

Simulation-based Assessment of Two Different Daylight Requirements: Daylight Factor and LEED 2.2

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ABSTRACT: Daylighting is an essential technique for realizing green and sustainable building design to ensure occupant comfort. Although the benefits of daylight are widely acknowledged, daylight-related issues have not been addressed in preliminary building design. In order to assess and predict daylight performance, we can select two different requirements: daylight factor (DF) and LEED 2.2 daylight requirement. The minimum recommended DF is over 2% and LEED 2.2 requires that a minimum daylight illumination of 25 footcandles (FC) be achieved in at least 75% of all regularly occupied areas. Therefore, in this paper, we provide a simplified method to evaluate the daylight performance necessary to meet these two daylight requirements. Based on a series of computer simulations using RADIANCE, the main results obtained contained fenestration criteria to meet daylight requirements including DF and LEED 2.2 (area percentage over 25 FC). Moreover, regression models and simple evaluation tools can be developed to correlate the two daylight requirements and fenestration parameters such as window area, visible transmittance (VT), and regularly occupied area. This can be used as a pre-design tool not only to obtain more credits in LEED 2.2 green building rating systems but also to evaluate DF that meets the recommended level.

Keywords: Daylight Factor, LEED 2.2, Daylight Requirement, 25 footcandle, Visible Transmittance, Window area, Floor area, Regularly occupied area

1. INTRODUCTION

Daylighting in an office building, now widely recognized as an important energy-conservation design strategy, requires careful architectural design and effective window management in order that its benefits are realized to the maximum [1]. It is widely known that energy savings of 10–40% can be achieved by employing a daylighting scheme depending on the building envelope and climate zones [2]. Recently, there has been

increasing interest in incorporating daylight in architectural and building designs in order to reduce energy usage. Apart from energy consumption, indoor daylighting is also related to human well being and performance [3]. Moreover, a recent survey showed that most occupants prefer natural light to artificial light; surely, the admission of sunlight and natural ventilation follows, at least in part, from this preference [4]. However, although the benefits of daylight are widely acknowledged, the daylighting

approach to design remains to be employed in common practice [5]. Over the last few decades, daylighting has been progressively ignored in building planning. Moreover, the forecast of daylighting behavior is generally tackled in an inadequate manner and considered only when the project is finished [6]. Recently, a survey was conducted to investigate whether select glasses provide the recommended DF. The results revealed that glazing was mostly used inappropriately in 70% of the buildings in the Gulf region [7]. Owing to these problems, only 14% of Colorado's LEED certified projects have managed to successfully obtain LEED daylight credit of "EQ 8.1 Daylight and view." [8].

In sum, all building planners should consider that fenestration is responsible for fulfilling the daylight requirement. Therefore, this paper provides a simplified method to evaluate the qualified daylight area based on the two different daylight requirements.

2. DAYLIGHT REQUIREMENTS

2.1 Daylight Factor

Traditionally, daylighting is often determined in terms of the daylight factor (DF). By definition, the DF is the ratio of the internal illuminance to the illuminance afforded by unobstructed sky, and it is expressed as a percentage [9]. For daylighting calculations, design criteria are often expressed in terms of average daylight factors with computations based on a CIE overcast sky [10]. The British Standard Code of Practice for daylighting [11] uses the average DF as a means to judge daylight space [12]. According to the guide published by the British Council for offices, an average DF of 2% to 5% is recommended for an office workplace [13]. As pointed out in literature [14], an average DF of 5% or more will ensure that an interior looks bright and that electric lighting is not required as much. An average DF of less than 2% generally

makes a room look dull, leading to frequent use of artificial lighting.

2.2 LEED 2.2 Daylight Requirement

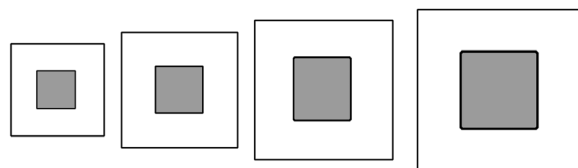
The Leadership in Energy and Environmental Design (LEED) scheme is promoted by the US Green Building Council to encourage, among other things, the design of low energy consuming buildings. LEED is a nationally accepted benchmark for the design, construction, and operation of high performance green buildings [15]. In the US in particular, certification by LEED is the most widely used green building certification system. The certification is in great demand in countries like Canada and India as well.

