A comparative study between Daylight Factor Based Metric and other Daylight Metrics for Daylighting Design

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Abstract: The calculation of the daylight illuminance for a given position in a building is a key step in daylighting schemes. In order to predict the daylight performance of room space and set a scale for architects to use when comparing aspects of various daylighting schemes, there are a number of rules of thumb and design metrics. The Daylight Factor based metric is under the traditional overcast sky excluding direct sunlight. It is frequently formalized within national standards in many countries. However, such metric does not consider the dynamic variations in daylight illuminance. Recently, daylight factor calculations have been extended for all sky conditions. It means that Daylight Factor based metric is no longer static and it can take into account the building directions, solar positions and the effects of direct and reflected sunlight. This paper provides a review of the daylight factor based metric and gives an overview of the current dynamic daylight metrics. The daylight factor based metric and other dynamic daylight metrics are analysed. The findings would be useful to practitioners engaged in visual comfort, fenestration and daylighting design and evaluation.

Keywords: Daylight factor; useful daylight illuminance; daylight autonomy; dynamic daylight metrics.

1. Introduction

Hong Kong is one of the most densely populated and built-up cities in the world and electricity is mainly expended by building stocks. Currently, over 90% of electricity is consumed by building sectors. Daylighting is an impressive and sustainable development strategy (Sudan et al., 2015) and the design concept is an important issue for the architecture and the building research to enhance visual comfort, physical health, energy-efficiency and green building development.

In order to predict the daylight performance of room space and set a scale for building designers to use when comparing aspects of various daylighting schemes, researchers put forward a number of rules of thumb and design metrics, such as Daylight Autonomy (DA), Useful Daylight Illuminance (UDI) and daylight factor (DF). DA was originally proposed by the Association Suisse des Electriciens. Later, Reinhart and Walkenhorst (2001) redefined the total natural lighting percentage for DA as a dynamic

Imaginable Futures: Design Thinking, and the Scientific Method. 54th International Conference of the Architectural Science Association 2020, Ali Ghaffarianhoseini, et al (eds), pp. 11–20. © 2020 and published by the Architectural Science Association (ANZAScA).

lighting evaluation indicator. Recently, Nabil and Mardaljevic (2005 and 2006) proposed the UDI, which is defined as the illuminances at the work plane within the range of 100lux - 2000lux. Daylight Factor Approach (DFA) is the most commonly accepted daylight performance metric, though it provides the worst daylighting condition (Hopkinson et al., 1966) under the traditional overcast sky. Such DFA is not flexible enough to predict the dynamic variations in daylight illuminance when the sun's location varies and the sky condition becomes non-overcast (Littlefair, 1989). Moreover, DF has limitations in assessing the daylighting performance of a room space under a real daylight climate (Bian and Ma, 2017). Lately, DF calculations have been extended under all sky conditions (Li et al, 2018). It means that Daylight Factor Based Metric (DFBM) is no longer static and it can take into account the building directions, solar positions and the effects of direct and reflected sunlight. This paper provides an overview of the DFBM as well as the latest Dynamic Daylight Metrics (DDM). The DFBM and other DDM are analyzed and the design implications are discussed.

