A simplified method of calculating Daylight Autonomy through spatial parameters for atriums in shopping streets

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Abstract

A simplified method of calculating annual climate-based daylighting metrics, Daylight Autonomy (DA), can help architects quickly understand annual daylighting performance during the design stage. However, generating building models and calculating annual simulations are both laborious and time-consuming. In order to offer architects a quick method of predicting DA within an atrium and adjacent spaces in interior shopping streets, this paper presents a quantitative model between spatial parameters and DA₃₀₀ values. First, spatial parameters and daylighting performance within 28 interior shopping streets were examined. Then, three typical atrium spaces and the thresholds of associated spatial parameters were extracted from descriptive statistical analysis. Orthogonal test was used to test variables in daylight simulations using DIVA-for-Rhino. Other statistical analysis methods include the differential analysis, the correlation analysis, and the regression analysis. The formulas of using important spatial parameters for each atrium type to predict DA₃₀₀ values at representative points are concluded. An excel sheet is programmed for architects to quickly obtain DA₃₀₀ values by modifying these spatial parameters.

Introduction

Many researchers have explored the impacts of spatial parameters upon daylighting performance. Hopkinson and Petherbridge (1996) found that in a single-side room, Daylight Factor (DF) near the window usually reaches 10% and drops to 2-3% when the distance is two meters away from the window. When the depth reaches six meters, DF reaches the minimum value. Zhang Xin and Han Tianci (2012) made a table based on 162 simulation results so that designers could predict an average DF based on specific spatial height and spatial depth, along with window width and window height. Baker et al (2013) explored the effects of plan ratio on daylighting performance within five meters from the side window in a four-story building.

In addition to single-side window space, researchers are also interested in more complex spaces like atriums. Baker et al (1993) studied the variation of the DF with varying gallery depths in an atrium. Samant (2010) reviewed the effects of spatial parameters and surface reflectance on daylighting in an atrium and its adjacent spaces. Yunus et al (2011) evaluated the daylighting

performance within glazed atrium spaces by measuring lighting data within physical scale models under tropical skies. Reinhart (2014) indicated that the maximum height should be less than 2.5 times the width in an atrium primarily relying on daylight. Calcagni and Paroncini (2004) mentioned that the effective daylighting depth of adjacent spaces of an atrium is less than 4m.

In addition to explorations of static daylighting index, limited studies explored relationships between spatial parameters and annual climate-based daylighting performance. Kim and Song (2013) simulated Daylight Autonomy (DA) of 112 four-side atrium models with varying geometric forms and four orientations. The results show that the effect of Plan Aspect Ratio (PAR) on DA is negligible. The Aspect Ratio (AR) has little effect on DA₇₅₀ and DA₁₀₀₀, and the range of DA₇₅₀ and DA₁₀₀₀ are about 15% and 20%, respectively. However, AR has greater influence on DA₂₀₀₀ with the range as high as 48%.

Although many studies have explored relationships between the daylighting index and spatial parameters, most of them focused on the static daylighting index or only considered limited spaces and receiver positions. This paper is an extensive investigation of a previous one (Jin, Li, Kang, & Kong, 2017), which explores the relationship between daylighting qualities and subjective evaluation within public shopping spaces. Jin et al. studied eight shopping centers with the areas varying between 67,000 and 210,100 m² from four cities in China. Subjective evaluations of natural and artificial lighting environments including satisfaction levels and brightness perception were collected using surveys. Physical lighting data were measured by illuminance meters and HDR image techniques. From the correlations between illuminance- and luminance-based metrics and subjective assessments, the authors proposed mean luminance of a scene of 1,000 cd/m² for mixed natural-and-artificial-lighting shopping centers and 75 cd/m² for artificial lighting shopping centers. In order to extend the research scope from instantaneous to long-term lighting environments, this study explores the relationship between spatial morphological parameters and the annual climate-based lighting metrics. This study first proposes three commonly utilized daylighting atriums and the associated spatial parameters thresholds, then propounds simplified methods of calculating DA₃₀₀ at representative points by spatial parameters for three types of atriums.

Methodology

Typical model determination

Within the investigation of 28 interior shopping streets in five Chinese cities (Harbin, Shanghai, Beijing, Xi'an, Shenyang, and Xiamen) (Jin, Li, Kang, & Kong, 2017), 21 of these interior shopping streets utilize toplighting, nine use sidelighting, and four utilize a mix of toplighting and sidelighting. Therefore, these three types of daylighting designed atriums of conceptualized rectangles were studied: toplighting atriums, sidelighting atriums, and mixed toplighting and sidelighting atriums. For toplighting atriums, three spatial parameters were proposed: width, height, and the ratio of spatial length to width. Figure 1 illustrates the parameters. Table 1 show six values for each parameter, which were derived from the 30 interior shopping streets. Based on the Orthogonal test designed in SPSS, 48 simulation models were generated and run for DA₃₀₀ results.