In November 2005, a new version, LEED 2.2, was released. As of January 1, 2006, all LEEDs for new construction projects must register under LEED version 2.2. The LEED rating system recognizes the importance of natural light entering a building so that the satisfaction and productivity of the building's occupants are improved while reducing the global energy consumption [7]. Therefore, daylighting is one of the factors that must be considered while determining the LEED credit rating. The daylight requirement for EQ Credit 8.1 is phrased as follows: "Achieve a minimum daylight illumination level of 25 FC in a minimum of 75% of all regularly occupied areas" [16]. Three options are available to determine LEED compliance: calculation of glazing factor (option 1), simulation (option 2), and measurement (option 3). From these three options, computer simulation was selected in this research and it requires that a model demonstrates 25 horizontal FC under clear sky conditions, at noon, on the equinox, and at 30 inches above the floor.

One of the most important parameters in LEED 2.2 is the area classified as the "regularly occupied area." In LEED requirement, spaces such as photocopy rooms, storage areas, mechanical plant rooms, laundry, and other low-occupancy support areas are excluded from this classification. In

this paper, a regularly occupied area is assumed to be an open-plan office area.

3. METHODOLOGY



Type A Type B Type C Type D

Figure 1: Four Office Types

Table I: Description of Four Office Type

Floor Dimension	Type A	75 × 75 ft		
	Type B	110 × 110 ft		
	Type C	145 × 145 ft		
	Type D	180 × 180 ft		
	Type A	Type B	Type C	Type D
Af	5,625	12,100	21,025	32,400
Ao	4,500	9,680	16,820	25,920
H	9 ft			

Note: Af; Floor area (sq.ft), Ao; Regularly occupied area (sq.ft), H: Floor to Ceiling Height.

Table II: Main Simulation Parameters

Parameters	Value
Model Size	Office Type A, B, C & D
Window Size	10, 30, 50, 70 & 90 %
Visible Transmittance (VT)	19.0% (Bronze) 41.9% (Blue-Green) 62.3% (Green coated Low-e) 79.5% (Clear Low-e)
Interior Reflectance	Wall 50 %, Floor 30 % & Ceiling 80 %

Table III: Location of Selected Cities

City	Latitude	Longitude
London	51.32° N	0.50° W
Chicago	41.59° N	87.54° W
Dubai	25.13° N	55.17° E

Table IV: Outdoor Horizontal Footcandles

City	Clear Sky*	Overcast Sky*
London	4,831	1,159
Chicago	6,028	1,399
Dubai	7,422	1,697

* Simulation results by RADIANCE program (Equinox at noon), 1 FC ≈ 10 lux.

3.1. Office types & Regularly occupied area

In this research, we considered a typical office floor, because LEED was proposed as a guide to high-performance commercial projects [15]. In order to assess a typical office building, four office types were selected, as shown in Figure 1. The floor space was divided into a core zone and an open office area, yielding a regular occupancy area. As mentioned above and shown in Table I, the regularly occupied area (white) was considered in each simulation because LEED 2.2 requirements are based on this area. Therefore, the core area (gray) was excluded for calculating daylight performance. The area percentage of the regularly occupied area was 80 in all four office types. The floor-to-ceiling height was 9 ft. To avoid the effect of ground reflectance, the prototype was considered to be on an upper floor of a high-rise office building. The floor was assumed to be located at a height of about 150 ft over the ground, yielding a reflectance of 30%. The assumptions and main parameters are listed in Table II.

A comparative study was also conducted using RADIANCE [17], a package for simulating and visualizing lighting using the backward ray-tracing technique. Using RADIANCE, a 3D model of the typical open-plan floor was modeled and simulated. The workplane FC data on a grid with a spacing of 5 ft were calculated at a height of 30 in above the floor [16], and the total simulation points were set as 225, 484, 841, and 1,296 (See Figure 2).

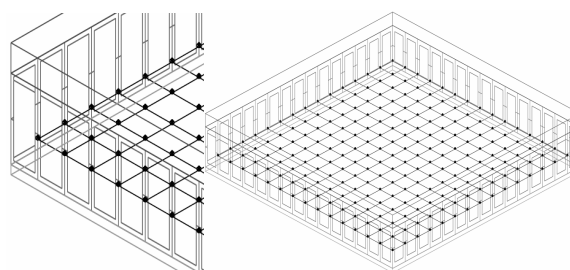


Figure 2: Reference Points Layout (Type B, Window size; 70%)