2. Daylight metrics

2.1. Daylight autonomy

The minimum Daylight Autonomy (DA_{min}) is defined as the percentage of year when a minimum illuminance requirement is met by daylight alone and it is often used as the typical recommendation for a given task (BS8260,1992; IES, 1993). It means that DA_{min} would be quite appropriate for estimating the lighting energy saving under standard daylight-linked on-off lighting controls. However, DA_{min} cannot reflect excessive indoor daylight. To deal with visual glare issue, maximum Daylight Autonomy (DA_{max}) was proposed. The threshold is typically ten times the design illuminance of a space. This upper threshold criterion is a measure of the appearance of direct sunlight or other glare conditions, and it gives an indication of the frequency and location for large illuminance contrasts in a given space. In 2006, Zach Rogers (2006) proposed continuous Daylight Autonomy (DA_{con}) as a basic modification of DA. DA_{con} represents the percentage of the floor area that exceeds 300 lux for at least 50% of the time giving partial credit below 300 lux. For example, if an interior grid point has 150 lux in a given time due to daylight, DA300 would give it 0 point whereas DAcon300 would give it 150/300=0.5 point. This daylight metric would be useful for estimating the energy savings for dimming or multi-level switching controls. Spatial Daylight Autonomy (DA_{spa}) describes how much of a space receives sufficient daylight (IES, 2012). Specifically, it describes the percentage of floor area that receives the threshold illuminance for a standard percentage (e.g. 50%) of the annual occupied hours. Unlike DA, DA_{spa} returns a single number for space. The main limitation is that DA_{spa} does not include glare or direct sunlight. DA is not limited to the type of all-overcast skies. Considering the dynamic variations of sky brightness distribution throughout the year, it can more accurately evaluate the natural lighting quality of office space during the year.

2.2. Useful daylight illuminance

For each point in the room, there is a set of three metrics: the percentage of time that a point was less than the minimum threshold (<100 lux), which may not be any useful assistance in the perception of the visual environment or performance of visual tasks; more than the maximum threshold (>2000 lux), which may produce visual or thermal discomfort; between the bounds of minimum and maximum (100- 2000 lux), which is called useful daylight illuminance (UDI) (Nabil and Mardaljevic, 2006). UDI can reflect the natural lighting distribution in different illuminance intervals, because it can independently evaluate the natural lighting conditions above 2000lx, and can be used to predict the glare conditions in office space.

2.3. Daylight factor

Daylight factor approach (DFA) is the conventional method for calculating the interior daylight under overcast conditions (Hopkinson et al. 1966). The DFA can be logically computed via simple calculation tools (CIBSE, 1997) without the use of daylight data. Point Daylight Factor (PDF) is defined as the ratio of illuminance due to daylight at a point on the indoors working plane to simultaneous outdoor illuminance on a horizontal plane from an unobstructed hemisphere of CIE standard overcast sky. The DF has shown the effectiveness of daylight-linked controls in saving energy on electric lighting (Leslie et al, 2005). Average Daylight Factor (ADF) indicates the visual adequacy of the daylighting in space as a whole rather than any particular point (Longmore, 1975). ADF is directly related to the window area and less-detailed input data than those provided by the PDF, which is useful in the sketch design stage (Lynes and Littlefair, 1990). Vertical Daylight Factor (VDF) accounting for light approaching from the sky and daylight reflected from opposite buildings and the ground onto a vertical surface has been appropriately used for compact city regions with vast external obstructions (Ng, 2003). In Hong Kong, the VDF has been used to specify the daylighting performance of buildings (Buildings Department, 2015).

In 2003, CIE adopted a series of 15 sky luminance distributions as the international standard models (ISO, 2004), representing the sky conditions in many places and covering the entire possible sky spectrum found in nature. The calculation of DFs can be extended to include non-overcast skies. It means that DFA is no longer a static metric. Compared with DA and UDI, the main advantage of DFA is that DFs are strongly correlated with the room parameters, particularly the window area, the visual transmittance and building orientation. It could be easily to change the room parameters (i.e. t and W) to meet the DF criteria. In addition, DFs can be obtained based on simple design tools such as chart, diagrams and simple formula.

3. Case study and proposed methodology

3.1. Case study

The PDF, ADF, VDF, UDI and different forms of DA for the 15 unobstructed CIE Standard Skies were estimated based on the following case study. The centre of the vertical window faces south. The reflectance of wall, ceiling and floor is 0.5, 0.8 and 0.2, respectively. Totally, 9 reference points were used to demonstrate the proposed approach. The spacing of 1 m between the reference points and a height of 1 m above the floor. Fig. 1 presents the layout of the room and the reference points arrangement for estimating the DFs and other daylight metrics.

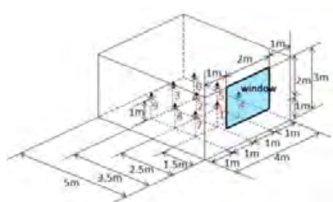


Figure 1: Room layout and reference points.

