DAYLIGHT PREDICTION IN INDIVIDUAL FLOORS USING WELL INDEX

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Received: 20.12.2016; Revised: 29.01.2017; Accepted: 8.05.2017

Abstract

This research is focused on assessing daylight performance in different floors based on the building proportion. Previous studies showed that atrium with the same Well Index (proportion) will receive the same daylight. This study aims to examine the relation between daylight in different floors of a building, using Well Index.
Using DIVA for Rhino and DesignBuilder as the optimized daylight and energy simulation tools, this paper employs Daylight Autonomy (DA) and thermal performance as measured metrics.
The research findings have demonstrated that Well Index can be a valid indicator to characterize proportion for assessing daylight at individual floors in buildings. This methodology improves the existing research method by proving that spaces with the same Well Index will have very close dynamic daylight metrics under the same condition, assumptions and material properties.

Streszczenie

Celem przedstawionych badań jest ocena wydajności oświetlenia naturalnego dla różnych pomieszczeń w zależności od proporcji zabudowy. Wcześniejsze badania wykazywały, że atrium opisane tym samym wskaźnikiem WI otrzymują tyle samo oświetlenia naturalnego. Celem tego stadium jest analiza zależności pomiędzy oświetleniem naturalnym na różnych kondygnacjach budynku z wykorzystaniem współczynnika WI.
W artykule wykorzystano DIVA for Rhino and DesignBuilder jako zoptymalizowane narzędzie do symulacji oświetlenia naturalnego i energii. Jako jednostki pomiaru przyjęto Daylight Autonomy (DA) i parametry termiczne.
Udowodniono, że współczynnik WI może służyć jako wiarygodny wskaźnik oceny ilości oświetlenia naturalnego poszczególnych kondygnacji w budynkach. To podejście stanowi udoskonalenie dotychczasowych metod badawczych przez udowodnienie, że przestrzenie z tym samym WI będą miały bardzo zbliżone parametry dynamiczne oświetlenia naturalnego w tych samych warunkach, dla tych samych założeń i właściwości materiałowych.

Keywords: **Atrium building; Daylight; Daylight Autonomy; Simulation; Well Index.**

1. INTRODUCTION

Well Index (WI), defined in Eq. (1), has been used to characterize the proportion of atrium buildings [1].

$$WI = H (W+ L) / 2 * W * L \tag{1}$$

where H – height, W – width, L – length.

Cartwright (1986) developed an atrium sizing rule, investigating the relationship between the proportion of an atrium and daylighting [2]. Szerman (1992) reviewed the impact of atrium design parameters on the average Daylight Factor (DF) inside the adjoining spaces [3]. Samant and Yang (2007) explored the impact of surface reflectance on DF in atria based on Well Index [4]. This study showed that wall and ceiling reflectance could be kept as common materials using constant reflectance.

For instance, the following two atria have the same Well Index (WI=1.0).

18 m * 18 m central atrium in a four-story building (building height = 18 m)

14 m * 69 m central atrium in a five-story building (building height = 22.5 m)

The goal of the present study is to validate a method to evaluate daylight performance of different floors in buildings based on the building proportion (WI) regardless of their dimensions. This research requires a numerical analysis, in order to provide the designers with a database of daylight and thermal characteristic based on the WI. This finding will provide the designers with the possibility to evaluate their projects in early stages of the design without simulation complications. This research is to explore applicability of the Well Index to characterize building proportion when dynamic daylighting metrics (CBDM) are adopted as performance indicators, since static metrics do not account for the climate condition of the site and the orientation of the building. Specifically, the questions are:

- Will atria with the same Well Index result in the same daylight metrics at the bottom floor?
- Will atria with the same Well Index result in the same daylight performance across all floors?
- Will atria with the same Well Index result in the same thermal performance across all floors?
- Will it be possible to generalize Well Index methodology from atria to buildings?

These questions are studied under the same conditions, such as the climate, atrium specification, material properties and simulation settings.

It has been demonstrated that Well Index is an effective indicator for characterizing atrium proportions in studies that used Daylight Factor as the performance indicator [1, 2]. The previous research by Mohsenin and Hu (2015) demonstrated that Well Index could be used to characterize atrium proportion when CBDM metrics are adopted [5]. The present study evaluates whether atria with the same WI will receive the same daylight and thermal metrics across different floors.