Table 1: Orthogonal analysis variables for toplighting atriums.

Level Parameter	1	2	3	4	5	6
W_T (m)	5	9	14	18	23	27
H_T (m)	5	10	15	20	25	30
L_T/W_T	1.0	1.2	1.4	1.6	1.8	2.0

Figure 1: The spatial parameters in the toplighting atrium.

Given that studied sidelighting atriums and mixed-toplighting-and-sidelighting atriums have similar spatial dimensions, four spatial parameters were proposed: width length, height, and window orientation. Figure 2 illustrates the spatial parameters. Table 2 shows four values for each parameter, which were derived from 10 studied sidelighting atriums and mixed atriums. Based on the Orthogonal test designed in SPSS, 32 simulation models were generated and run for DA₃₀₀ results for sidelighting atriums and mixed atriums, respectively.

Table 2: Orthogonal analysis variables for sidelighting atriums.

Level Parameter	1	2	3	4
W_S or W_m (m)	9	18	27	-
L_S or L_m (m)	27	36	45	54
H_S or H_m (m)	5	10	20	30
Orientation	South	East	North	West

a) the sidelighting atrium. b) the mixed atrium.

Figure 2: The spatial parameters in the sidelighting and minxed-toplighting-and-sidelighting atrium.

Simulations

DA values were simulated by DIVA-for-Rhino. DIVA integrates Radiance and Daysim, which are widely used in dynamic daylighting simulations, glare evaluations, and shading analysis (Jakubiec & Reinhart, 2011; Yun, Yoon & Kim, 2014). According to the Appendix D of Standard for lighting design of buildings (GB 50034-2013), the reflection coefficient of interior walls, ceilings, floors, and exterior ground were 0.7, 0.8, 0.4 and 0.2, respectively. Given that this study focused on the influence of spatial parameters on DA values, the correction factor for different glazing transmittances will be investigated in future studies. Hence, the glazing transmittance for three types of atriums was set as 1 to obtain the upper thresholds of DA values. Interior furniture or partition walls were excluded for the reference of dynamic daylighting performance during the design stage.

This study used Beijing in the third daylight climate zone as the representative weather. BEIJING.545110_CSWD downloaded from EnergyPlus was used in 112 runs of simulation. The daytime schedule was from 8 a.m. to 6 p.m. with 3,650 accumulated hours throughout an entire year. The simulated plane was 0.75 meters away from the floor with a 0.5m of the point spacing, and the target illuminance of DA was 300 lux.

Simulated positions settings

In order to speed up the 112 simulations, representative points for three types of atriums were first determined according to DA₃₀₀ distributions across atriums. Table 3 summarizes all the selected points. For each DA₃₀₀ value, the subscript represents its atrium type, and the superscript represents its position. For example, DA_T^C uses T to represent toplighting atriums and C to represent the point at the centre of the atrium. For toplighting atriums, the point at the centre of a rectangular atrium (DA_T^C) 0.75m above the floor presented high DA₃₀₀ values in low variation. Based on simulated results, DA₃₀₀ values at the centre of four peripheries were similar, so one point, DA_T^P , represents the four points. Additionally, for galleries facing four orientations, points were selected at two-meter intervals along the central lines. For example, as shown in Table 3, DA_T^S represents the DA₃₀₀ value at the point in the southern gallery with varying distance from the closest atrium periphery. All the selected points for toplighting atriums are illustrated in Figure 3.

Table 3: Representative DA_{300} points and definitions for three types of atriums.

Toplighting atriums	
DA_T^C	The point at the centre of an atrium
DA_T^P	The point at the centre of the atrium periphery
DA_T^E	The points along the central line of the eastern gallery with 2m, 4m, 6m, 8m, and 10m away from the closest periphery
DA_T^S	The points along the central line of the southern gallery with 2m, 4m, 6m, 8m, and 10m away from the closest periphery
DA_T^W	The points along the central line of the western gallery with 2m, 4m, 6m, 8m, and 10m away from the closest periphery
DA_T^N	The points along the central line of the northern gallery with 2m, 4m, 6m, 8m, and 10m away from the closest periphery
Sidelighting atriums	
DA_S^D	The points along the central line of an atrium with varying distance from the window
DA_S^L	The points along one lateral with varying distance from the window
DA_S^5	The points along window-parallel line with 5m away from the south-facing or north-facing window
DA_S^{5N}	The points along window-parallel line with 5m away from the east-facing or west-facing window towards north
DA_S^{5S}	The points along window-parallel line with 5m away from the east-facing or west-facing window towards south
DA_S^G	The point at the end of the gallery opposite the window
DA_S^M	The point on the midpoint of the gallery sideline opposite the window
Mixed toplighting and sidelighting atriums	
DA_M^D	The points along the central line of an atrium with varying distance from the window
DA_M^5	The points along window-parallel line with 5m away from the south-facing or north-facing window
DA_M^{5N}	The points along window-parallel line with 5m away from the east-facing or west-facing window towards north
DA_M^{5S}	The points along window-parallel line with 5m away from the east-facing or west-facing window towards south
DA_M^G	The point at the end of the gallery opposite the window

Figure 3: The points for toplighting atriums.