3.2. Proposed methodology

The PDF can be calculated as the sum of three components, namely the Sky Component (SC), the Internally Reflected Component (IRC) and the Externally Reflected Component (ERC). Under an unobstructed sky, there is no outdoor illuminance reflected from opposing external vertical surfaces to the interior point (i.e. no ERC):

$$DF = SC + ERC \quad (1)$$

Previously, a nomograph and a Waldram diagram for calculating the SC were established (Li et al., 2006), the detailed calculation procedures can be referred to the previous papers (Longmore, 1975). The computation of the IRC can be based on the theory of the split-flux principle. Mathematically, IRC can be given as:

$$IRC = t \times W \times [(C \times R_{fw} + D \times R_{cw}) / A \times (1 - R)] \quad (2)$$

Where:

A = total area of all the interior surfaces m^2; C and D = the configuration factors of the daylight flux incident on the mid-height of the window pane from above and below the horizon, respectively, dimensionless; R = the average reflectance of all the interior surfaces, dimensionless; R_{cw} = the average reflectance of the ceiling and upper walls above the mid-height of the window, excluding the window wall, dimensionless; R_{fw} = the average reflectance of the floor and lower parts of the walls below the mid-height of the window, excluding the window wall, dimensionless; t = the visual transmittance of the window, dimensionless; W = window area, m^2.

The VDF is the sum of C and D. For an unobstructed sky, C is the vertical sky component (VSC) which is the ratio of the vertical illuminance to the horizontal sky-diffuse illuminance available at the same point. Constant VSC values of 40, 46 and 50% representing, respectively, the Standard Skies 1, 3 and 5 were obtained. For other 12 CIE Standard Skies, the VSC substantially relies on the solar location and the VSC could be identified by the scattering angle (χ). To provide precise VSC values for subsequent study, the template of Gaussian functions (Li et al., 2016) that depict the symmetric bell curve shape were used to correlate VSC with the χ for the 12 CIE Standard Skies as shown in Equation 3.

$$VSC = A_1 \times \exp\{-[(\chi - B_1) / C_1]^2\} + A_2 \times \exp\{-[(\chi - B_2)/ C_2]^2\} \quad (3)$$

Where:

A_1, B_1, C_1, A_2, B_2 and C_2 = the regression coefficients.

For non-overcast skies (i.e. Skies 7 to 15) the ground reflected component due to direct sunlight (E_{HB}) should be included. Mathematically, D can be expressed as:

$$D = (E_{HD} + E_{HB}) \times \rho_g / (2 \times E_{HD}) \text{ (with } E_{HB}) \quad (4)$$

$$D = 0.5 \times \rho_g / E_{HD} \text{ (without } E_{HB}) \quad (5)$$

$$E_{HB} = E_{NB} \times \sin\alpha_S \quad (6)$$

E_{HB} = horizontal direct solar illuminance, lux; E_{HD} = unobstructed horizontal sky-diffuse illuminance (lux); E_{NB} = direct normal sunlight, lux; α_S = solar altitude, degree; ρ_g = ground reflectance, dimensionless.

The approximate E_{HD} and E_{NB} may be either measured or obtained from a number of articles (Kittler *et al*., 1998). Under non-overcast skies, the sun can cast a large and well defined shadow in front of the window facade. To cater such effect, it can be assumed that only diffuse component was considered for those shaded areas (using Equation 5) (Li, 2006). According to the ADF equation proposed by Longmore (1975), the extra item is C over the floor area and lower parts of the walls under the mid-height of the window (A_{fw}) as presented in Equation (7).

$$ADF = t \times W \times (C / A_{fw}) + IRC \quad (7)$$

Obtaining the C and D, the IRC, PDF, VDF and ADF under the 15 unobstructed CIE Standard Skies can then be computed for further analysis. Use Eqs. 1 to 7 based on measured global, diffuse and direct daylight illuminance in 2005 for computing the daylight metrics.

