | point-in-time clsky@9 (100-1000 lux) |
|---|---|---|---|
| | Central Atrium | | |
| 0.1 | monitor w/3 | 0.74 | 0.71 |
| 0.1 | monitor w/6 | 0.5 | 0.97 |
| 0.1 | skylight | 0.74 | 0.69 |
| 0.2 | monitor w/3 | 0.53 | 0.86 |
| 0.2 | monitor w/6 | 0.36 | 0.85 |
| 0.2 | skylight | 0.56 | 0.75 |
| 0.3 | monitor w/3 | 0.36 | 0.69 |
| 0.3 | monitor w/6 | 0.11 | 0.58 |
| 0.3 | skylight | 0.58 | 0.76 |
| 0.4 | monitor w/3 | 0.35 | 0.64 |
| 0.4 | monitor w/6 | 0.08 | 0.36 |
| 0.4 | skylight | 0.58 | 0.78 |
| 0.5 | monitor w/3 | 0.28 | 0.64 |
| 0.5 | monitor w/6 | 0.22 | 0.53 |
| 0.5 | skylight | 0.42 | 0.69 |
| 0.75 | monitor w/3 | 0.22 | 0.48 |
| 0.75 | monitor w/6 | 0.11 | 0.35 |
| 0.75 | skylight | 0.33 | 0.59 |
| 1 | monitor w/3 | 0.15 | 0.31 |
| 1 | monitor w/6 | 0.01 | 0.17 |
| 1 | skylight | 0.25 | 0.49 |
| 1.25 | monitor w/3 | 0.08 | 0.24 |
| 1.25 | monitor w/6 | 0.01 | 0.14 |
| 1.25 | skylight | 0.21 | 0.38 |
| 1.5 | monitor w/3 | 0 | 0.17 |
| 1.5 | monitor w/6 | 0 | 0.11 |
| 1.5 | skylight | 0.17 | 0.26 |
| 1.75 | monitor w/3 | 0 | 0.09 |
| 1.75 | monitor w/6 | 0 | 0.08 |

Table 15 Continued

| | | | |
|---|---|---|---|
| 1.75 | skylight | 0.1 | 0.17 |
| 2 | monitor w/3 | 0 | 0 |
| 2 | monitor w/6 | 0 | 0.04 |
| 2 | Skylight | 0 | 0.08 |
| | Attached Atrium | | |
| 0.1 | monitor w/3 | 0.97 | 0.57 |
| 0.1 | monitor w/6 | 0.97 | 0.75 |
| 0.1 | skylight | 0.75 | 0.69 |
| 0.2 | monitor w/3 | 0.73 | 0.71 |
| 0.2 | monitor w/6 | 0.58 | 0.73 |
| 0.2 | skylight | 0.69 | 0.72 |
| 0.3 | monitor w/3 | 0.49 | 0.85 |
| 0.3 | monitor w/6 | 0.19 | 0.71 |
| 0.3 | skylight | 0.63 | 0.75 |
| 0.4 | monitor w/3 | 0.71 | 0.69 |
| 0.4 | monitor w/6 | 0.6 | 0.72 |
| 0.4 | skylight | 0.83 | 0.5 |
| 0.5 | monitor w/3 | 0.61 | 0.69 |
| 0.5 | monitor w/6 | 0.53 | 0.69 |
| 0.5 | skylight | 0.75 | 0.56 |
| 0.75 | monitor w/3 | 0.58 | 0.76 |
| 0.75 | monitor w/6 | 0.50 | 0.79 |
| 0.75 | skylight | 0.58 | 0.63 |
| 1 | monitor w/3 | 0.55 | 0.83 |
| 1 | monitor w/6 | 0.47 | 0.89 |
| 1 | skylight | 0.41 | 0.70 |
| 1.25 | monitor w/3 | 0.57 | 0.77 |
| 1.25 | monitor w/6 | 0.53 | 0.8 |
| 1.25 | skylight | 0.51 | 0.695 |
| 1.5 | monitor w/3 | 0.6 | 0.71 |
| 1.5 | monitor w/6 | 0.6 | 0.72 |
| 1.5 | skylight | 0.61 | 0.69 |
| 1.75 | monitor w/3 | 0.58 | 0.76 |
| 1.75 | monitor w/6 | 0.58 | 0.77 |
| 1.75 | skylight | 0.60 | 0.72 |
| 2 | monitor w/3 | 0.56 | 0.81 |
| 2 | monitor w/6 | 0.55 | 0.81 |
| 2 | skylight | 0.59 | 0.75 |

There are other atrium daylighting design guidelines provided in text books, such as *Mechanical and Electrical Equipment for Buildings* (MEEB), which are more general. For instance, MEEB indicates the relationship between the atrium depth and the daylight regardless of the atrium type and its location (Stein, 2006). This research, however, provides preliminary data for daylight in atrium buildings, which are based on specific design parameters, such as roof aperture design and atrium type.