2. RESEARCH METHODOLOGY

2.1. Definition of Key Terms

Spatial Daylight Autonomy (sDA)

Spatial Daylight Autonomy 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 amount of hours annually. 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 [9]. (Illuminating Engineering Society, 2012).

Annual Sunlight Exposure (ASE)

Annual Sunlight Exposure is a metric describing potential for excessive sunlight exposure by calculating the percent of the space that exceeds a certain illuminance level more than a specified number of annual hours [7]. For instance, $ASE_{(1000,\ 250h)}$ represents the percentage of space, where the illuminance level is more than 1000 lux for 250 annual occupied hours.

2.2. Simulation Settings

This study expands upon previous research by quantifying the relationship between daylight performance and atrium Well Index along with other parameters by using DIVA [8] for daylighting and DesignBuilder [9] for thermal analysis. DIVA needs the three-dimensional model, location (weather file), glazing transmittance, and light sensors as its numerical input model to calculate different light quantities. The quantity explored in this study is sDA and ASE, representing LEED requirements. Both of these daylight quantities are measured as an average throughout different floors of the building and at the bottom floor throughout all sensors. “The DesignBuilder Radiance simulation provides a detailed multi-zone physics-based calculation of illumination levels on the working plane of a building” [10]. Both DIVA and DesignBuilder use Radiance as their daylight simulation engine, while DIVA provides more advanced dynamic metrics such as Daylight Autonomy. Both of these softwares provide information whether a building is meeting LEED requirements.

This research provides designers with the idea of how Well Index and Daylight Autonomy could be used to understand if a design meets LEED requirements rather than an exact evaluation. As for thermal analysis, DesignBuilder’s engine is stronger in calculating thermal metrics for buildings compared to DIVA.

The effect of adding thermal values would be to provide general heating consumption based on Well Index to increase the energy-efficiency estimation. If Well Index could also provide the thermal estimation, it would be a useful metric to evaluate a building with, using the simulated data gathered in a table format.

The present study assesses daylight in a 9 * 9 m area adjacent to the atria or aperture, assuming, 9 m for building thickness, with floor height of 4.5 m. Central, attached and semi-enclosed types of atria are explored in this study. While central atria have an atrium surrounded by all adjacent spaces, attached atria are open from two sides, providing the potential to be compared to buildings across a street in an urban context. Semi-enclosed atria on the other hand are enclosed by three edges of the building, similar to a U-shape building. In order to expand the results from atria to buildings, the atrium space is considered as the street surrounded by adjacent buildings with different heights. To generalize the study from atria to buildings in an urban context, the roof is assumed open to the sky instead of using skylight or other types of glazing. The simulation utilizes the following Radiance parameters to calculate daylight metrics.

Table 1.
Radiance Ambient Parameters [14]

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 1 summarizes the Radiance ambient parameters, on which this study is based. The research setting considered in this study is U.S. climate zone (3).

This study assumes generic materials with typical surface reflectance in offices, such as floor at 20%, ceiling at 80%, wall at 50% and double-pane Low-E glazing with a 65% visible light transmittance for roof glazing. The atrium partition (the wall between atrium and adjoining space) is defined as a single-pane glazing with an 88% transmittance. The simulation also considers furniture with 50% reflectance to get more realistic results. Table 2 shows the U-values of the materials used for thermal simulations.

3. WELL INDEX FINDINGS

Results from computer simulations show that the average sDA and ASE of the adjoining spaces across all floors are the same. Table 3 shows the results from testing additional Well Indices in different atrium types and roof aperture designs. The results confirmed that daylight results are reasonably close when the WI and atrium types are the same in Table 3. For

Table 2.
U-Value of Materials for Thermal Simulation

Building material	U-value ($W/m^2·K$)
Roof: Asphalt+Air gap+Plasterboard	0.249
Wall: Brickwork+XPS extruded polystyrene+Concrete block	0.352
Ground floor: UF foam+Cast concrete+screed+Wooden flooring	1.987
Roof glazing: Double-pane Low-E 65%	1.959

