USER INTERFACE FOR ATRIUM DAYLIGHT AND THERMAL PERFORMANCES

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ABSTRACT

This paper provides an overview of a research-based daylight and thermal analysis tool as a product in the field of building technology. This research develops an online interface to allow designers to assess the energy performance of their atrium design in early project phases.

With current emphasis on building performance modeling, there is a need for designers to assess their building strategies. Though, most of the building simulation process is considered after the design process because of the complexity of simulation tools. The present study applied a validated method using atrium's proportion (Well Index) to characterize daylight and thermal performance per square feet of atrium buildings to collect a database of energy metrics of atria. Previous study indicated Well Index as the sole indicator of daylight properties of an atrium under the same conditions (climate zone, atrium type, roof aperture type and material properties).

This research employed computer simulation using DIVA for Rhino for daylighting and DesignBuilder to evaluate thermal performance of the building. The collected database is created using simulations for different atrium proportions in U.S. climate zone 3, where using atria could improve building performance based on the clear sky condition. The User Interface of the atrium performance requires inputs for climate zones, atrium types, proportion and its roof type. The performance metrics that this interface provides include dynamic daylight metrics, point-in-time metrics, as well as annual heating and cooling/ square feet of an atrium.

Keywords Atrium Database, Daylight Properties, Thermal Analysis, Building Performance, User Interface

1. INTRODUCTION

The goal of this research is to evaluate the choice of atrium type and its design proportion to improve the energy efficiency of atrium buildings. This research is an example of using evidence-based design in architecture.

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. The objectives of this research are to provide architects with a daylight and energy database to assist them with more energy-efficient design decisions. This research is therefore to achieve an atrium database expert system to reduce energy consumption in the office building sector without using detailed energy simulations for designers.

2. RESEARCH METHODOLOGY

2.1. DEFINITION OF KEY TERMS

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.

Dynamic Daylight Metrics

Dynamic Daylight Metrics are daylight prediction metrics which defines various luminous quantities using sun and sky conditions derived from meteorological datasets. *Dynamic Daylight Metrics* include Spatial Daylight Autonomy and Annual Sunlight Exposure (Beckers, 2012).

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):

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

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.

For instance, the following two atria have the same Well Index (WI=0.5).

- 27.43 m×27.43 m (90 ft.×90 ft.) central atrium in a three-story building (building height = 13.72 m= 45 ft.)
- 30.48 m×91.44 m (100 ft.×300 ft.) central atrium in a five-story building (building height = 22.86 m= 75 ft.)

2.2. LITERATURE REVIEW

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. This expert system provides daylighting data that are based on point-in-time analysis for limited design options (Figure 1). 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

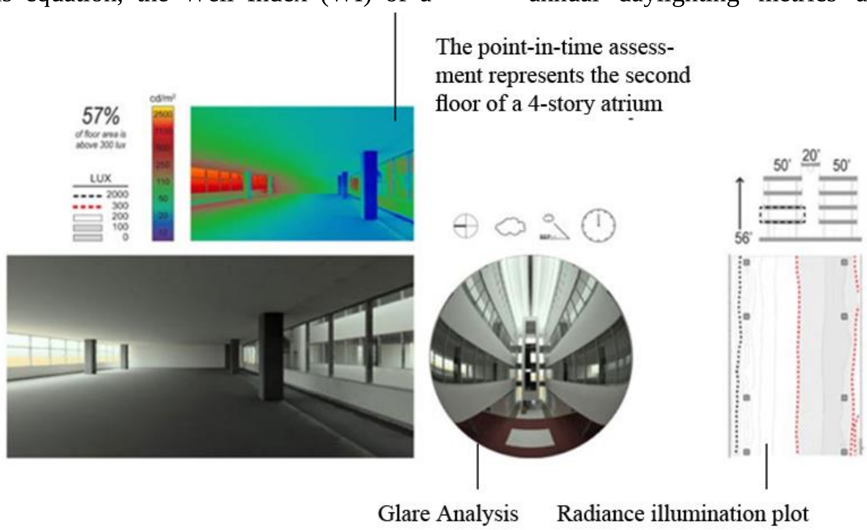

Figure 1 Daylighting Pattern Guide Interface (New Buildings Institute, 2015)

daylight method.

Compared to *Daylighting Pattern Guide*, 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 focusing on a certain or building orientation or level.