3.3. Sky classification

The measured data included the daylight illuminance were recorded from January 2005 to December 2005. The centre of the vertical window faces south from 9:00 to 16:00 in True Solar Time under the 15 CIE unobstructed skies. It is inevitable that there are some periods of missing data for various reasons, including instrumentation malfunction, power failure and photometers damage. After the quality- control test, a total of 17640 sets of databased on intervals of 10 min measurement were analysed in this study.

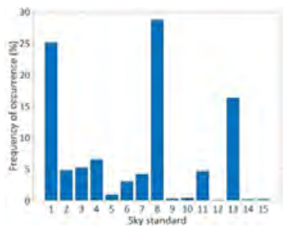


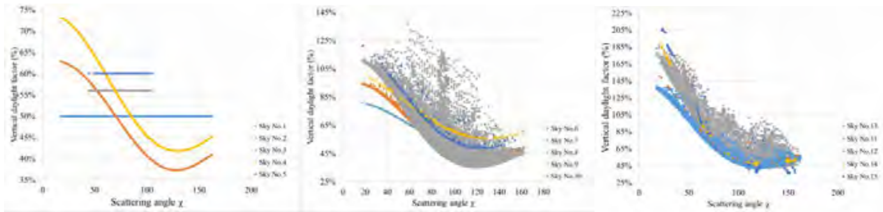
Figure 2: Frequency of occurrence of the 15 sky standards.

Accordingly, the frequency of occurrence of the 15 standard skies using the best-fitting sky luminance distributions approach is presented in Figure 2 (Li et al, 2014). It revealed that Skies 1, 8 and 13 are the typical sky conditions in Hong Kong, representing 25%, 29% and 16%, respectively. The overcast and intermediate skies (Skies. 1–10) represent about 78.7% of the Hong Kong sky conditions. The clear skies (i.e. Skies. 11–15) account for the remaining 21.3%.

4. Results and discussions

4.1 The performances of DFs

Figure 3 presents the VDF at various χ under the 15 unobstructed CIE Standard Skies. It indicates that VDFs strongly depend on the sun position. Except from Skies 1, 3 and 5, maximum VDFs for individual skies appear at low χ of around 20° and drop with increase of χ. When χ is between 115°and 125°, VDFs are at their minimum values and then increase slightly as the χ goes further. For overcast sky conditions (Figure 3(a)), VDFs do not vary according to the χ under Skies 1, 3 and 5, which are 50%, 56% and 60%. Under Skies 2 and 4, the curves of VDFs vs. χ vary gently. The C is the dominant value of VDFs because the D is just a constant of 10% for overcast skies. For intermediate (Figure 3(b)) and clear (Figure 3(c)) sky conditions containing certain amount of direct component, the VDFs vary substantially with χ. The largest and lowest VDFs are respectively, 207% and 36% both occurring in Sky 15. The correlation of VDF and χ indicates that VDF is an important parameter for building orientation designs.



(a) Overcast sky conditions (b) Intermediate sky conditions (c) Clear sky conditions

Figure 3: Vertical daylight factor vs. scattering angle (χ).

In order to obtain ADF equal to 1%, 2%, 3%, 4% and 5% under Sky 1, different window areas and transmittances were set. Table 1 shows the results. As the window area and transmittance increase, ADF rises gradually. It indicates that ADF can be obtained easily by changing these two parameters. This is very useful during the initial design phase of building scheme as complex calculations to get the suitable indoor daylight environment are not required.

Table 1: Correlations between window area, window transmittance and ADF under Sky No.1.

Cases	Average daylight factor (%)	Window area (m^2)	Window transmittance
1	1	2	0.4
2	2	4	0.45
3	3	4	0.7
4	4	5	0.75
5	5	6	0.75

The ranges of ADFs under 15 CIE Standard Skies are shown in Table 2. Under overcast sky conditions, the change of ADFs in each case is not obvious. Therefore, it is necessary to evaluate the ADFs under intermediate and clear sky conditions to reflect the indoor daylight performance. When ADF is less than 2% under Sky 1, the average ADFs of Skies 6-15 are not more than 4.5%, and the maximum ADF is 6.2% under Sky 13. However, as the window transmittance and area increase, the ADFs become larger and average ADF under Sky 13 can be three times more than under Sky 1. It will not only cause visual discomfort, but also will generate a large amount of cooling load.