Table 3.
Well Index across different floors

WI	type *	H (m)	W (m)	L (m)	Avg $sDA_{300,50\%}$	Avg $ASE_{1000,250}$	Bottom $sDA_{300, 50\%}$	Heating/m^3 (kWh)	Top floor WI
1	C	4*4.5	18	18	0.63	0.51	0.29	0.17	0.25
1	C	5*4.5	14	69	0.63	0.46	0.25	0.16	0.20
1	SE	4*4.5	18	18	1.0	0.7	1.0	0.17	0.25
1	SE	5*4.5	14	69	1.0	0.7	1.0	0.16	0.20
0.5	C	3*4.5	27	27	0.81	0.67	0.59	0.18	0.15
0.5	C	5*4.5	30	90	0.85	0.67	0.65	0.19	0.1
0.5	A	4*4.5	36	36	1	0.8	1	0.18	0.15
0.5	A	5*4.5	30	90	0.97	0.75	0.94	0.19	0.1
2	C	4*4.5	9	9	0.33	0.24	0	0.15	0.5
2	C	5*4.5	7.6	22.5	0.32	0.22	0	0.16	0.4
2	A	4*4.5	9	9	0.63	0.49	0.47	0.15	0.5
2	A	5*4.5	7.6	22.5	0.63	0.49	0.47	0.16	0.4

* C= central, A= attached, SE= Semi-enclosed

instance, the first two rows of the table indicate that atria with the same WI receive the same Daylight Autonomy as average between floors and in the bottom floor. This means that both of these spaces (with different dimensions) receive the same percentage of occupied times of the year with 300 lux illuminance. Heating/m^3 indicates a close relation in buildings with the same WI. The last column of the table provides a new Well Index for the top floor, indicating that one can read daylight and thermal metrics for that floor, matching the new Well Index. This part is more explained in the following paragraphs. These findings demonstrated that atrium proportion can be characterized by Well Index rather than by dimensions for the purposes of daylighting and thermal assessments.

To summarize, this research compares daylight level at individual floors in the same building types with the same Well Index. The results in Table 3 indicate that sDA and ASE remain the same for only the bottom floor in different 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 proportion and a new Well Index (Fig. 1). Now that floor of interest has been transformed into the bottom floor of a new building, its performance can be predicted by using the bottom floor performance data. For example, Figure 1 shows this thought process for assessing daylight in the third floor of a four-story building with WI=2.0. In this case, the simulation results indicate that daylight metric in the third floor of a building with WI=2.0 equals to the daylight in a two-story building with the same width of 9 m and height of 9 m, resulting in WI = 1.0.

Eq. (1) implies that the height (H) is the changing factor for different floors of interest. As a result, the sliding concept illustrates how to see individual floor as the bottom or average (middle) floor of a building with a new Well Index. This finding expands the concept and use of Well Index more than characterizing atria, but also as a means of characterizing every floor of an atrium/ building with the same indexing concept. When we have the index number, estimating daylight performance could be easily achieved for architects through tables or online tools, using the same data. This means that the performance of an individual floor that has the same Well Index is the same as the average for a building with the same Well Index.

Table 3 also represents that the daylight performance for the top story of a building can be read from the new Well Index data. Well Index of the top-story is calculated as a one-story building with the same width and length. Attached atrium results could be expanded to buildings across a street/ obstruction to generalize the Well Index methodology for aperture in buildings. To adjust WI formulae for any floor of a building, H (height) represents the window-head-height; W (width) is the distance from the aperture to the obstructive object or an open urban space (street width) and L is the aperture length. This study showed that sDA and ASE in the second floor (top) of a building (adjacent to a three-story) building is very close to sDA and ASE in the second floor (adjacent to a two-story) similar building (Figure 2: south-facing results). In this case, the atrium width is envisioned as an outdoor open space with the same width of a 9 meter wide street. Although the two-story option can result in more opening for light, but the assumption remains valid in the cases that the height difference between the floor of interest and the obstruction is minor. The last consideration that the daylight estimation across a street brings is about the orientation of the floor of interest, whether it is receiving south or north light. As a result, if daylight level is calculated for north and south facing glazing, this database could be used by urban planners and designers to estimate daylight in individual floors of a