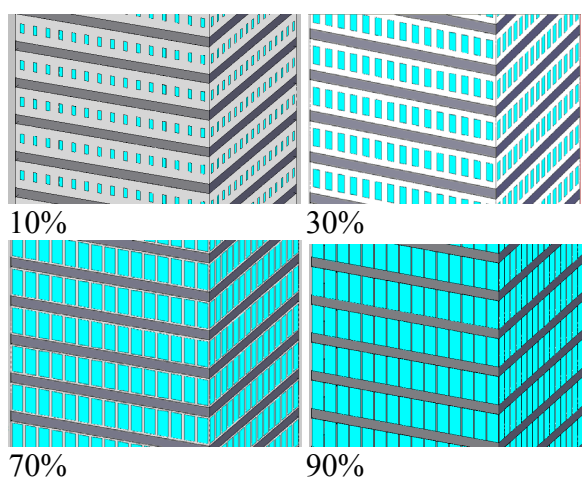


Figure 3: Proposed Window Configuration (window area percent of net wall area; floor to ceiling)

3.2. Location and Outdoor FC

In order to study universal feasibility, three locations with different latitudes were selected, namely, London, Chicago, and Dubai. Specific data are presented in Table III. As mentioned above, the only difference between the DF and LEED was in the sky conditions. As shown in Table IV, the external horizontal FCs of the three cities were obtained. The FC increased as the proximity of a city to the equator grew.

3.3. Window area and type

The main two critical factors determining the amount of daylight entering a building are the window area and type. According to ASHRAE Standard [18] and IECC [19], the maximum recommended window area is 50% of the wall area (ASHRAE) and the maximum window area should be 40% of the above-grade wall area (IECC). However, 10%–90% of the net wall area (floor to ceiling) was considered in this research in keeping with current trends in office building façades. For a given window area, the type of glass controls the amount of daylight entering the building. In daylight calculation, visible transmittance is directly proportional to daylight performance [20]. The investigated glazing types were bronze

glazing, blue-green glazing, green-coated low-e glazing, and clear low-e glazing. The value of the visual transmittance (VT) for each of these types is shown in Table II.

4. PARAMETRIC ANALYSIS RESULTS

A study of two different daylight requirements using RADIANCE was carried out. A simulation analysis was performed to investigate the effect of the window size, VT, and regularly occupied area on the four typical office floors. Every case was simulated under different locations, sky conditions, and office types while changing the various fenestration parameters. In total, 480 sets of cases were simulated for the analysis. In order to evaluate DF and LEED 2.2 requirements, the ratio of indoor FC to external FC and the number of sensor points with FC over 25 were calculated.

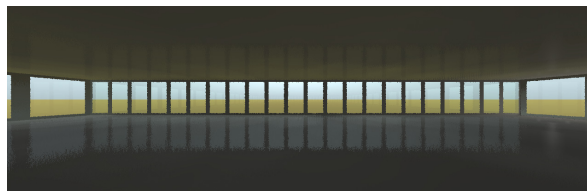
Two sets of results were thus generated. The first set contained the average DF under overcast sky conditions (see Table V); Figure 4 shows the RADIANCE output image. The indoor FC was greater when the selected city was located on lower latitude by higher outdoor FC. However, as shown in Table V, it can be found that the DF in the three cities, under the same simulation conditions, was identical. This implies that the DF does not depend on the location. Therefore, anywhere under an overcast sky, the ratio of the indoor average FC to the outdoor FC is constant when all properties are the same.

Table VI shows the second set: the results of the “area percentage over 25 FC” under a clear sky based on the LEED 2.2 requirements. Figure 5 shows the difference in the penetration of sunlight by location. Because the sun altitude was lower for higher latitudes, the solar penetration increased in London.

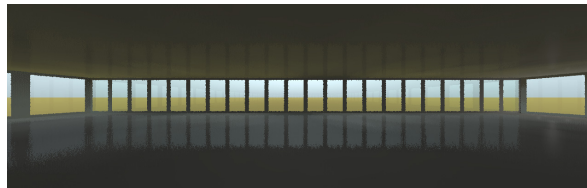
In the subsequent step, a regression analysis was conducted to investigate the effects of various parameters such as the window area, VT, and regularly occupied area. To verify the relationship between the

Table V : Results of Daylight Performance, Average Daylight Factor (%)