Similarly, the ranges of PDFs at 9 reference points under all sky conditions in the whole year are shown in Table 3. The minimum and maximum average PDF are found to be 0.8% at Points 6 and 9 for Case 1 and 14.7% at Point 1 under Case 5. Generally, the PDF at each reference point rises as the ADF increases from Case 1 to Case 5. However, the increments for different points are distinct. Specifically, Points 1, 4 and 7 which are closer to the window have the largest increases of average PDF (around 10%), while Points 3, 6 and 9 have the lowest increases (around 5%). PDFs of Points 5 and 8 and Points 6 and 9 on both side of the room are equal, which are less than the PDFs at the points in the centre of the room. It indicates that the points away from the window centre are less affected by daylight. Point daylight illuminance can be obtained by multiplying the PDFs with the E_{HD}. It means that PDF can be used for calculating the UDI and different forms of DAs.

Table 2: Ranges of average daylight factor under 15 CIE Standard Skies (%)

Sky No.	Case 1		Case 2		Case 3		Case 4		Case 5	
	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.
1	1	1	2	2	3	3	4	4	5	5
2	0.75-1.17	0.96	1.57-2.42	1.97	2.42-3.74	3.05	3.26-5.04	4.11	3.83-5.91	4.83
3	1.13	1.13	2.32	2.32	3.59	3.59	4.83	4.83	5.67	5.67
4	0.86-1.36	1.1	1.78-2.79	2.2	2.76-4.31	3.51	3.71-5.81	4.73	4.36-6.82	5.55
5	1.22	1.22	2.5	2.5	3.87	3.87	5.21	5.21	6.12	6.12
6	0.96-1.5	1.17	1.97-3.08	2.42	3.05-4.76	3.74	4.11-6.41	5.04	4.83-7.52	5.91
7	0.83-1.68	1.2	1.72-3.44	2.47	2.66-5.32	3.83	3.58-7.17	5.16	4.2-8.41	6.05
8	0.7-2	1.2	1.46-4.16	2.5	2.26-6.42	3.86	3.04-8.65	5.21	3.58-10.2	6.12
9	1.21-1.7	1.4	2.48-3.48	2.87	3.84-5.38	4.45	2.17-7.25	5.99	6.06-8.49	7.03
10	1.05-2.04	1.53	2.17-4.17	3.15	3.36-6.46	4.87	4.52-8.7	6.56	5.31-10.2	7.7
11	0.89-2.19	1.53	1.84-4.49	3.15	2.84-6.95	4.86	3.83-9.37	6.56	4.5-1.099	7.69
12	1.03-1.85	1.58	2.12-3.79	3.26	3.28-5.86	5.04	4.42-7.89	6.79	5.19-9.25	7.96
13	0.87-2.96	2.06	1.81-6.2	4.27	2.8-9.57	6.59	3.78-12.9	8.88	4.44-15.19	10.44
14	1.19-2.11	1.94	2.45-4.33	3.97	2.78-6.7	6.14	5.1-9.03	8.28	5.98-10.58	9.7
15	1.68-2.71	2.08	3.46-5.67	4.28	2.35-8.75	6.62	7.2-11.79	8.92	8.45-13.88	10.47

Table 3: Ranges of point daylight factor at 9 reference points (%).