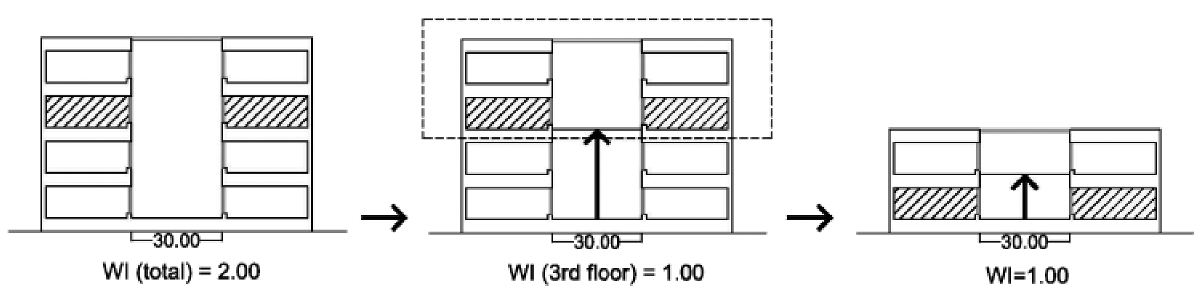

Figure 1.
Sliding concept of individual floors in atria to calculate Well Index in individual levels

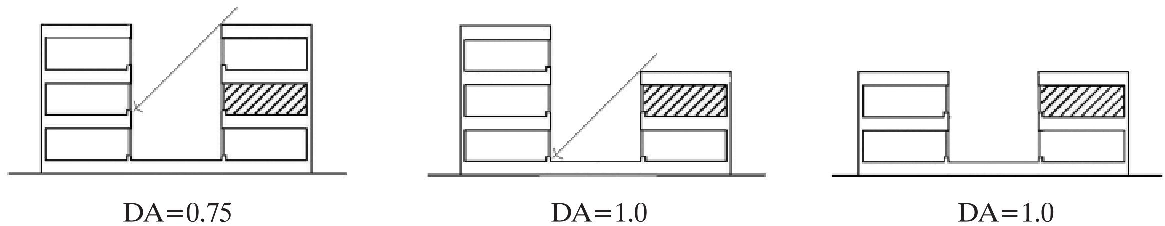

Figure 2.
Expanding the concept of Well Index from atria to the urban context

building across a street. This finding could assist urban planners in future urban code developments for daylighting.

Efforts have been made in the present study to explore both heating and cooling loads in adjoining spaces in relationship to the atrium's Well Index. 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 heating energy performances of atria with the same Well Index in terms of per-cubic-meter of an atrium. This study modeled adjacent spaces to atria in DesignBuilder as adiabatic spaces and measured heating/ cooling in the whole space per cubic meter for different Well Indices. Heating loads per cubic meter of atrium itself are calculated. The results show that the loads remain the same among atrium with the same Well Index under the same conditions. The reason behind the fact that cooling loads did not remain the same might be because of the complexity of temperature difference calculations. This finding demonstrates that the Well Index approach provides a way to assess not only the average dynamic daylight metrics, but also the thermal metrics of every individual floor. Therefore, one can calculate dynamic daylight metrics and heating energy performance of atria at a 0.1 intervals to cover more dimension variations.

4. CONCLUSION

Well Index was used before as a static measurement technique, while this study used it practically to explore the relationship between WI and building energy performance. So, if we have the Well Index and there will be a database table developed, one can estimate the energy performance of the building toward LEED requirements. This study has investigated the effects of atrium proportion (characterized by Well Index) on daylighting and heating/m3. The research findings have demonstrated that Well Index can be a valid indicator to characterize proportion for assessing daylight at individual floors in buildings. This methodology improves the existing research method by proving that spaces with the same Well Index will have very close dynamic daylight metrics in the same location and under the same assumptions (material properties and simulation settings). This finding demonstrates that the Well Index approach provides a way to assess not only the average dynamic daylight metrics, but also the metrics of every individual floor. This paper visualized the Well Index concept across different floors of an atrium/ building and the differences between average daylight prediction and individual floor Well Indices.

Therefore, one can calculate dynamic daylight metrics and energy performance of atria at 0.1 intervals of Well Index to cover more dimension variations. 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 interval) to provide designers with a table or an online database to estimate their designs.

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