## 4.2 Energy Assessment

The energy performance of a building is dependent upon the volume of the interior spaces. Because atria with the same Well Index can have different volumes, this project assesses energy performances of atria with the same Well Index in terms of per-cubic-feet of an atrium. Both annual cooling and heating per atrium volume are simulated by using DesignBuilder, whereas peak heating and cooling loads are predicted by using hand calculations. Table 13 and Table 14 show the annual cooling and heating per cubic foot of an atrium space, assuming the atrium has adiabatic walls. The results show that, for the same Well Index and roof aperture type, the cooling and heating loads per cubic foot of atrium space are also reasonably close. This finding makes the thermal load results applicable based on Well Index, regardless of the dimensions or height of the atrium building.

Peak cooling and heating calculation are based on the impact of the aperture type, and are measured for an atrium with one inch of width:

**Atria with monitor roof w/3**

Peak Heating = $U_{(Btu/\ ft2\text{-}hr\text{-}F)} \times A_{(ft2)} \times \Delta T_{(F)} = ((0.44\times w) + 2\times(0.345\times w/3)) \times (68\text{-}16) / w\times w/3\ ft^3 = 0.01\ kBtu/ft^3\text{-}hr$

Peak Cooling = $Q_{roof} + Q_{window} + Q_{ventilation} / w\times w/3 = 0.04\ kBtu/ft^3\text{-}hr$

$Q_{window} = U \times A \times CLTD_{window} + A \times SC \times SHGF \times CLF = (2\times(0.345\times w/3)\times 13) + (2\times w/3)\times(0.88\times 64.5\times 0.665)$ kBtu/ft$^3$-hr

**Atria with skylight**

Peak Heating = $U\times A\times \Delta T = (0.345\times w) \times (68-16) / w = 0.02$ kBtu/ft$^3$-hr

Peak Cooling = $Q_{roof} + Q_{window} + Q_{ventilation} / w = 0.04$ kBtu/ft$^3$-hr

$Q_{window} = U \times A \times CLTD_{window} + A \times SC \times SHGF \times CLF = (w\times 0.345\times 13) + w\times(0.88\times 268\times 0.67)$ kBtu/ft$^3$-hr

Table 16 summarizes peak heating and cooling results.

Table 16
Peak Cooling and Heating Based on the Aperture Type in Atrium Buildings

| Roof Type | Peak Cooling (kBtu/ft$^3$-hr) | Peak Heating (kBtu/ft$^3$-hr) |
|---|---|---|
| monitor w/3 | 0.04 | 0.01 |
| monitor w/6 | 0.02 | 0.01 |
| skylight | 0.17 | 0.02 |

## 4.3 The Impact of Atrium Type

The secondary results are basically focused on the comparison of dynamic daylight metrics among different types of atria. Comparing dynamic daylight metrics between central and attached atrium types using different roof apertures demonstrates that the $ASE_{3000, 250}$ remains the same in both central and attached atrium types, while for both the average and bottom floor $sDA_{300, 50\%}$ are higher in attached atria.

Figure 18 and Figure 19 illustrate the comparison of average dynamic daylight metrics among central, attached and semi-enclosed atria with WI=0.5 for and WI=1, respectively, in climate zone 3. The results show that attached atrium types have higher $sDA_{300,\ 50\%}$ and reasonably low ASE. Based on the WI and roof type, semi-enclosed atria could have higher $sDA_{300,\ 50\%}$ and higher ASE, indicating increased glare possibility.