Reference points	Case 1		Case 2		Case 3		Case 4		Case 5	
	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.
1	1.67-6.31	3.12	5.08-9.66	6.64	7.88-14.95	10.3	9.86-19.05	12.97	11.08-21.81	14.7
2	0.64-3.67	1.47	2.26-6.48	3.6	3.5-10.01	5.57	4.43-12.83	7.07	4.9-14.84	8.03
3	0.38-2.2	0.82	1.25-4.75	2.24	1.92-7.32	3.46	2.63-9.93	4.72	2.98-11.42	5.39
4	1.19-5.04	2.34	3.79-7.97	5.15	5.88-12.33	7.99	8-16.68	10.85	9.09-18.96	12.3
5	0.54-3.04	1.21	1.83-5.69	3	2.83-8.78	4.65	3.92-12.01	6.4	4.3-13.73	7.18
6	0.37-2.14	0.8	1.22-5.69	2.19	1.88-7.18	3.37	2.44-9.41	4.38	2.79-11	5.1
7	1.23-2.05	2.42	3.79-8	5.15	5.88-12.37	7.99	8-16.73	10.82	9.09-19.01	12.27
8	0.54-2.98	1.21	1.83-5.7	3	2.83-8.79	4.64	3.92-12.03	6.4	4.3-13.73	7.17
9	0.37-2.11	0.8	1.22-4.67	2.19	1.88-7.2	3.37	2.44-9.41	4.38	2.79-11.02	5.09

4.2. Analysis of UDI and different DAs

UDIs were calculated based on PDFs (indoor illuminance = PDF x E_{HD}) at 9 reference points. Table 4 shows the results. Daylight illuminances in the ranges of 100-2000lux account for a high proportion of annual daylight illuminance for some points in Cases 1 and 2. This means that the indoor daylight environment available for people to live or work, should be neither too dim nor too bright to cause

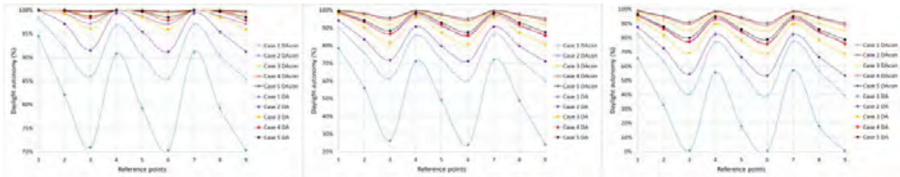
visual discomfort. As the ADFs increases (i.e. Cases 3, 4 and 5), the proportion of daylight illuminances greater than 2000lux become more, especially at the reference points near the window. In Case 5, the percentage of daylight illuminances greater than 2000lux is 75% at Point 1, while at Point 9 is only 20%. It indicates that points close to the window get more daylight and are more prone to glare, while points farther away from the window receive less daylight. It seems that the centre point (i.e. Point 2) may represent the overall daylight performance of the room. If the daylight factor of centre point is known, the corresponding UDI for the room may be computed.

Table 4: Useful daylight illuminance at 9 reference points (%).

Reference points	Case 1			Case 2			Case 3			Case 4			Case 5		
	< 100 lux	100-2000 lux	> 2000 lux	< 100 lux	100-2000 lux	> 2000 lux	< 100 lux	100-2000 lux	> 2000 lux	< 100 lux	100-2000 lux	> 2000 lux	< 100 lux	100-2000 lux	> 2000 lux
1	6	94	0	0	63	37	0	38	62	0	28	72	0	25	75
2	18	82	0	3	97	0	1	74	26	0	57	43	0	50	50
3	29	71	0	8	92	0	4	96	0	2	84	14	1	74	24
4	9	91	0	1	82	18	0	51	49	0	36	64	0	30	70
5	21	79	0	5	95	0	2	86	13	0	64	36	0	56	43
6	30	70	0	9	91	0	5	96	0	2	89	9	1	78	20
7	9	91	0	1	81	18	0	51	49	0	36	64	0	30	70
8	21	79	0	5	95	0	2	86	13	0	64	36	0	56	43
9	30	70	0	9	91	0	4	96	0	2	89	9	1	78	20

The calculation results of DA and DA_{con} at 9 reference points are shown in Figure 4. Three indoor illuminance thresholds (100, 300, and 500 lux) were set. Since daylight illuminance below the threshold will also be counted as a credit in the DA_{con}, DA is generally less than DA_{con} for all the cases, especially, when ADF is less than 2% under Sky 1 (i.e. Cases 1 and 2). When ADF further increases (from Case 2 to Case 5), the difference between DA and DA_{con} at each point becomes smaller. DA and DAcon would be increase as the window area and light transmittance increase. As the minimum threshold was set from 100 lux to 500 lux, both DA and DA_{con} distinctly decrease for all the cases with the reductions of DA_{con} less than that of DA. The reduction of DA_{con} or DA at the rear points is generally greater than that at the points near the window. The above analysis indicates that these two forms of DA can be used for evaluating the energy savings of dimming or multi-level switching daylight-linked lighting control systems with different target illuminance settings.

