Climate-Based Daylight Metrics applied for Sustainable and High-Quality Design Strategy of office spaces

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Abstract
Daylight using in office space not only has the energy-saving potential, but also achieve visual requirements and improve work efficiency. In the past, "Daylight factor (DF)" has always been the mainstream of building daylight specifications. However, "static" Daylight factor cannot fully reflect the change of time, nor the relationship between building orientation and external shading. In recent years, "Dynamic Daylight Metrics" based on meteorological data has become a new evaluation trend, which can accurately evaluate the daylight quality in the annual working hours of the building. To evaluate the daylight condition of Taiwan's office space, this study used the " Typical Meteorological Year (TMY3)" as the database of climate, and applied the dynamic lighting index "Spatial Daylight Autonomy (sDA)" and "Annual solar Exposure value (ASE)" as the dynamic daylight evaluation index, which are commonly used internationally. Through simulation with DIVA for Rhino software, daylight design strategies such as window-to-wall ratio, window types, shading for office space were discussed to achieve the purpose of sustainable building design and high-quality daylight environment.

Keywords: Dynamic Daylight Metrics, Spatial Daylight Autonomy, Annual solar Exposure value, Daylight Design, TMY3

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Introduction

According to statistics, lighting energy consumption of buildings accounts for about 25% of the total energy consumption. If natural light is fully used, it can not only save a lot of daytime lighting energy, but also effectively enhance work efficiency (Vine et al., 1998). In particular, Taiwan is in a low latitude area with long sunshine hours and excellent natural lighting design potential.

In recent years, European and American countries have promoted "Dynamic Daylight Metrics", which can complete the local climate data, spatial geometry and material reflectance, and make the indoor space lighting assessment closer to the actual situation. . For example, the US Green Building Council (USGBC) Green Building Evaluation Index LEED V4 specifically mentions (USGBC, 2013): To enhance the link between building users and nature, to enhance the physiological regularity of people staying up late, while introducing natural light to reduce lighting energy consumption, Dynamic lighting design is an indispensable design project.

This study takes Taiwan's common office space as the research object and takes Taichung City as the research site. Typical Meteorological Year 3 (TMY3) is used as the climate data, and the "Spatial Daylight Autonomy (sDA) " and "Annual Sun Exposure (ASE)" are used as dynamic daylight metrics. This study uses DIVA for Rhino software to simulate and verify daylight distribution, and evaluates the appropriate window type, lighting depth and shading design method for office space, in order to achieve the purpose of green building energy-saving design and high-quality lighting environment.

Theory and Method

1. Dynamic daylight metrics

(1) Spatial Daylight Autonomy, sDA
Spatial Daylight Autonomy (sDA) describes how much of a space receives sufficient daylight. Specifically, it describes the percentage of floor area that receives at least 300 lux for at least 50% of the annual occupiable hours, which is the standard recommended by IES. The occupiable hours are usually set from 8:00 to 18:00, in total of 10 hours. This indicator helps find a space suitable for using sDA for a long-term period. If the sDA exceeds 75%, the daylight is considered to be excellent; 74% to 55% means acceptable daylight, and if less than 55%, the daylight is considered to be poor.

(2) Annual Sunlight Exposure, ASE
Although sDA encourages a high proportion of spatial daylight, the increase in spatial daylight also greatly increases the potential of glare and solar thermal energy. Therefore, the ASE indicator is designed to limit the excessive amount of sunlight in space. The base value for ASE is ASE1000, 250, which means ASE measures the percentage of floor area that receives at least 1000 lux for at least 250 occupied hours per year. IES also points out that if the ASE in the space is higher than 10%, it means that it may be too bright, causing visual discomfort.

2. Simulation software for dynamic daylight

DIVA for Rhino is a highly optimized daylighting and energy modeling plug-in application with the functions of radiation Map, real rendering, climate-based daylight indicators, and glare analysis at annual and specific time points. This plug-in application reviews the compliance with LEED metrics and calculation of energy and load in a single thermal comfort zone. In view of the high precision and better operating interface of DIVA for Rhino and its support of the calculation and review of dynamic daylight indicators, this study will use DIVA for Rhino as the simulation software for office space dynamic daylight, and examine and analyze each result of the dynamic daylight in the aforementioned setting of office space and facade window. The operation settings are shown as below:

A. Build a model: Use Rhinoceros to build a spatial model and then divide it into different layers according to the building components such as ceilings, walls or windows.

B. Set the base location: Import the data from TMY3 (.epw).

C. Set the grid node: Set the sensing node for calculating the illuminance. The node position is set to the height of the working plane, which is 76cm above the floor. The interval between each node is set at 50cm as recommended.