For sidelighting spaces, DA_{300} values decrease with the increasing distance between the calculated point and the window increasing. The points along the central line perpendicular to the window with varying distance away from the window were selected (DA_S^D). Considering that DA_{300} values along both atrium laterals with varying distances from the window were similar, the points along one side were simulated (DA_S^L). Figure 5 shows the percent of peak DA_{300} values along one lateral from all 32 simulations for sidelighting spaces. The point 5m away from the window demonstrated the highest frequency. Given that sidelighting atriums were enclosed along three sides, DA_{300} at the points along the line parallel with the window and 5m away were calculated. For sidelighting atriums facing south and north, DA_{300} values along the 5m-parallel-window line towards east or west were symmetrical so points along one side (DA_S^5) were calculated. For sidelighting atriums facing east or west, DA_{300} values along the 5m-parallel-window line towards south or north were asymmetrical. Hence, DA_S^{5N} represents the points towards north and DA_S^{5S} represents the points towards south. All the selected points for sidelighting atriums are illustrated in Figure 4. For mixed toplighting and sidelighting atriums, all the selected points were the same except for the exclusion of points along both lateral. Based on the 32 simulations for mixed atriums, DA_{300} values along either lateral had slight variations so that these points were excluded. Table 3 All the selected points for mixed atriums are illustrated in Figure 5.

Figure 4: The points for sidelighting atriums.

Figure 5: The points for mixed atriums.

For each type of atrium space, Well Index (WI), a commonly utilized index for atrium space (CITE related

articles), was calculated first. Then, formulas of DA_{300} results at selected points were generated based on varying WI values for designers to obtain quick annual daylighting performance within an atrium.

Results

The result section presents the calculation procedures and proposes the formulars of calculating DA_{300} by spatial parameters for toplighting atriums, sidelighting atriums, and mixed toplighting and sidelighting atriums, respectively.

Relationships between DA_{300} and spatial parameters in the toplighting atrium

The sensitivity analysis based on the DA_{300} and the spatial parameters was conducted by one-way ANOVA, and the results are shown in Table 4. There is no significant correlation between the aspect ratio of plane and DA_{300} ($p>0.05$). However, significant correlation is found between other spatial parameters and DA_{300} ($p<0.05$). According to the F value, the spatial parameters that have the greatest influence on the DA_{300} are the Well Index.

Table 4: The results of sensitivity analysis based on spatial parameters and DA_{300} .

Spatial parameters	F	Sig
Length (North-South)	13.106	0.000**
Length (East-west)	2.025	0.004**
Height	11.082	0.000**
Well Index	1852.679	0.000**
Aspect ratio of plane	1.049	0.391
Aspect ratio of section	66.778	0.000**
Window area	1.799	0.011*
Spatial volume	2.297	0.001**

** $p<0.01$, * $p<0.05$.

The variation of DA_T^C with WI was explored by the regression analysis based on the data of center point in the toplighting atrium, and the correlation coefficient R^2 is 0.99, Standard Deviation is 16.7, where the DA_T^C is calculated using:

$$DA_T^C = -4.4 \times (WI_T)^2 + 2.9 \times WI_T + 96.3 \quad (1)$$

where DA_T^C is the DA_{300} at the centre point of toplighting atriums, WI_T is the Well Index for toplighting atriums. WI_T varies between 0.14 and 5.14, and the responding DA_T^C varies between 3% and 97%. When WI_T equals to 1.5, daylighting effect reaches the maximum, and DA_T^C is greater 90% with little change. When WI_T varies from 1.5 to 3.5, DA_T^C is greater than 50%.

The 608 data of DA_T^P at the centre of the atrium periphery were divided into four groups according to the North, the South, the West and the East for non-parametric test. This study shows there is no significant difference among various orientation groups ($p=0.435$).

Therefore, regression analysis was carried out on the average DA_T^P of each orientation and WI , and the R^2 is 0.98, Standard Deviation is 15.9, where the DA_T^P is calculated using:

$$DA_T^P = -3.4 \times (WI_T)^2 - 0.5 \times WI_T + 96.6 \quad (2)$$

where DA_T^P is the DA_{300} on the center point of the atrium periphery in the toplighting atrium, WI_T is the Well Index in the toplighting atrium.

Table 5: The matrix of DA_{300} formula on the center line of the gallery in the toplighting atrium.