Table 5 shows the results of spatial daylight autonomy (50%, 70% and 80% of the occupied hours) with different illuminance thresholds (100 lux, 300 lux, 500lux and 700 lux). With the exception of $DA_{spa\ 100,50\%}$ and $DA_{spa\ 100,70\%}$, the values of other DA_{spa} are below 50% because of the small window area and low transmittance of Case 1. For other four cases, the values of $DA_{spa\ 50\%}$ with 100lux, 300lux and 500lux are equal to 100%. It indicates that 50% of the total occupied hours may be too small to evaluate the annual daylighting performance. The values of DA_{spa} decrease significantly by increasing both the percentage of occupied hours and illuminance threshold. DA_{spa} can only represent the percentage of the total floor area that can meet the defined criteria, but it cannot reflect which part of the room fulfilling the criteria. Besides, the DA_{spa} cannot indicate the excessive daylight in the room, especially for non- overcast skies in which the direct sunlight dominants.



(a) target illuminance > 100lux (b) target illuminance > 300lux (c) target illuminance > 500lux

Figure 4: Comparisons of daylight autonomy and continuous daylight autonomy.

Table 5: Spatial daylight autonomy (%).

Cases	DA_{spa} 100, 50%	DA_{spa} 100, 70%	DA_{spa} 100, 80%	DA_{spa} 300, 50%	DA_{spa} 300, 70%	DA_{spa} 300, 80%	DA_{spa} 500, 50%	DA_{spa} 500, 70%	DA_{spa} 500, 80%	DA_{spa} 700, 50%	DA_{spa} 700, 70%	DA_{spa} 700, 80%
1	100	100	44	44	33	0	33	0	0	11	0	0
2	100	100	100	100	100	67	100	44	33	67	33	11
3	100	100	100	100	100	100	100	67	44	100	67	33
4	100	100	100	100	100	100	100	100	67	100	67	44
5	100	100	100	100	100	100	100	100	78	100	100	67

5. Conclusions

Useful Daylight Illuminance (UDI) and Daylight Autonomy (DA) are useful daylight metrics, but they require typical annual daylight data which may not be always available for many places. Climate-based daylighting metrics and daylight factor based metrics have been studied in this paper. The absolute daylight illuminances at the indoor points can be obtained by multiplying the daylight factor by the corresponding horizontal sky diffuse illuminance. The computed daylight illuminances can be used for estimating the UDI and different forms of DA. The results show that the centre point could represent the overall daylight performance of the room, DAs and UDI can be computed by using the daylight factor of a particular point. DA and DAcon have similar patterns as the PDFs, these two forms of DA can be used for evaluating the energy savings of dimming or multi-level switching daylight-linked lighting control systems with different target illuminance settings. The criterion "50% of the total occupied hours" for DAspa may not be appropriate to evaluate the annual daylighting performance. It cannot indicate the excessive daylight in the room under non-overcast skies. As the 15 CIE skies represent the actual skies for many places and cover the whole probable spectrum of skies found in nature, the daylight factor approach (DFA) could be globally adopted and would be useful to practitioners engaged in architectural and daylighting designs and evaluations. In future works, the grid density would be further increased to minimize the uncertainties. The effects of other room parameters (i.e. window orientation and surface reflectance) on daylight metrics will be analysed. A series of computer simulations will be conducted for the validations.

Acknowledgements

Work described was fully supported by a General Research Fund from the Grant Council of HKSAR [Project No. 9042504 (CityU 11209217)]. Wenqiang Chen was supported by a City University of Hong Kong Postgraduate Studentship.