D. Specify the material: Specify the material in the form of geometry in the space for the analysis of daylight or energy performance. In order to ensure the accuracy of simulation, the reflectance of indoor material and the transmissivity of glass in this study take the reflectance of office space materials recommended by IES as the base value. The material settings are shown in Table 1.

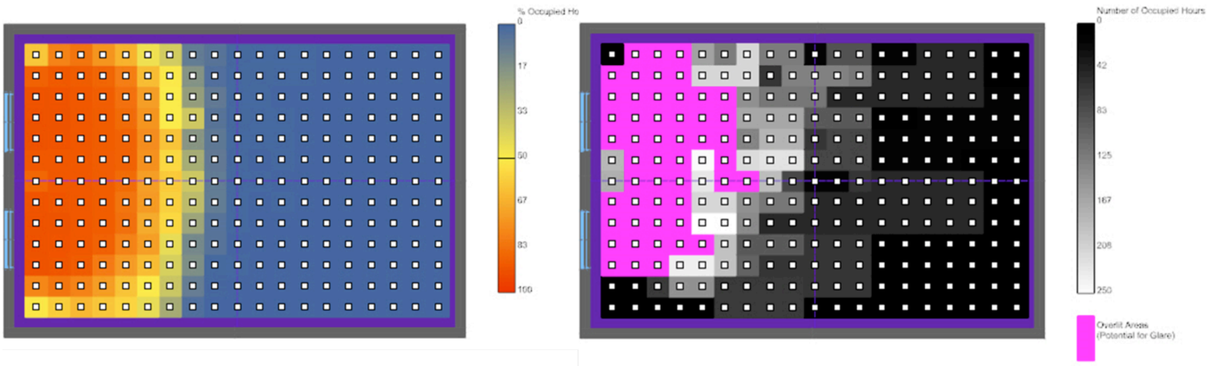


Figure 1: simulation results of DIVA dynamic lighting indicators (left: sDA; right: ASE)

Table 1: Material reflectance and glass transmittance setting

Ceiling reflectance	Wall reflectance	Floor reflectance	sunshade light guide reflectance	Glass transmittance
70%、80%	50%、70%	20%、40%	90%	80%

Process and Result of Research

1. Research object and space setting

There are two main problems in the design of natural daylighting in office space: (1) poor uniformity of illumination. Due to the deep depth of the office space, the gradient of spatial illumination becomes larger. If the illumination at the window position is relatively high, the indoor illumination would be relatively low. (2) Glare on the working plane. Since the illuminance value at the window position is high, and the problem of glare is prone to occurring, the visual discomfort is more likely to happen on users. In order to solve the above two problems, this study will carry out the natural daylighting simulation of the reflectance of window opening type, sunshade light-guide device and material, in order to improve the spatial daylighting.

In this study, the common office space building model is taken as the reference, and the unit space size is set by a multiple of 3 m. The space size for the simulation is set to be 6m wide and 9m deep, and the space height is set to 3.6m.

Based on the reflectance of the building material, the position of the inner and outer sunshade light guiding system, or the presence or absence of the sunshade light guiding system, each type of the office unit space will undergo 8 sets of dynamic daylighting simulation. Simulation No. 01 and 02 are conducted with the presence or absence of external sunshade. No. 03 and 04 are conducted with the conditions that the internal or external light guide plate is set up to import more uniform light. No. 05 to 08 feature the external sunshade and internal "light guide" to test the ceiling reflectance, wall space reflectance and floor reflectance respectively.