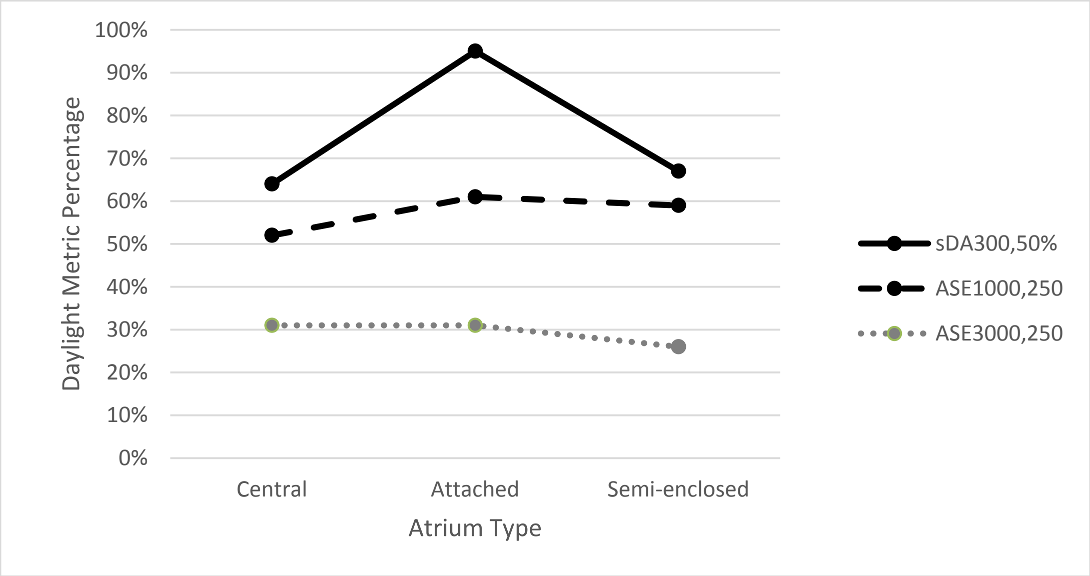


Figure 18. Comparison of average dynamic daylight metrics among atrium types with WI=0.5 and skylight roof (climate zone 3)