	Formulas
2m	$DA_T^N = 1.8(WI_T)^3 - 21.3(WI_T)^2 + 19.2WI_T + 92$ $R^2=0.97$; $0.12 \leq WI_T < 3.1$; STDEV=24
	$DA_T^S = 0.8(WI_T)^3 - 17.3(WI_T)^2 + 14.5WI_T + 92.8$ $R^2=0.98$; $0.12 \leq WI_T < 3.0$; STDEV=23
	$DA_T^E = (WI_T)^3 - 15.6(WI_T)^2 + 12.4WI_T + 93.2$ $R^2=0.98$; $0.12 \leq WI_T < 3.3$; STDEV=22
	$DA_T^W = 1.3(WI_T)^3 - 17.2(WI_T)^2 + 13.6WI_T + 93$ $R^2=0.98$; $0.12 \leq WI_T < 3.2$; STDEV=22
4m	$DA_T^N = -10.1(WI_T)^4 + 77.9(WI_T)^3 - 189.8(WI_T)^2 + 115WI_T + 77.4$ $R^2=0.95$; $0.12 \leq WI_T < 2.5$; STDEV=34
	$DA_T^S = 6.6(WI_T)^4 - 5.5(WI_T)^3 - 56.8(WI_T)^2 + 40.8WI_T + 87.9$ $R^2=0.97$; $0.12 \leq WI_T < 2.1$; STDEV=30
	$DA_T^E = -0.02(WI_T)^4 + 16.9(WI_T)^3 - 76.4(WI_T)^2 + 50.9WI_T + 86$ $R^2=0.96$; $0.12 \leq WI_T < 2.4$; STDEV=30
	$DA_T^W = -0.4(WI_T)^4 + 18.7(WI_T)^3 - 77.8(WI_T)^2 + 48.7WI_T + 86.9$ $R^2=0.97$; $0.12 \leq WI_T < 2.4$; STDEV=30
6m	$DA_T^N = -13.7(WI_T)^4 + 93.2(WI_T)^3 - 194.5(WI_T)^2 + 85.5WI_T + 84$ $R^2=0.93$; $0.12 \leq WI_T < 2.1$; STDEV=34
	$DA_T^S = 16.5(WI_T)^4 - 5.6(WI_T)^3 - 90.6(WI_T)^2 + 38.8WI_T + 88.7$ $R^2=0.87$; $0.12 \leq WI_T < 1.6$; STDEV=28
	$DA_T^E = -17.1(WI_T)^4 + 114.2(WI_T)^3 - 238(WI_T)^2 + 118WI_T + 76.7$ $R^2=0.94$; $0.12 \leq WI_T < 2.3$; STDEV=33
	$DA_T^W = -16.2(WI_T)^4 + 107.7(WI_T)^3 - 220.6(WI_T)^2 + 100.2WI_T + 80.5$ $R^2=0.95$; $0.12 \leq WI_T < 2.1$; STDEV=33
8m	$DA_T^N = -11.9(WI_T)^4 + 75.5(WI_T)^3 - 137.1(WI_T)^2 + 21WI_T + 94.4$ $R^2=0.92$; $0.12 \leq WI_T < 2.0$; STDEV=33
	$DA_T^S = -76(WI_T)^4 + 333.2(WI_T)^3 - 460.1(WI_T)^2 + 148.3WI_T + 76.8$ $R^2=0.86$; $0.12 \leq WI_T < 1.4$; STDEV=30
	$DA_T^E = -40.8(WI_T)^4 + 209(WI_T)^3 - 332.3(WI_T)^2 + 117.9WI_T + 78.6$ $R^2=0.92$; $0.12 \leq WI_T < 1.6$; STDEV=32
	$DA_T^W = -37.7(WI_T)^4 + 189.3(WI_T)^3 - 288.5(WI_T)^2 + 81.1WI_T + 84.9$ $R^2=0.93$; $0.12 \leq WI_T < 1.6$; STDEV=32
10m	$DA_T^N = -12.6(WI_T)^4 + 68(WI_T)^3 - 92.8(WI_T)^2 - 34WI_T + 101.3$ $R^2=0.92$; $0.12 \leq WI_T < 1.7$; STDEV=31
	$DA_T^S = -246.5(WI_T)^4 + 791.3(WI_T)^3 - 787.1(WI_T)^2 + 170.1WI_T + 78.5$ $R^2=0.89$; $0.12 \leq WI_T < 1.3$; STDEV=33
	$DA_T^E = -73.7(WI_T)^4 + 291.4(WI_T)^3 - 344.5(WI_T)^2 + 55.8WI_T + 88.3$ $R^2=0.94$; $0.12 \leq WI_T < 1.5$; STDEV=31
	$DA_T^W = -92.9(WI_T)^4 + 337.3(WI_T)^3 - 358.1(WI_T)^2 + 34.9WI_T + 92.2$ $R^2=0.95$; $0.12 \leq WI_T < 1.6$; STDEV=31

The DA_{300} within the gallery is affected by the orientation according to the result of differential analysis and depth of the position by the distribution of DA_{300} . Therefore, the data is classified by depth and orientation, and quantitative relationship between DA_{300} and WI_T is shown in Table 5. The left column of Table 5 lists the depth of select points at two-meter intervals and the right column lists the formular at each point accordingly. STDEV represents the standard deviation for each formular. DA_{300} of smaller unit depths can be estimated by Linear interpolation.