References

Bian, Y. and Ma, Y. (2017) Analysis of daylight metrics of side-lit room in Canton, south China: A comparison between daylight autonomy and daylight factor, Energy and Buildings, 138, 347-354.

Buildings Department (2015) Practice Note for Authorized Persons, Registered Structural Engineers and Registered Geotechnical Engineers APP-130, Lighting and Ventilation Requirements-Performance-based Approach.

Code of Practice for Daylighting. (1992) British Standard Institution, London, UK, British Standard BS8206 Part 2.

CIBSE (1997). Code for interior lighting. London, UK.

Hopkinson, R.G., Petherbridge, P. and Longmore, J. (1966) Daylighting, Heinemann, London, UK.

IES. (1993) Lighting Handbook Reference & Application, ed., Illuminating Engineering Society of North America, New York.

IES. (2012) Approved Method: Spatial Daylight Autonomy and Annual Sunlight Exposure, IES LM-83e12, USA.

ISO. (2004) CIE S 011/E:2003. Spatial Distribution Daylight-CIE Standard General Sky. In (Vol. ISO Standard 15469), Geneva.

Kittler, R., Darula, S. and Perez, R. (1998) A set of standard skies, Polygrafia, Bratislave.

Leslie, R.P., Raghavan, R., Howlett, O. and Eaton, C. (2005) The potential of simplified concepts for daylight, Lighting Research and Technology, 37(1), 21-40.

Li, D.H.W. (2007) Daylight and energy implication for the CIE standard skies, Energy Conversion and Management, 48(3), 745-755.

Li, D.H.W., Cheung, G.H.W. and Lau, C.C.S. (2006) A simplified procedure for determining indoor daylight illuminance using daylight coefficient concept, Building and Environment, 41(5), 578-589.

Li, D.H.W., Cheung, Chau, T.C. and Wan, K.K.W. (2014) A review of the CIE general sky classification approaches, Renewable and Sustainable Energy Reviews, 31, 563-574.

Li, D.H.W., Li, C., Lou, S.W., Tsang, E.K.W. and Lam, J.C. (2015) Analysis of vertical sky components under various CIE Standard General Skies, Indoor and Building Environment, 25(4), 703-711.

Li, D.H.W., Li, S.Y., Chen, W.Q. and Lou, S. (2018) Analysis of Point Daylight Factor (PDF) Average Daylight Factor (ADF) and Vertical Daylight Factor (VDF) under various unobstructed CIE Standard Skies, Paper presented at the The 9th edition of the international SOLARIS conference, Chengdu.

Littlefair, P.J. (1989) Predicting hourly internal daylight illuminances for dynamic building energy modelling, Garston, UK: Building Research Establishment.

Longmore, J. (1975) Daylighting: a current view, Light and Lighting, 68, 113-119.

Lynes, J.A. and Littlefair, P.J. (1990) Lighting energy savings from daylight: Estimation at the sketch design stage, Lighting Research and Technology, 22(3), 129-137.

Nabil, A., and Mardaljevic, J. (2005) Useful daylight illuminance: a new paradigm for assessing daylight in buildings, Lighting Research and Technology, 37(1), 41-59.

Nabil, A. and John Mardaljevic, J. (2006) Useful daylight illuminances: A replacement for daylight factors, Energy and Buildings, 38, 905-913.

Ng, E. (2003) Studies on daylight design and regulation of high density residential housing in Hong Kong, Lighting Research and Technology, 35(2), 127-139.

Reinhart, C.F. and Walkenhorst O. (2001) Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds, Energy and Buildings, 33, 683-697.

Reinhart, C.F., Mardaljevic, J. and Rogers, Z. (2006) Dynamic daylight performance metrics for sustainable building design, Leukos, 3(1), 7-31.

Sudan, M., Tiwari, G.N. and Al-Helal, I.M. (2015) A daylight factor model under clear sky conditions for building: An experimental validation, Solar Energy, 115, 379–389.