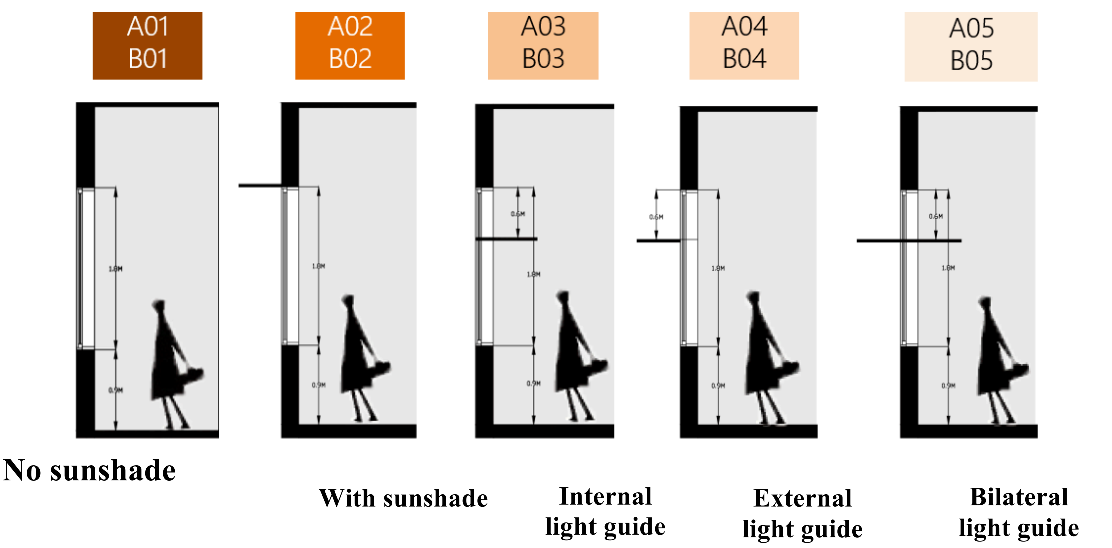


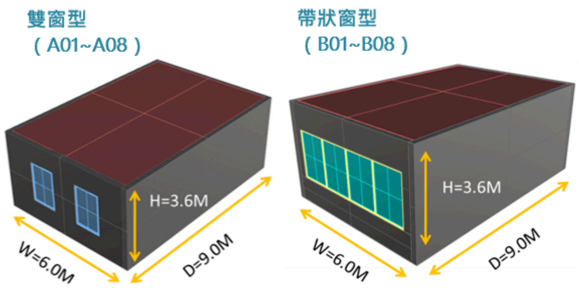
Figure 2: Sunshade and light guide device settings

2. Dynamic Daylight Simulation of Unit Type Office Space: Single-sided Window opening (take the south orientation as an example)

In this research, the unit type office space is divided into two types of window modes: "double window type" and " ribbon window", and different sunshade light guiding forms of window opening and indoor material reflectance. The biggest difference that separates the ribbon window from double window in terms of daylighting lies not only at the large opening area of the ribbon window, but also at the continuous ribbon-shaped daylighting, resulting in the relatively light contrast between the brightness and darkness in the room. Thus, the uniformity will also be better.

(1) Influence of "double window" and "ribbon window" on dynamic daylight

Taking the south-oriented window opening as an example, the daylighting simulation results of the double window type and the ribbon window are shown in the table. The total window opening area of the ribbon window type is about 2 times that of the double window type, and the sDA value is also about twice that of the double window type. However, if the 55% of sDA value is taken as the base value of the amount of indoor daylighting, under the current single window opening condition, neither the double window type nor the ribbon window type can achieve the ideal amount of daylight during the working hours. In the aspect of the ASE value, the value of ribbon window type is about 3% higher than the double window type. Especially if the window opening is equipped with a sunshade light guide device, the ASE value can be below the recommended value of 10%. Overall, B07 is the model that is the closest to the ideal daylighting state.



Double window type (A01~A08)

Ribbon window type (B01~B08)

Figure 3: Simulation model

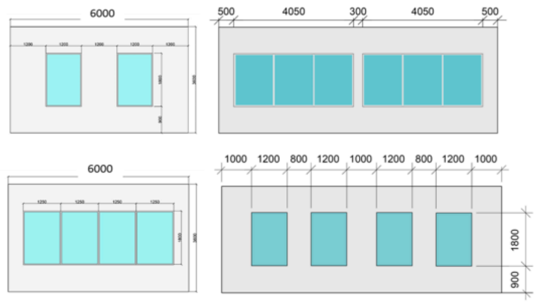


Figure 4: Facade setting of simulation models

Table 2: sDA and ASE of double window type office (south orientation)

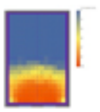
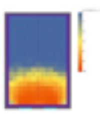
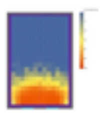
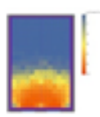
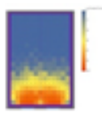
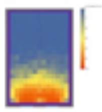
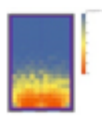
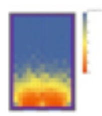
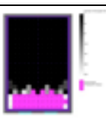
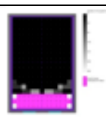
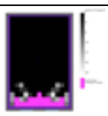
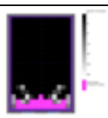
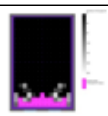
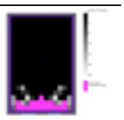
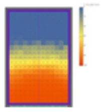
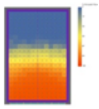
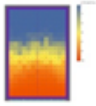
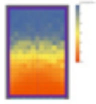
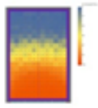
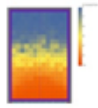
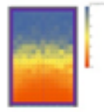
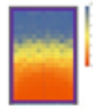
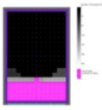
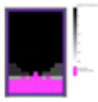
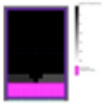
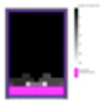
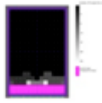
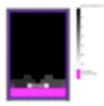
reflectance	A1	A2	A3	A4	A5	A6	A7	A8
ceiling	70%	70%	70%	70%	70%	80%	70%	70%
wall	50%	50%	50%	50%	50%	50%	70%	50%
floor	40%	40%	40%	40%	40%	40%	40%	20%
sDA								
	28.7%	28.7%	22.7%	27.5%	19.8%	19%	20.2%	19.8%
ASE								
	18.6%	15%	14.2%	12.1%	7.7%	7.7%	7.7%	7.7%