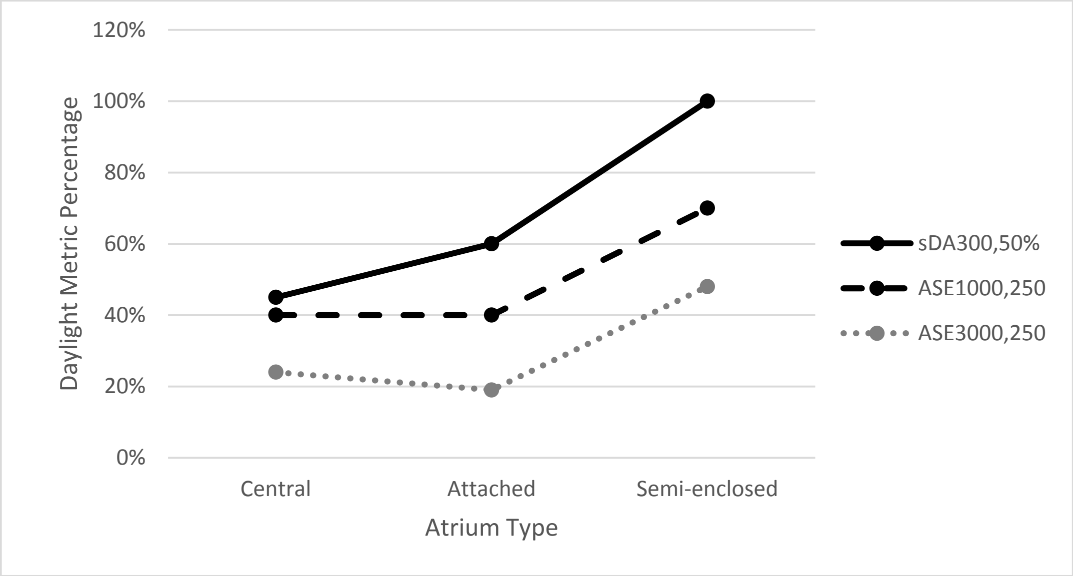


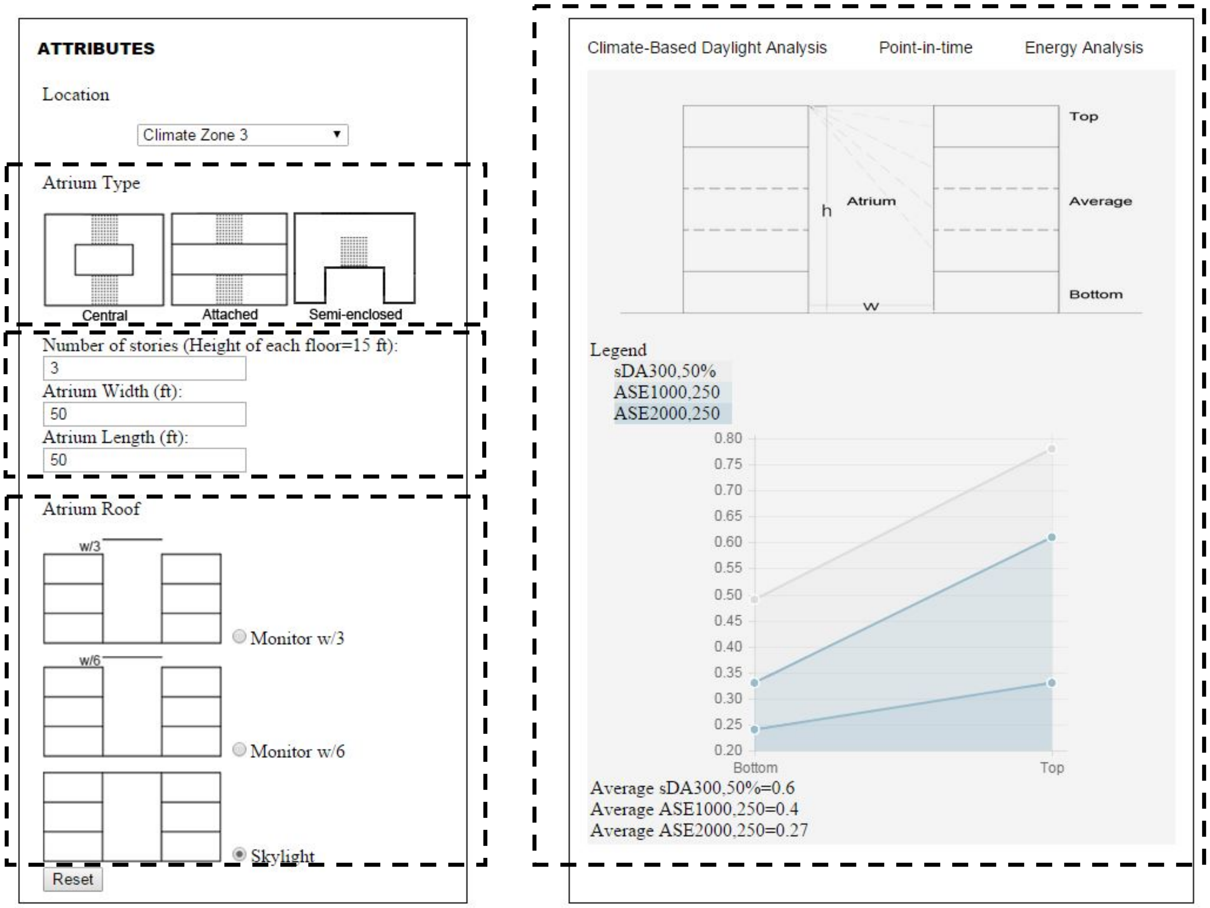
Figure 19. Comparison of average dynamic daylight metrics among atrium types with WI=1 and skylight roof (climate zone 3)

### 4.4 User Interface Design

To make the use of this database more accessible to designers, this research developed an online user interface (UI). The interface is a website that provides step-by-step energy results for atrium buildings. The atrium design interface includes climate, atrium type, roof aperture design, and atrium dimensions (for calculating Well Index) as inputs. The outputs are daylight and thermal performance data. The daylight and thermal components of the output include:

- Daylight chart illustrating the relation between Well Index and annual dynamic daylight metrics for the bottom and top floor, in addition to the average metrics across all floors.
- Graphical representation of daylight illumination distribution in different floors under selected solar angles and sky conditions.
- Heating and cooling load chart to demonstrate the impact of Well Index changes on heating and cooling loads.

Other atrium roof aperture designs and climate conditions can be added to the database to expand the database for atrium buildings. Figure 20-Figure 22 show the structure of the database interface. This website provides the user with the possibility of evaluating atrium designs by selecting the atrium type, its dimensions and roof aperture type. The program will calculate Well Index based on the dimensions entered. This tool is created by using PHP and JavaScript, and is hosted on the NC State Web server. The URL is: www4.ncsu.edu/~smohsen.