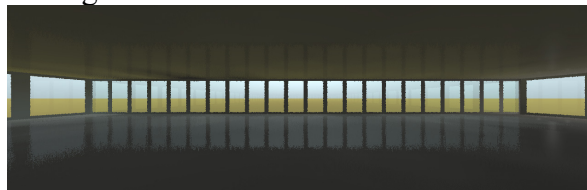
Type	Location VT (%)	London					Chicago					Dubai				
		Window Size (%)					Window Size (%)					Window Size (%)				
		10	30	50	70	90	10	30	50	70	90	10	30	50	70	90
A	19	0.39	0.89	1.60	1.71	2.11	0.38	0.89	1.33	1.71	2.09	0.38	0.88	1.32	1.71	2.09
	41.9	0.83	1.93	2.86	3.78	4.56	0.83	1.94	2.86	3.74	4.57	0.83	1.94	2.86	3.75	4.57
	62.3	1.34	3.12	4.64	6.05	7.41	1.32	3.13	4.65	6.06	7.42	1.33	3.12	4.61	6.08	7.43
	79.5	1.86	4.40	6.55	8.60	10.48	1.85	4.39	6.58	8.62	10.51	1.89	4.38	6.54	8.59	10.48
B	19	0.29	0.67	0.99	1.28	1.56	0.29	0.68	0.98	1.28	1.56	0.29	0.67	0.98	1.28	1.56
	41.9	0.62	1.44	2.14	2.81	3.42	0.63	1.44	2.15	2.81	3.43	0.62	1.45	2.15	2.80	3.43
	62.3	0.99	2.34	3.47	4.54	5.56	1.05	2.35	3.47	4.53	5.56	0.99	2.33	3.47	4.54	5.55
	79.5	1.41	3.30	4.92	6.44	7.87	1.39	3.30	4.91	6.41	7.88	1.39	3.29	4.92	6.42	7.84
C	19	0.19	0.46	0.68	0.91	1.12	0.19	0.45	0.69	0.91	1.12	0.19	0.46	0.69	0.91	1.12
	41.9	0.41	0.99	1.49	1.99	2.44	0.41	0.99	1.49	1.99	2.45	0.42	0.99	1.50	1.99	2.46
	62.3	0.66	1.59	2.42	3.19	3.96	0.66	1.58	2.40	3.20	3.95	0.65	1.58	2.42	3.19	3.95
	79.5	0.92	2.22	3.40	4.54	5.60	0.92	2.24	3.40	4.51	5.60	0.92	2.24	3.39	4.52	5.60
D	19	0.14	0.34	0.52	0.69	0.86	0.14	0.34	0.52	0.70	0.86	0.14	0.34	0.52	0.69	0.86
	41.9	0.30	0.73	1.13	1.51	1.88	0.30	0.75	1.14	1.52	1.87	0.30	0.74	1.12	1.51	1.89
	62.3	0.48	1.19	1.81	2.44	3.04	0.49	1.19	1.82	2.45	3.01	0.48	1.19	1.81	2.44	3.03
	79.5	0.68	1.67	2.59	3.45	4.28	0.69	1.67	2.58	3.48	4.32	0.68	1.66	2.59	3.45	4.32



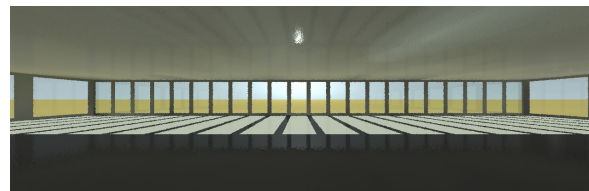
London 51.32° N



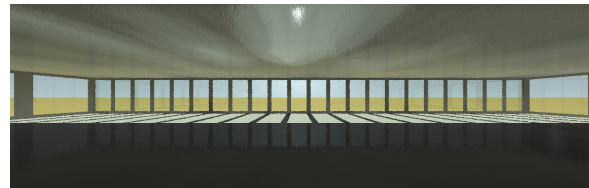
Chicago 41.59° N



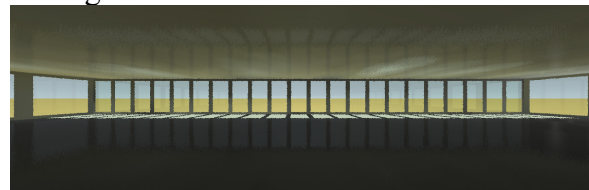
Dubai 25.13° N

Figure 4: RADIANCE image (overcast sky)

London 51.32° N



Chicago 41.59° N



Dubai 25.13° N

Figure 5: RADIANCE image (clear sky)