In order to develop this expert system, the present study investigates atria factors influencing daylight and thermal metrics. Shape, roof aperture transmittance, and surface reflectance are indicated as important atrium factors that influence daylight performance**,** according to Calcagni and Paroncini (2004). Furthermore, because of the limited impact of reflectance of wall surfaces on daylight distribution (Samant and Yang, 2007), this research assumes the reflectance for building surfaces as a controlled metric.

2.3. RESEARCH METHOD

This research provides daylight and thermal performance database for atrium buildings in U.S. climate zone 3. This database is collected based on the fact that atria with the same Well Index receive very close daylight and thermal metrics per cubic feet of the atrium building. Previous study by Mohsenin and Hu (2015) indicates Well Index as the sole indicator of daylight in an atrium under the same conditions (climate zone, atrium type, roof aperture type and material properties). This finding makes daylight and thermal results applicable based on Well Index, regardless of the dimensions or height of the atrium building.

This research focuses on central, attached and semi-enclosed atria (Figure 2) with monitor and skylight roof aperture types. The present study applies computer simulation method, using DIVA for Rhino (Solemma LLC) for daylighting and DesignBuilder for thermal analysis. For each atrium type, the database is structured through Well Index intervals of 0.1 with skylight and monitor roof designs. For each atrium type with variations of WI and roof designs, dynamic daylight metric, point-in-time illuminance, in addition to annual and peak heating and cooling load per cubic feet of an atrium is simulated to generate the database. Dynamic daylight metrics include average and per floor $sDA_{300, 50\%}$, $ASE_{1000, 250}$ and $ASE_{3000, 250}$. The collected data is then stored in a library to call the data using an online User Interface (UI).

The climate, building material reflectance/ thermal resistance and simulation settings are controlled as set assumptions. This paper assumes generic materials with typical surface reflectance, such as floor at 20%, ceiling at 80%, wall at 50% and double 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. TABLE 1 and TABLE 2 indicate simulation settings used in DIVA for Rhino and U-values used in DesignBuilder respectively to obtain accurate results. Although the energy performance of a building is dependent upon the volume of the interior spaces and 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. This finding makes the thermal load results applicable based on Well Index, regardless of the dimensions or height of the atrium building. TABLE 3 indicates examples of atrium dimensions used in the simulations.

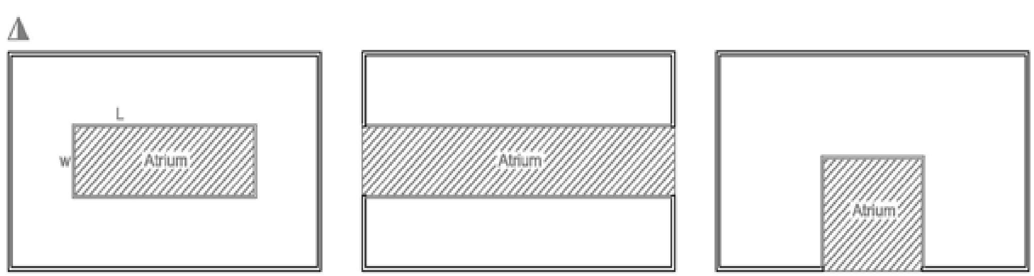

Figure 2 Atrium types plan view (left to right): central, attached and semi-enclosed (Huang, 2003)

TABLE 1: Radiance ambient parameters

Parameters	Description	Setting
ab	ambient bounces	6
aa	ambient accuracy	0.1
ar	ambient resolution	300
ad	ambient divisions	1000
as	ambient super-samples	256

TABLE 2: U-Value of materials for thermal simulation

Building material	U-value
Roof:Asphalt+Air gap+Plasterboard	0.044
Wall: Brickwork+XPS extruded polystyrene+Concrete block	0.062
Roof glazing: Double-pane Low-E 65%	0.345

TABLE 3: Examples of atrium dimensions used in the simulations

Well Index	Atrium size
0.5	3-storey 27.43 m×27.43 m (90*90 ft.)
0.5	5-storey 91.44 m×30.48 m (300*100 ft.)
1	3-storey 13.72 m×13.72 m (45*45 ft.)
1	5-storey 68.58 m×13.72 m (225*45 ft.)
2	3-storey 6.86 m×6.86 m (22.5*22.5 ft.)
2	5-storey 11.43 m×11.43 m (37.5*37.5 ft.)