**ATTRIBUTES**

Location: Climate Zone 3

Atrium Type

Number of stories (Height of each floor=15 ft): 3

Atrium Width (ft): 50

Atrium Length (ft): 50

Atrium Roof

○ Monitor w/3

○ Monitor w/6

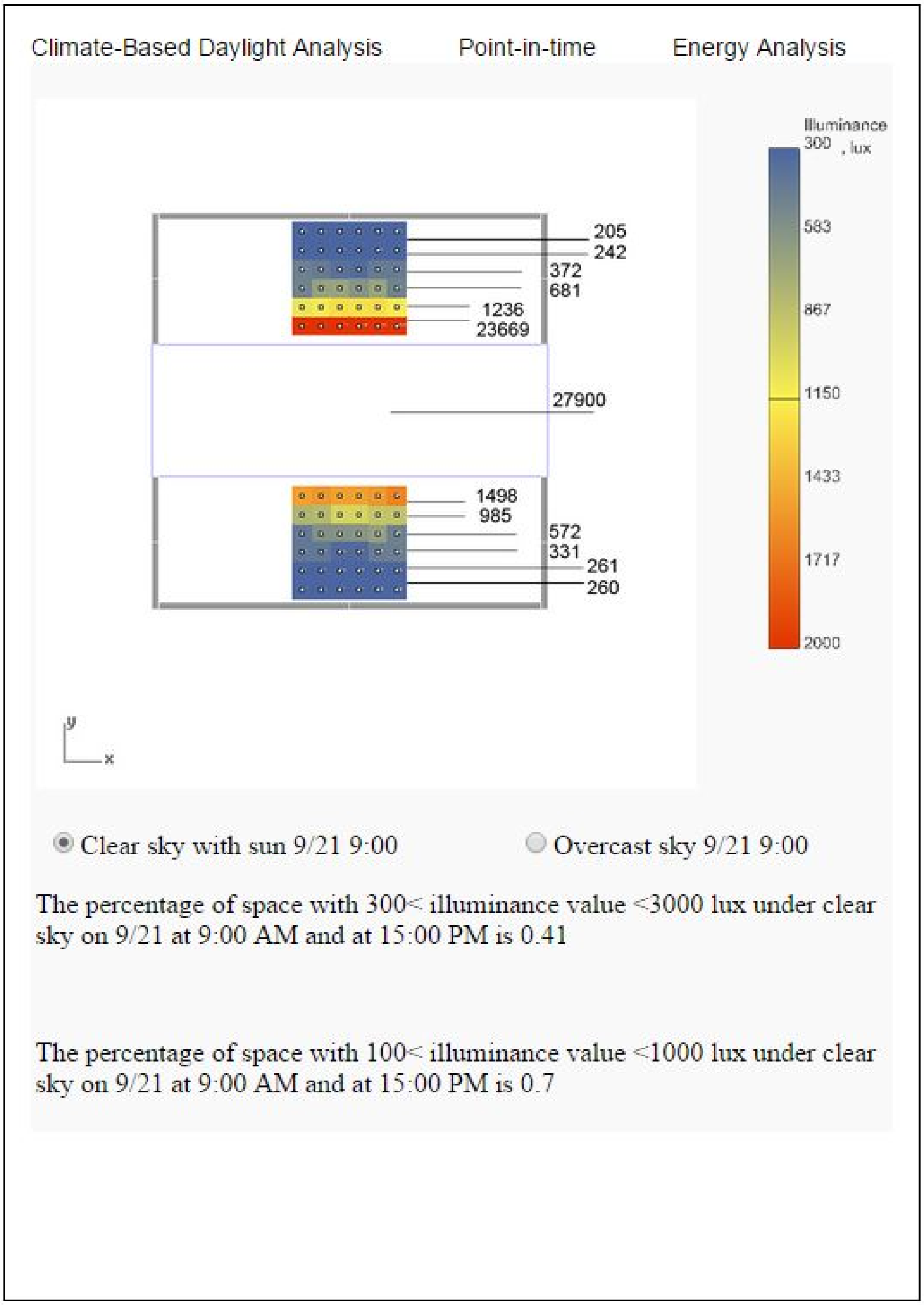
● Skylight

Average sDA300,50%=0.6

Average ASE1000,250=0.4

Average ASE2000,250=0.27

Figure 20. User Interface Design of Atrium Database

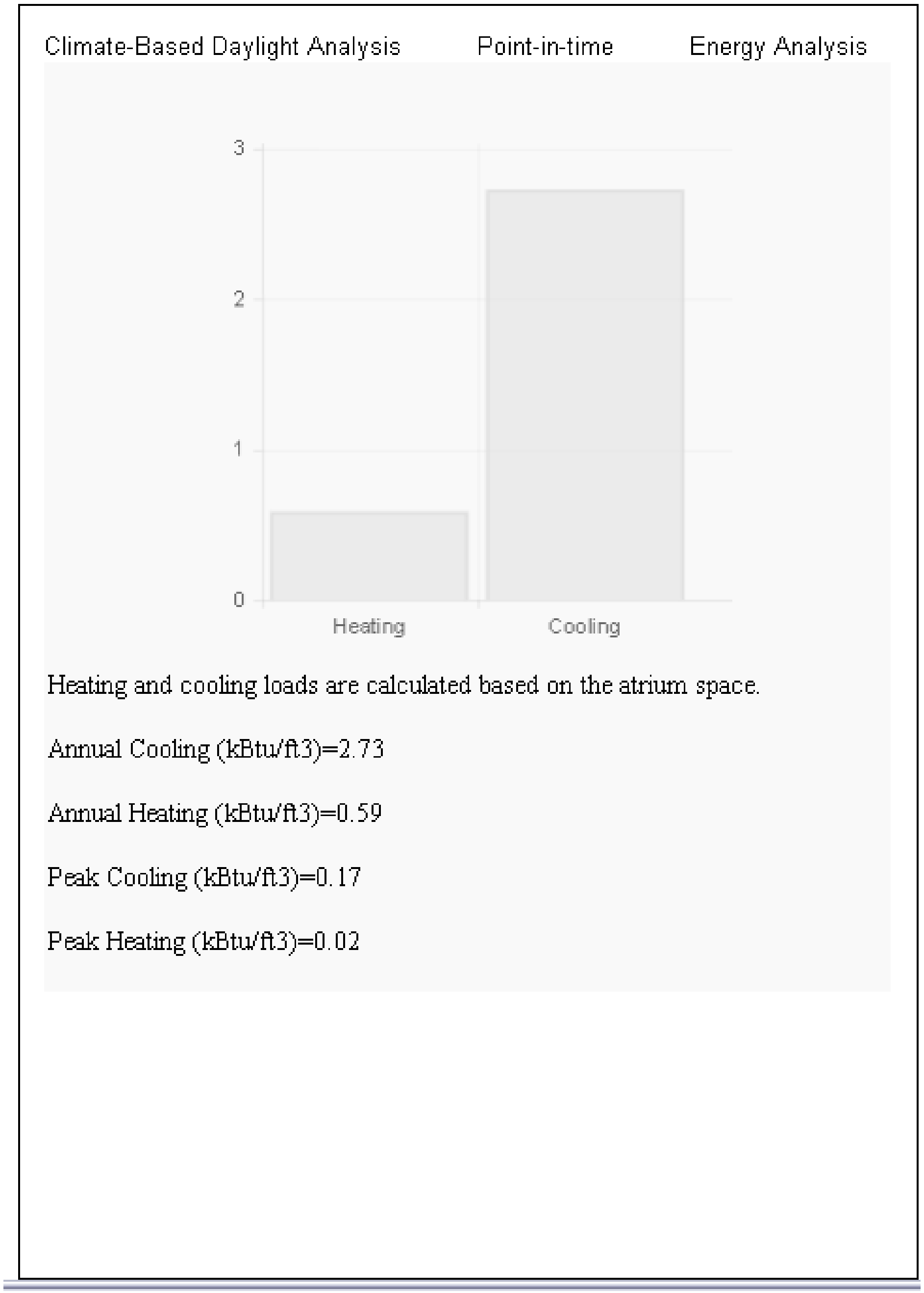


● Clear sky with sun 9/21 9:00 ○ Overcast sky 9/21 9:00

The percentage of space with 300< illuminance value <3000 lux under clear sky on 9/21 at 9:00 AM and at 15:00 PM is 0.41

The percentage of space with 100< illuminance value <1000 lux under clear sky on 9/21 at 9:00 AM and at 15:00 PM is 0.7

Figure 21. Point-in-time tab of the user interface



Heating and cooling loads are calculated based on the atrium space.