According to the data of the gallery width, the minimum value is recommended not smaller than four meters. In order to ensure that daylighting within the galleries is effective, the DA_{300} needs to reach 50%. Based on the results of table 6, it is calculated that when $WI_T < 1.27$, the requirements can be met.

Relationships between DA_{300} and spatial parameters in the single-side daylighting atrium

According to the location of a window and the formula of the WI , a WI_S^D in the single-side daylighting atrium is calculated by Equation (3):

$$WI_S^D = D_S \times (W_S + H_S) / 2 \times W_S \times H_S \quad (3)$$

where WI_S^D is the Well Index in the single-side daylighting atrium, W_S is the width of window (m), H_S is the height of window (m), D_S is the depth of the test point (m). There is statistically significant difference among various orientation groups ($p=0.000$). Therefore, the data is grouped by the orientation variable. The regression relationships between DA_S^D and four orientations are shown in Table 6.

Table 6: The formulas of DA_S^D .

	WI_S^D range	Formulas
South	0.02~4.5	$DA_S^D = -0.68(WI_S^D)^6 + 7.97(WI_S^D)^5 - 33.07(WI_S^D)^4 + 59.75(WI_S^D)^3 - 54.8(WI_S^D)^2 + 18.06WI_S^D + 94.53$ $R^2=0.97$; STDEV=27
East	0.02~3.5	$DA_S^D = -2.47(WI_S^D)^6 + 24.45(WI_S^D)^5 - 86.04(WI_S^D)^4 + 130.06(WI_S^D)^3 - 92.95(WI_S^D)^2 + 24.27WI_S^D + 94.44$ $R^2=0.97$; STDEV=30
North	0.02~2.8	$DA_S^D = -3.34(WI_S^D)^6 + 32.04(WI_S^D)^5 - 108.1(WI_S^D)^4 + 156.49(WI_S^D)^3 - 110.21(WI_S^D)^2 + 27.887WI_S^D + 94.27$ $R^2=0.96$; STDEV=28
West	0.02~3.5	$DA_S^D = -0.03(WI_S^D)^6 - 0.84(WI_S^D)^5 + 11.72(WI_S^D)^4 - 45.32(WI_S^D)^3 + 55.45(WI_S^D)^2 - 27.73WI_S^D + 99.08$ $R^2=0.99$; STDEV=33

When the WI_S^D is less than the lower limit, 0.02 in this Table, DA_S^D is calculated by assigning WI_S^D the lower limit. When WI_S^D is greater than upper limit, the DA_S^D is 0.

Table 7: The WI_S^D results when DA_S^D is 50%.

	South	East	North	West
WI_S^D	2.52	2.15	1.9	2.23

When DA_S^D is 50%, WI_S^D results based on four orientations are shown in Table 7. The authors recommended these values as the upper limits for WI_S^D .

According to the correlation analysis, WI_S^G that affects the distribution of DA_S^G within the gallery relative to side-window is used the formula:

$$WI_S^G = d_S^G \times (W_S + H_S) / 2 \times (W_S \times H_S) \quad (4)$$

where WI_S^G is Well Index in the gallery relative to side-window, W_S is the width of the window (m), H_S is the height of the window (m), d_S^G is the depth of the gallery relative to side-window (m).

In addition, the total DA_S^G within the gallery opposite the window is effect by the DA_S^M that is on the midpoint of the gallery sideline. DA_S^M can be calculated by the formulas of DA_S^D in Table 7. Multivariate regression analysis was performed for DA_S^G , DA_S^M and WI_S^G , and the formulas of DA_S^G for each orientation are shown in Table 8.

According to the regression curve, the fastest decrease of DA_S^G is the space facing north, the space facing east is second, and the space facing west is the slowest. Although the overall decrease in the space facing south is faster than that of facing west, the former has a higher rate than the latter according to the standard that the DA_{300} should be greater than or equal to 50%. Therefore, the DA_{300} effect in the space facing south is better than that of facing west.

Table 8: The formulas of DA_S^G .