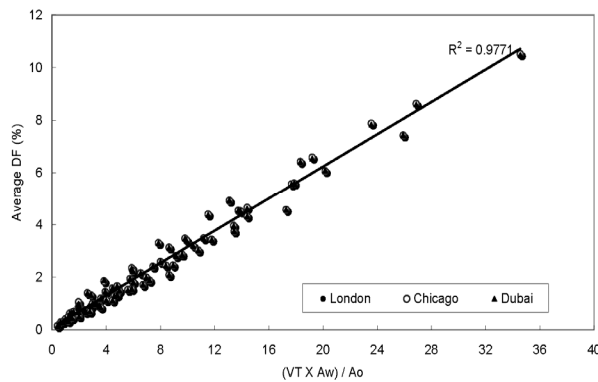
daylight performance and the simulation parameters, the daylighting aperture, defined here as the product of the window VT and the window to perimeter floor area ratio, was used [21,22,23]. Krarti et al. [23] used A_w/A_p as the window to perimeter floor area ratio to verify artificial lighting energy savings in the perimeter zone.

However, we used A_w/A_o as the window to regularly occupied area ratio to analyze the daylight performance in A_o . Therefore, to assess the two daylight performances, we used the following relationship:

$$\frac{(VT \times A_w)}{A_o} \quad (1)$$

Table VI: Results of Daylight Performance, Area percent over 25FC (%)

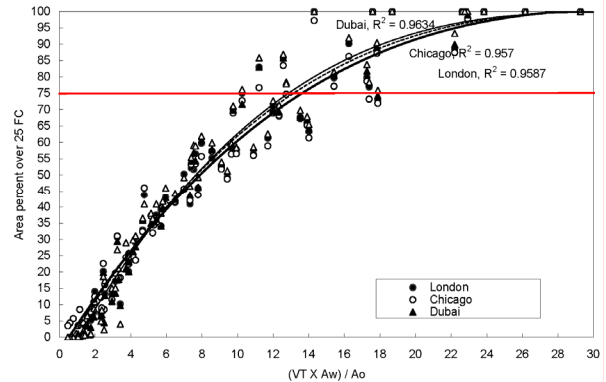
Type	Location	VT (%)	London					Chicago					Dubai				
			Window Size (%)					Window Size (%)					Window Size (%)				
			10	30	50	70	90	10	30	50	70	90	10	30	50	70	90
A		19	8.5	18.2	34.1	55.7	72.7	8.5	10.2	39.2	59.7	75.0	0	9.7	34.1	60.8	71.6
		41.9	8.5	54.0	83.5	100	100	8.5	51.7	85.8	100	100	4.5	56.8	85.8	100	100
		62.3	24.4	76.7	100	100	100	24.4	83.0	100	100	100	21.0	83.0	100	100	100
		79.5	46	97.2	100	100	100	43.8	100	100	100	100	40.9	100	100	100	100
B		19	5.7	12.2	22.4	36.5	45.6	5.7	7.3	20.1	37.5	50.3	0	6.5	20.1	36.2	49.2
		41.9	6.0	37.2	57.3	69	77.1	5.7	37.2	55.2	70.8	79.7	5.7	34.9	57.8	69.5	80.5
		62.3	16.1	53.4	74.7	87.2	97.7	13.3	56.5	74.7	88.0	97.9	12.8	54.4	78.4	89.1	99
		79.5	31.0	69.0	86.2	100	100	30.7	70.1	90.1	100	100	29.4	69.8	91.1	100	100
C		19	4.3	7.7	11.5	24.6	34.4	4.3	5.2	13.1	24.0	36.0	0	3.0	11	26.3	35.4
		41.9	4.5	25.6	41.7	51.8	58.9	4.3	25.3	41.4	53	61.3	1.2	23.1	42.3	53.4	62.1
		62.3	10.7	39.9	56.4	67.3	73.2	7.6	40.5	58.5	67.7	76.9	6.3	39.7	58.6	67.7	78
		79.5	22.6	53.3	68.3	78.7	87.4	20.2	52.2	68.0	79.8	88.5	19.8	54.2	69.3	81.8	89.9
D		19	3.5	5.9	9.0	18.1	23.6	3.5	3.5	8.3	17.4	29.0	0	1.3	6.9	17.7	27.7
		41.9	3.5	19.6	32.0	42.0	48.8	3.5	17.1	35.3	40.9	49.3	1.0	13.5	35.5	43.8	51.2
		62.3	5.5	32.4	43.8	56.0	61.4	4.8	32.9	45.9	56.4	63.4	3.5	35.9	46.3	58.4	63.9
		79.5	12.4	40.7	56.5	65.2	71.9	14.0	43.0	57.8	66.1	73.0	10.7	43.0	58.5	66.8	74.3

**Figure 6:** Correlation between Average DF and ‘(VT × Aw) / Ao’

where VT: visible transmittance; Aw: total window area; Ao: regularly occupied area.