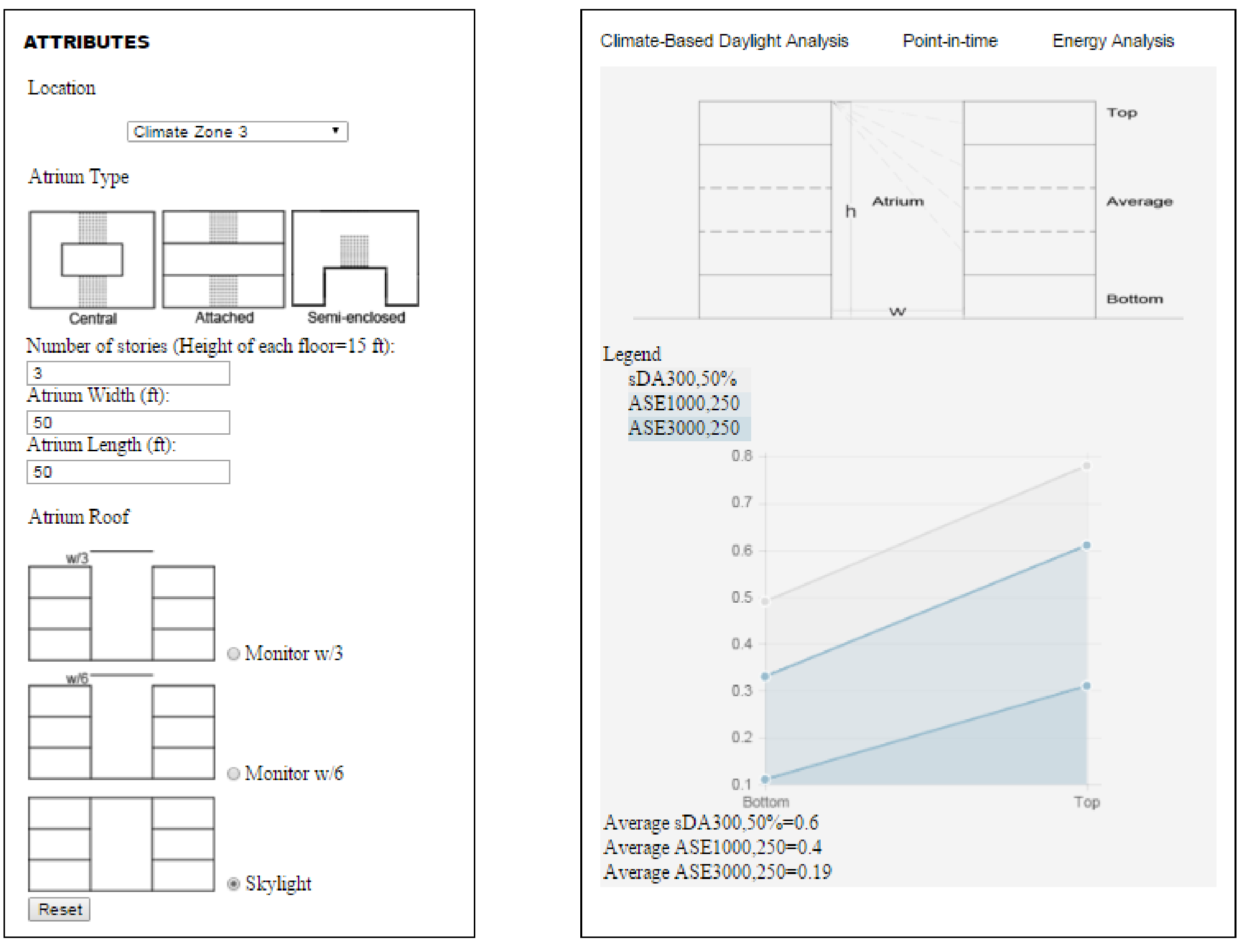

Figure 3 User Interface Design of Atrium Database

3. RESULTS

To make this database more accessible to designers, this research develops an online user interface (UI). The interface is a website that provides step-by-step energy results for atrium buildings. Figure 3 shows the structure of the database interface. The atrium design interface includes climate, atrium type, roof aperture design, and atrium dimensions as inputs. The program will calculate Well Index based on the dimensions entered. 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 (Figure 4).
- 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. This website provides the user with the possibility to evaluate atrium designs by selecting the type, dimensions and roof designs. For instance, when the user selects a central three-story building with atrium dimension of 9.14 m (30 ft.) by 13.72 m (45 ft.) and a monitor roof with 1.52 m (5 ft.) glazing, the following is a summary of the results for the adjacent space to the atrium:

Average $sDA_{300,50\%}$ = 0.11
Average $ASE_{1000,250}$ = 0.04
Average $ASE_{3000,250}$ = 0.02

Top floor $sDA_{300,50\%}$ = 0.33
Top floor $ASE_{1000,250}$ =0.19
Top floor $ASE_{3000,250}$ =0.17

Annual Cooling (kJ/m^3) = 40,989.8 = 1.1 $kBtu/ft^3$
Annual Heating (kJ/m^3) = 29,061.9 = 0.78 $kBtu/ft^3$
Peak Cooling (kJ/m^3) = 1,862.9 = 0.05 $kBtu/ft^3$
Peak Heating (kJ/m^3) = 372.6 = 0.01 $kBtu/ft^3$
Note: 1 Btu = 1,055.05 J

To optimize the design option, the results should be compared with LEED (Leadership in Environmental and Energy Design) or other green building rating systems. 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). 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 can gain 2 points.

The example we explored with average $sDA_{300,50\%}$ = 0.11 and average $ASE_{1000,250}$ = 0.04 does not meet LEED requirements. Heating and cooling results are similarly provided for each option per cubic feet of the space, which can inform the designer of the total heating and cooling to get compared with optimum Energy Use Intensity (EUI), which is the annual energy used per square foot of a building.

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). To be more specific, 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.

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).