Annual Cooling (kBtu/ft3)=2.73

Annual Heating (kBtu/ft3)=0.59

Peak Cooling (kBtu/ft3)=0.17

Peak Heating (kBtu/ft3)=0.02

Figure 22. Energy analysis tab of the user interface

## 4.5 Conclusion and Discussion

In closing, this dissertation adds to the existing pool of knowledge on the design of daylit atria by providing the following major findings:

Well Index can be used to characterize atrium proportion to facilitate the assessment of daylighting and energy performances. This finding represents both methodological and technical improvements in the field of study:

*Methodological Improvements:*

This research provides a methodology to assess energy performance of an atrium based on the Well Index, which is a measure to characterize atrium proportions. This methodology improves the existing research method by demonstrating that atria with the same Well Index will have very close dynamic daylight metrics and energy performance per cubic feet of an atrium under the same assumptions (climate zone, atrium type, roof aperture type and material properties). Confirming the compatibility of Well Index with climate-based daylight metrics and energy modeling is therefore one of the most important methodological achievements of this research to the existing body of knowledge. Another major finding is that the Well Index concept is not only valid for assessing the average daylight and energy performance data for an atrium, it also remains valid for the bottom floor of the atrium.

*Technical Improvements:*

In addition to the methodological improvements, this research provides designers with a daylight and energy performance database based on the Well Index, which is essentially an expert system for atria with WI=0.1 to WI=2 with 0.1 intervals. This will allow designers to gain access to the performance data without conducting complex and time-consuming computer simulations. The database is established by using climate-based daylight modeling, considering different types of atria, proportions and roof aperture types. Another technical improvement is that this study has validated DIVA for Rhino in assessing daylit atria by comparing the simulated results with physical model experimental results.

The current study has explored the impact of roof aperture design (monitor and horizontal skylight) on both daylight, annual and peak energy performance of atrium buildings. To assess the impact of monitor roof glazing height, the study has examined this factor as a ratio of glazing height to atrium width. The results demonstrated that monitor glazing heights of one third and one sixth of the width provide more desirable results, since sDA and ASE do not change significantly between one third and one sixth of the width, while glazing heights greater than half of the width cause a significant amount of glare.

The impact of atrium type on daylighting and thermal performances are examined for central and attached atrium types. As a result, the database reflects results for each atrium type, Well Index value and roof aperture design. This database is measured for U.S climate zone 3, although it can be completed by adding other U.S climate zones. The results of this study are summarized under the following categories:

Dynamic Daylight Metrics: $\mathrm{sDA}_{300,\ 50\%}$, $\mathrm{ASE}_{1000,\ 250}$, $\mathrm{ASE}_{3000,\ 250}$

Point-in-Time Illuminance Lux values

Annual Heating and Cooling / $\mathrm{ft}^3$

Peak Heating and Cooling / $\mathrm{ft}^3$

Comparing dynamic daylight metrics between central and attached atrium types using different roof apertures demonstrates that the $ASE_{3000,\ 250}$ remains the same in both central and attached atrium types, while both the average and bottom floor $sDA_{300,\ 50\%}$ are higher in attached atria. The results show that attached atrium types have higher $sDA_{300,\ 50\%}$ and reasonably low ASE.

The current study has also simulated the impact of furniture on daylight assessments. Furniture and partitions are modeled in an office with exterior 7-ft partitions and 3.6-ft internal partitions. The final furniture layout is derived from studying cases with different partition sizes (see section 3.1.4), which concluded that furniture has a significant impact on daylighting performance and should be modeled in simulation studies. The office layout used in the current research is furnished with 7-ft partitions to divide larger spaces and 3.6-ft partitions to divide individual office workspaces, assuming 50% surface reflectance.

The data generated in the project are made available to designers by an online user interface, which provides preliminary daylighting and energy modeling results in the early stages of atrium design. The user inputs include the atrium type, dimensions of their atrium (length, width and height) and roof aperture type. The interface is designed to calculate the Well Index for the entire atrium and the top floor. As a result, the output includes daylighting data for the average, bottom floor, and top floor of the atrium.

This research has also evaluated atria based on the LEED v.4 daylight credit. Researchers recommended replacing $ASE_{1000,\ 250}$ with $ASE_{3000,\ 250}$ to optimize daylight design in atrium buildings.

Future research can be carried out to cover energy performance data in atrium buildings for all U.S climate zones. The database can also cover more atrium types, such as semi-enclosed atria, and more roof aperture types, such as saw tooth. The next step of inquiry might further explore atria as open urban spaces and provide more in depth study for shading in the urban context.

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# APPENDICES

# Appendix A

*LEED v4 BD+C Daylight (USGBC, 2013)*

To connect building occupants with the outdoors, reinforce circadian rhythms, and reduce the use of electrical lighting by introducing daylight into the space.