Figure 6 presents the correlation between the average DF and $(VT \times Aw)/Ao$ under overcast skies. It is evident from this figure that $(VT \times Aw)/Ao$ is approximately proportional to the average DF. As mentioned previously, although the average FC and outdoor FC were different in the three locations, there was no change in the average DF when the simulation conditions were the same. This equation has a coefficient of determination, R^2 , of 0.977.

This verifies how well the correlation fits

**Figure 7:** Correlation between ‘Area percent over 25 FC’ and ‘(VT × Aw) / Ao’

the data. Moreover, this relationship makes it possible to evaluate the fenestration parameters and office types that lead to the variation of the average DF. When $(VT \times Aw)/Ao$ is greater than 6, a minimum average DF of 2% can be achieved.

For LEED 2.2 daylight requirements, Figure 7 shows the relationship with respect to $(VT \times Aw)/Ao$, as x was varied from 0 to 30, in terms of the area percentage over 25 FC, and y was varied from 0% to 100%. The coefficient of determination, R^2 , was found to be 0.959 in London, 0.957 in Chicago, and 0.963 in Dubai. These results reveal a strong

relationship between the area percentage over 25 FC and $(VT \times Aw)/Ao$. With the coefficient of determination, R^2 , being over 0.95 for all three cases, it is argued that the LEED 2.2 requirements are well correlated with $(VT \times Aw)/Ao$ although which is slightly less than that under overcast skies. When $(VT \times Aw)/Ao$ was greater than 12.7 (Dubai), 13.0 (Chicago), and 13.5 (London), a minimum area percentage of over 25 FC could be achieved.

As shown in Figure 7, there were small differences among the three cities. Because Dubai's outdoor FC was higher than that of London, under the same conditions, the area with FC over 25 (London) was larger than that in the case of Dubai. Conversely, because London's sun altitude was lower, more sunlight penetrated the inside area in this city, as shown in Figure 5. Therefore, a small difference existed due to the conflicts in two factors: outdoor FC and sun altitude.

With these figures and results, an area percentage exceeding 25 FC can be predicted, based on the daylight requirements of LEED 2.2. Further, the results can be applied to other areas on the same latitude. This is because the sun altitude on equinox at solar noon is the same when the location is at the same latitude on a sun-path diagram [24,25].

Therefore, these two guidelines for fenestration criteria presented in this section are related to the window area, VT, and regularly occupied area. These simplified tools can hence be used as guidelines to evaluate the indoor daylight performance and meet the recommended DF requirement or obtain credit in the LEED 2.2 rating system.

5. CONCLUSION

In this paper, we presented the results of a simulation-based daylighting analysis for typical office spaces. The main objectives were to (i) evaluate the impact of the window parameters—glazing area and VT—and regularly occupied area and (ii) to provide guidelines to meet two daylight requirements.

Therefore, parametric simulations were conducted and a simplified method, based on the results of a regression analysis, was developed for preliminary prediction of daylight performance of two daylight requirements, average DF and LEED 2.2 daylight requirement.

We found that the two different performance parameters, the average DF, and area percentage over 25 FC were related with $(VT \times Aw)/Ao$. Based on our regression analysis, R^2 values over 0.98 indicated a strong correlation among the WWR, VT, office area, regularly occupied areas, and daylight requirements. When $(VT \times Aw)/Ao$ was greater than 6, a minimum average DF of over 2% could be achieved. For the average DF under overcast sky conditions, the ratio of the average FC to the external horizontal FC was constant when all other properties were same.

In LEED 2.2, when $(VT \times Aw)/Ao$ was greater than 12.7 (Dubai), 13.0 (Chicago), and 13.5 (London), a minimum area percentage over 25 FC could be achieved. Although differences in geographical location were large, differences in terms of daylight performance results were only small, due to the external FC and sun altitude. Even though the simulations were performed in three different cities, the results could be applied to locations with similar latitudes, i.e., 25°, 42°, and 51° N.

Therefore, these simplified tools can be used as guidelines on how to estimate daylight performance and how to design fenestration in order to meet two different daylight requirements. In particular, using the schematic design process, we can predict daylight performance and verify whether our design meets these two daylight requirements or not. We hope that these criteria will enable architects and engineers, who are responsible for designing or selecting building fenestration, achieve better daylight performance through the consideration of fenestration design, properties, sky conditions, and locations.

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