	WI_S^G range	Formulas
South	0.02~1.21	$DA_S^G = DA_S^M \left(\begin{matrix} -1.8(WI_S^G)^4 + 4.58(WI_S^G)^3 \\ -3.16(WI_S^G)^2 - 0.54WI_S^G + 1 \end{matrix} \right)$ $R^2=0.95$; STDEV=20
East	0.02~1.08	$DA_S^G = DA_S^M \left(\begin{matrix} -2.38(WI_S^G)^4 + 6.61(WI_S^G)^3 \\ -4.98(WI_S^G)^2 - 0.22WI_S^G + 0.98 \end{matrix} \right)$ $R^2=0.88$; STDEV=29
North	0.02~0.51	$DA_S^G = DA_S^M \left(\begin{matrix} -4.67(WI_S^G)^4 + 10.49(WI_S^G)^3 \\ -5.87(WI_S^G)^2 - 0.93WI_S^G + 1.01 \end{matrix} \right)$ $R^2=0.86$; STDEV=26
West	0.02~1.40	$DA_S^G = DA_S^M \left(\begin{matrix} -1.56(WI_S^G)^4 + 4.58(WI_S^G)^3 \\ -3.75(WI_S^G)^2 + 0.04WI_S^G + 0.98 \end{matrix} \right)$ $R^2=0.88$; STDEV=32

When the WI_S^G is less than the lower limit, 0.02 in this Table, the DA_S^G is calculated by assigning equal to the lower limit. When the WI_S^G is greater than the upper limit, the DA_S^G is 0.

On the edge lines of two side-galleries near the window in the sidelighting atrium, no significant difference was found between left and right side in DA_S^L ($p=0.453$). However, differences were found among different orientation groups according to the differential analysis ($p=0.000$). The formulas of DA_S^L and DA_S^D for different orientation groups by regression analysis are shown in Table 9. From the coefficient of the formula, it can be seen that reduction from the center to the edge is very small.

Table 9: The relationships between DA_S^L and DA_S^D .

	Formulas
South	$DA_S^L = 0.99DA_S^D - 2.57$; $R^2=0.99$; STDEV=38
East	$DA_S^L = 0.97DA_S^D - 2.38$; $R^2=0.99$; STDEV=41
North	$DA_S^L = 0.96DA_S^D - 2.20$; $R^2=0.98$; STDEV=41
West	$DA_S^L = 0.98DA_S^D - 2.83$; $R^2=0.99$; STDEV=39

WI_S^5 is determined according to the correlation analysis between DA_{300} and spatial parameters ($R^2=0.719$; $p=0.000$). The formula of WI_S^5 is as follows:

$$WI_S^5 = 0.5 \times (d_S^5)^2 \times (W_S + H_S) / (W_S \times H_S) \quad (5)$$

where WI_S^5 is the Well Index within window-parallel line with 5m away from the window in the sidelighting atrium, W_S is the width of the window (m), H_S is the height of the window (m), d_S^5 is the depth of the test point position(m).

On the window-parallel line with 5m away from the window in the sidelighting atrium, no significant difference was found between left and right sides gallery when the window faces South and North ($p>0.05$). However, differences were found on both sides when the window faces East and West ($p<0.05$). Therefore, data simulated is divided into six groups based on the results of differential analysis. Additionally, regression analysis results for each group of data are shown in Table 10.

Table 10: The formulas of DA_S^5 , DA_S^{5N} and DA_S^{5S} .

	WI_S^5 range	Formulas
South	0.01~25.5	$DA_S^5 = 0.145(WI_S^5)^2 - 7.358WI_S^5 + 95.644$ $R^2=0.97$; STDEV=31
North	0.01~9.6	$DA_S^5 = -5 \times 10^{-6}(WI_S^5)^6 + 6 \times 10^{-4}(WI_S^5)^5$ $-0.021(WI_S^5)^4 + 0.335(WI_S^5)^3$ $-1.57(WI_S^5)^2 - 11.285WI_S^5 + 93.524$ $R^2=0.99$; STDEV=37
East	0.01~9.3	$DA_S^{5S} = -5 \times 10^{-5}(WI_S^5)^5 - 0.004(WI_S^5)^4$ $+0.088(WI_S^5)^3 - 0.275(WI_S^5)^2$ $-11.9WI_S^5 + 95.518$ $R^2=0.98$; STDEV=37
	0.01~10	$DA_S^{5N} = -0.007(WI_S^5)^3 + 0.472(WI_S^5)^2$ $-11.268WI_S^5 + 96.027$ $R^2=0.98$; STDEV=32
West	0.01~16.8	$DA_S^{5N} = 0.156(WI_S^5)^2 - 7.449WI_S^5 + 91.518$ $R^2=0.96$; STDEV=30
	0.01~13.7	$DA_S^{5S} = 0.358(WI_S^5)^2 - 11.766WI_S^5 + 94.153$ $R^2=0.93$; STDEV=36

When DA_S^5 , DA_S^{5N} and DA_S^{5S} values are 50%, WI_S^5 results based on different positions are shown in Table 11. The authors recommend these values as the upper limits for WI_S^5 .