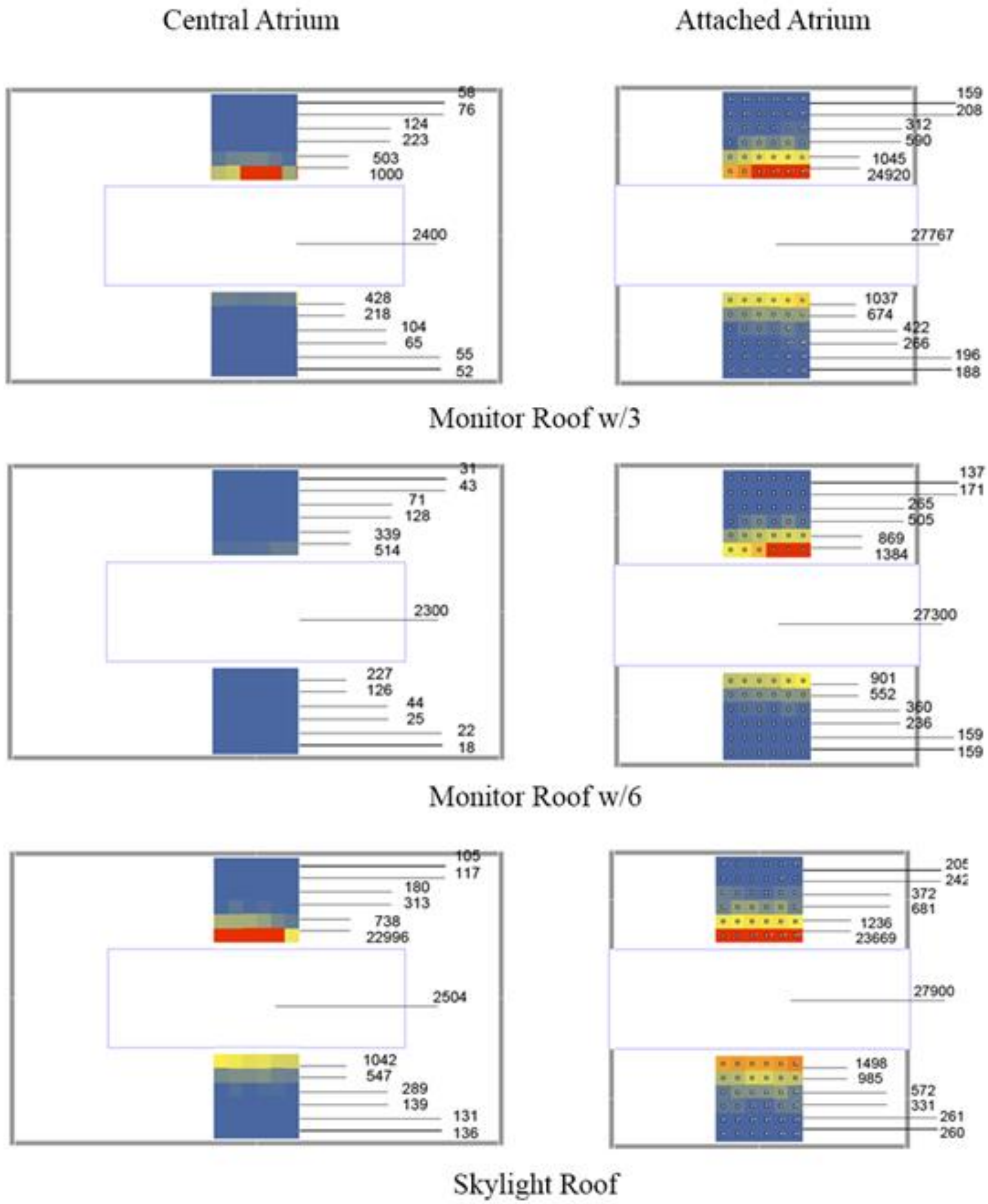

Figure 4 Point-in-time analysis of atrium buildings for WI=1 on Dec 21st at 9:00 a.m. under clear sky with sun

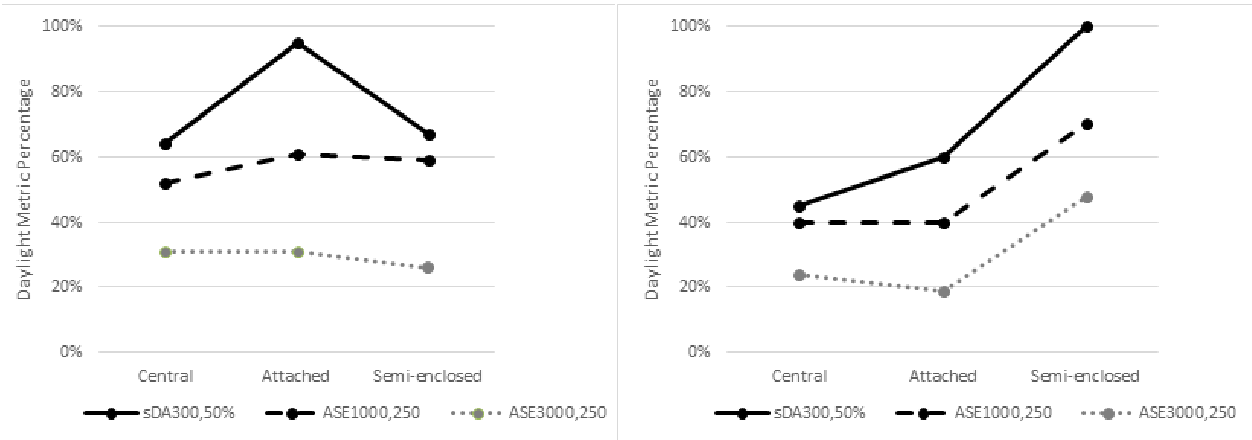

Figure 5 Comparison of average dynamic daylight metrics among atrium types with WI=0.5 (left) and WI = 1 (right) using skylight roof (climate zone 3)

4. CONCLUSION

The secondary results in this research 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$_{300, 50\%}$ is higher in attached atria. The example we explored with average sDA300,50$_{\%}$ = 0.11 and average ASE1000,250 = 0.04 does not meet LEED requirements. illustrates the comparison of average dynamic daylight metrics among central, attached and semi-enclosed atria with WI=0.5 and WI=1, respectively, in climate zone 3. The results show that attached atrium types have higher sDA$_{300, 50\%}$ and reasonably low ASE, which could be interpreted as meeting the minimum illuminance level while preventing from the glare. Based on the WI and roof type, semi-enclosed atria could have higher sDA$_{300, 50\%}$ and higher ASE, indicating increased glare possibility. Regarding optimized choices of atrium type and proportion, the results indicate that any type of atria could benefit a building if properly selected for its climate region. This database represents percentages that different design options provide.

In conclusion, this research provided an online database for designers to easier evaluate their choice of atria at early stages of design. The database needs to be expanded for different climate conditions. To optimize the design, the percentages of sDA$_{300, 50\%}$ and ASE$_{1000, 50\%}$ are provided for designers to compare with LEED v.4 criteria toward earning points for LEED certification. The point-in-time section of this online interface similarly provides information on the percentage of space with illuminance value between 300 and 3000 lux under clear sky on 9/21 at 9:00 AM which informs the designer about the possibility of earning LEED v.4 points.

WEBSITE

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

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