## Requirements

Provide manual or automatic (with manual override) glare-control devices for all regularly occupied spaces. Select one of the following three options.

### Option 1. Simulation: Spatial Daylight Autonomy (2–3 points, 1-2 points Healthcare)

Demonstrate through annual computer simulations that spatial daylight autonomy (sDA300, 50%) of at least 55%, 75%, or 90% is achieved. Use regularly occupied floor area. Healthcare projects should use the perimeter area determined under EQ Credit Quality Views. Points are awarded according to Table 17.

Table 17
LEED Points for Daylit Floor Area: Spatial Daylight Autonomy (USGBC, 2013)

| New Construction, Core and Shell, Schools, Retail, Data Centers, Warehouses & Distribution Centers, CI, Hospitality | | Healthcare | |
|---|---|---|---|
| sDA (for regularly occupied floor area) | Points | sDA (for regularly occupied floor area) | Points |
| 55% | 2 | 75% | 1 |
| 75% | 3 | 90% | 2 |

AND

Demonstrate through annual computer simulations that annual sunlight exposure1000, 250 (ASE$_{1000,250}$) of no more than 10% is achieved. Use the regularly occupied floor area that is daylit per the sDA$_{300/50\%}$ simulations.

The sDA and ASE calculation grids should be no more than 2 feet (600 millimeters) square and laid out across the regularly occupied area at a work plane height of 30 inches (76 millimeters) above finished floor (unless otherwise defined). Use an hourly time-step analysis based on typical meteorological year data, or an equivalent, for the nearest available weather station. Include any permanent interior obstructions. Movable furniture and partitions may be excluded.

**Option 2. Simulation: Illuminance Calculations (1–2 points)**

Demonstrate through computer modeling that illuminance levels will be between 300 lux and 3,000 lux for 9:00 and 15:00, both on a clear-sky day at the equinox, for the floor area indicated in Table 18. Use regularly occupied floor area. Healthcare projects should use the perimeter area determined under EQ Credit Quality Views.

Table 18
LEED Points for Daylit Floor Area: Illuminance Calculation (USGBC, 2013)

| New Construction, Core and Shell, Schools, Retail, Data Centers, Warehouses & Distribution Centers, CI, Hospitality | | Healthcare | |
|---|---|---|---|
| Percentage of regularly occupied floor area | Points | Percentage of perimeter floor area | Points |
| 55% | 1 | 75% | 1 |

| | | | |
|---|---|---|---|
| 75% | 2 | 90% | 2 |

Calculate illuminance intensity for sun (direct component) and sky (diffuse component) for clear-sky conditions as follows:

- Use typical meteorological year data, or an equivalent, for the nearest available weather station.
- Select one day within 15 days of September 21 and one day within 15 days of March 21 that represent the clearest sky condition.
- Use the average of the hourly value for the two selected days.

Exclude blinds or shades from the model. Include any permanent interior obstructions. Movable furniture and partitions may be excluded.

**Option 3. Measurement (2-3 points, 1-2 points Healthcare)**

Achieve illuminance levels between 300 lux and 3,000 lux for the floor area indicated in Table 19.

Table 19
LEED Points for Daylit Floor Area: Measurement (USGBC, 2013)

| NC, CS, Schools, Retail, Data Centers, Warehouses & Distribution Centers, Hospitality, CI | | Healthcare | |
|---|---|---|---|
| Percentage of regularly occupied floor area | Points | Percentage of perimeter floor area | Points |
| 75 | 2 | 75 | 1 |
| 90 | 3 | 90 | 2 |

With furniture, fixtures, and equipment in place, measure illuminance levels as follows:

- Measure at appropriate work plane height during any hour between 9:00 and 15:00 p.m.
- Take one measurement in any regularly occupied month, and take a second as indicated in Table 20.
- For spaces larger than 150 square feet (14 square meters), take measurements on a maximum 10-foot (3 meter) square grid.
- For spaces 150 square feet (14 square meters) or smaller, take measurements on a maximum 3-foot (900 millimeters) square grid.

Table 20
Timing of Measurements for Illuminance (USGBC, 2013)

| If first measurement is taken in … | take second measurement in … |
|---|---|
| January | May-September |
| February | June-October |
| March | June-July, November-December |
| April | August-December |
| May | September-January |
| June | October-February |
| July | November-March |
| August | December-April |

| | |
|---|---|
| September | December-January, May-June |
| October | February-June |
| November | March-July |
| December | April-August |