Table 11: The WI_S^5 results when DA_S^5 , DA_S^{5N} and DA_S^{5S} are 50%.

	South	North	East		West	
			DA_S^{5N}	DA_S^{5S}	DA_S^{5S}	DA_S^{5N}
WI_S^5	7.2	3.2	3.8	5	5.7	4.3

Relationships between DA_{300} and spatial parameters in the mixed toplighting and sidelighting atrium

On the central line of the side-window in the mixed toplighting and sidelighting atrium, WI_M^D is determined according to the correlation analysis between DA_{300} and spatial parameters ($p=0.000$), and the correlation coefficient R^2 values are higher than 0.8 in different orientation. The formula of WI_M^D is as follows:

$$WI_M^D = (W_M + H_M)(W_M + L_M)^2 H_M D_M / 8(W_M)^3 L_M \quad (6)$$

Where WI_M^D is the Well Index in the mixed toplighting and sidelighting atrium, W_M is the width of the side-window (m), H_M is the height of the side-window (m), L_M

is the length of the atrium (m), D_M is the distance from testing point to side-window (m).

The regression analysis results for WI_M^D and DA_M^D are shown in Table 12.

Table 12: The formulas of DA_M^D .

	Formulas
North	$DA_M^D = -0.037(WI_M^D)^2 - 0.373WI_M^D + 96.54$ $R^2=0.92$; STDEV=4.3
East	$DA_M^D = -0.017(WI_M^D)^2 + 0.319WI_M^D + 96.66$ $R^2=0.88$; STDEV=3.9
South	$DA_M^D = -0.038(WI_M^D)^2 - 0.114WI_M^D + 96.15$ $R^2=0.86$; STDEV=1.5
West	$DA_M^D = -0.116(WI_M^D)^2 + 0.182WI_M^D + 95.97$ $R^2=0.92$; STDEV=1.0

When DA_M^D is 50%, WI_M^D results based on four orientations are shown in Table 13. The authors recommend these values as the upper limits for WI_M^D .

Table 13: The WI_M^D results when DA_M^D is 50%.

	South	East	North	West
WI_M^D	33.5	30.5	32.5	20.5

In the gallery opposite the window, the influence of the height of window (H_M) and the depth of space (L_M) on DA_M^G is studied by the differential analysis. From the results of Table 14, it can be seen that in the small depth space, the window height has a significant influence on the DA_M^G ($p<0.05$), while the large depth space has no significant difference. Therefore, the latter can be calculated according to the formula of the matrix of DA_{300} formula in Table 6.

Table 14: Difference of DA_M^G with different height of side-window and depth of space.

	South	North	East	West
	$L_M < 3 \times H_M$		$L_M < 4.5 \times H_M$	
Sig.	0.002**	0.017*	0.000**	0.000**
	$L_M \geq 3 \times H_M$		$L_M \geq 4.5 \times H_M$	
Sig.	0.104	0.334	0.757	0.884

** $p<0.01$, * $p<0.05$.

The formulas of DA_M^G is determined by regression analysis, as shown in Table 15. According to the results, the DA_M^G within the space facing west is most sensitive to the height of the window, followed by the space facing east, and that of facing south or north has the weakest influence.

Table 15: The formulas of DA_M^G .

	Formulas
South	$DA_M^G = -0.009 (DA_T^S + H_M)^2 + 2.05 (DA_T^S + H_M) - 29.53$ $R^2=0.95$; STDEV=28
East	$DA_M^G = -0.009 (DA_T^E + 1.2H_M)^2 + 2.01 (DA_T^E + 1.2H_M) - 25.49$ $R^2=0.91$; STDEV=32
North	$DA_M^G = 10^{-4} (DA_T^S + H_M)^3 - 0.034 (DA_T^S + H_M)^2$ $+ 3.723 (DA_T^S + H_M) - 56.8$ $R^2=0.9$; STDEV=36
West	$DA_M^G = 3 \times 10^{-5} (DA_T^S + 2H_M)^3 - 0.018 (DA_T^S + 2H_M)^2$ $+ 2.98 (DA_T^S + 2H_M) - 67.97$ $R^2=0.91$; STDEV=28

On the window-parallel line with 5m away from the window, the difference of DA_M^5 , DA_M^{5N} and DA_M^{5S} in the mixed toplighting and sidelighting atrium is the same as DA_S^5 , DA_S^{5N} and DA_S^{5S} in the single-side daylighting space. DA_M^5 , DA_M^{5N} and DA_M^{5S} are analyzed by the DA_{300} value in the same position in the toplighting atrium and sidelighting atrium with the same size. The formulas are found by regression analysis, as shown in table 16.

Table 16: The formulas of DA_M^5 , DA_M^{5N} and DA_M^{5S} .

	Formulas
South	$DA_M^5 = -0.013(0.55DA_T^5 + 0.45DA_S^5)^2 + 2.05(0.55DA_T^5 + 0.45DA_S^5) + 10.05$ $R^2=0.93$; STDEV=23
North	$DA_M^5 = -0.015(0.55DA_T^5 + 0.45DA_S^5)^2 + 2.24(0.55DA_T^5 + 0.45DA_S^5) + 13.51$ $R^2=0.94$; STDEV=27
East	$DA_M^{5S} = -0.015(0.55DA_T^5 + 0.45DA_S^{5S})^2 + 2.3(0.55DA_T^5 + 0.45DA_S^{5S}) + 10.38$ $R^2=0.94$; STDEV=31
	$DA_M^{5N} = -0.013(0.55DA_T^5 + 0.45DA_S^{5N})^2 + 2.12(0.55DA_T^5 + 0.45DA_S^{5N}) + 7.97$ $R^2=0.94$; STDEV=22
West	$DA_M^{5N} = -0.013(0.55DA_T^5 + 0.45DA_S^{5N})^2 + 2.06(0.55DA_T^5 + 0.45DA_S^{5N}) + 10.31$ $R^2=0.95$; STDEV=20
	$DA_M^{5S} = -0.015(0.55DA_T^5 + 0.45DA_S^{5S})^2 + 2.26(0.55DA_T^5 + 0.45DA_S^{5S}) + 9.76$ $R^2=0.95$; STDEV=31

Conclusion

Substantial studies have shown the applicability and high-efficiency of calculating annual climate-based daylighting metrics within a space. Compared with instantaneous daylighting metrics, annual climate-based ones, like DA and Useful Daylight Illuminance (UDI) (Rea, 2000), can accurately and comprehensively provide daylighting

performance within a space from the long-term perspective. In other words, the duration that occupants stay within a space is a significant factor for daylighting designs. This paper explores the relationships between spatial parameters and DA_{300} values in atriums of interior shopping streets. The results are mainly used in the design stage to help architects master the daylight effect. The innovations are threefold.

First, typical daylighting spatial models of interior shopping streets, as well as the ranges of their spatial parameters, are proposed based on the survey within 28 interior shopping streets. The length and width of toplighting atriums vary between 8m and 80m, 5.4m and 37.6m, respectively. The length and width of sidelighting and mixed atriums vary between 14m and 54m, 9m and 27m, respectively. The range of side gallery width varies between 3.4m and 19m, and the floor of daylighting spaces is between one and eight.

Second, important spatial parameters that greatly influence DA_{300} values are proposed. The representative points within three types of atrium spaces are determined according to DA distributions. The representative points of toplighting atriums include the centre point and the central line of side galleries. The representative points within sidelighting atrium spaces are the central line perpendicular to the window, the atrium peripheries, and the five-meters window-parallel line. The representative points within mixed toplighting and sidelighting atriums are along the central line perpendicular to the window and the five-meters window-parallel line.

Third, quantitative models between the spatial parameters and DA_{300} values are summarized. The relationships between DA_{300} distributions and the spatial parameters of representative points are summarized. According to 50% DA_{300} , recommended values of WI and associated spatial parameters are proposed.

Figure 6: The automatic computing interface.

To assist architects to quickly obtain DA values within one type of atrium and adjacent spaces, the authors wrote an automatic computing interface in Excel, as shown in Figure 6, based on the proposed simplified calculation formulas. Three types of daylighting atriums were on three separate sheets. By entering spatial design parameters, architects can quickly obtain and adjust DA results.

Currently, only the spatial parameters are entered by users. Take the toplighting atrium as an example. A user can enter an atrium's dimension of 18m of length, 9m of width, 16m of height and 10m of gallery width in the Spatial Parameter Section. Consequently, DA values are displayed in the right graphic in the Output Section. If the floor height is 4 m, a user can change the height to 12 m to calculate the DA values on the second floor. The method of calculating DA values on the third and fourth floors is the same. The excel file can be downloaded through this link: <https://www.dropbox.com/sh/pjnx1uu9lpk9mlv/AADnpD4itisJ3lhFMnulGqSwa?dl=0>.

Future work

This paper presents the start of a project exploring daylighting atriums in shopping centers. The authors plan to continue this research in the following two aspects. First, the authors will conduct field studies to modify the proposed formulas with representative glazing transmittance in the reality. Simulation models calibrated by field measurements will be used to generate accurate lighting data (Kong, Utzinger, Humann, 2018). Second, the authors will add more functions and parameters to the excel sheets, including weather data from other cities in China, various interior and exterior material properties, and shading coefficients. Additionally, the authors will explore more variables so that users can have more controls over the excel sheet.

Acknowledgement

This work was supported by "the Fundamental Research Funds for the Central Universities" (No. 2019kfyXJJS096).

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