Table 3: sDA and ASE of ribbon window type office (south orientation)

reflectance	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**
ceiling	70%	70%	70%	70%	70%	80%	70%	70%
wall	50%	50%	50%	50%	50%	50%	70%	50%
floor	40%	40%	40%	40%	40%	40%	40%	20%
sDA								
	42.9%	45.7%	45.7%	49%	44.5%	46.6%	47%	44.5%
ASE								
	21.5%	18.2%	15.8%	18.2%	10.5%	10.5%	10%	10.5%

(2) Influence of the sunlight guiding device on dynamic daylighting

In the case of double window type with the absence and presence of sunshade, the sDA values are both 28.7%, but the ASE value is about 3% lower when there is the external sunshade device. In contrast, when the ribbon window is equipped with the ribbon horizontal external sunshade device, the sDA value, affected by the diffuse reflection ray of the device, is increased slightly by about 3%, and ASE is decreased by about 3%.

If the sunshade light guiding device is installed indoors, or extends beyond the inside of the room to the outside, the sDA of double window type will continue to drop, which is not conducive to the overall natural daylighting amount inside the room. However, the light guiding sunshade device is beneficial to the increase of the sDA value of the ribbon window type, because the light guiding sunshade device is installed between the clerestory and the general window, thus making the effects of light guiding and diffuse reflection ray the best.

(3) Influence of indoor material reflectance on dynamic daylighting

In general, if the indoor material has a high reflectance, it will help the light diffuse in space and improve the quality. However, when we observe the simulation results of overall dynamic daylighting, compared to the original control group (the ceiling reflectance is 70%, the wall space reflectance is 50% and the ground reflectance is 20%), the increase in reflectance of the indoor material exerts almost no effect on the sDA value and ASE value. Only when the wall space reflectance is increased to 70%, the sDA value rises slightly.

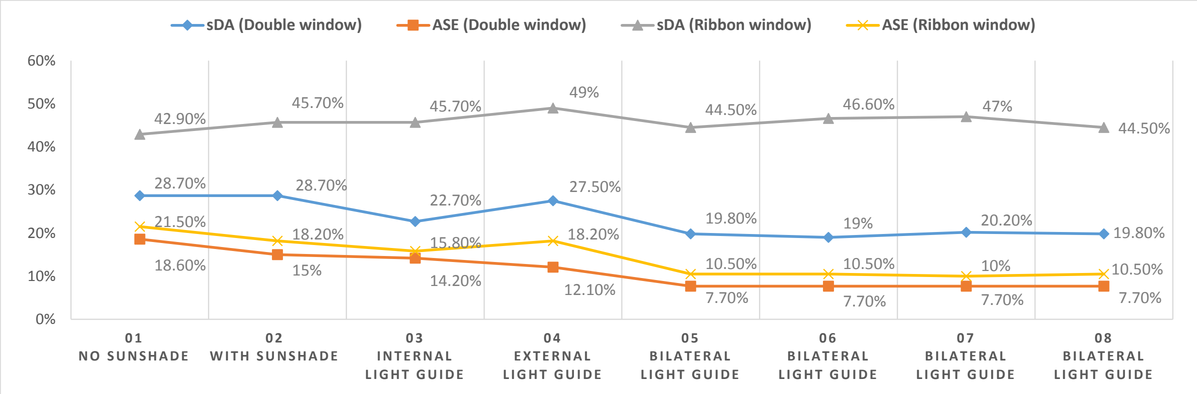


Figure 5: Simulation results of sDA and ASE with double window and ribbon window

3. Simulation of Dynamic Daylighting of Unit Type Office Space: Single-sided Window Opening (All Orientations)

(1) Double-window type

This study further simulates the dynamic daylighting of the double-window type and the ribbon window type, and the sDA and ASE values are shown in the table. Compared with the A01 and A02 of each orientation, except the sunshade of the south-oriented window, the sDA value will be reduced by 1.2% to 3.6% when there is a sunshade device, and the north-oriented window without the sunshade device features the highest sDA value, which is 36.4%. But the standard value of 55% still fails to be reached, requiring the daylighting to be improved. The north-oriented window features the best ASE value, all below the standard value of 10%. What follows is the A02 with sunshade in the south, and its ASE value is 15%. The ASE values of the west-oriented windows are all relatively high. The installation of a sunshade device can reduce the ASE value of each orientation by 1.6% to 4%.

In comparing the A01 to A05 of each orientation, the sDA value of the A01 without sunshade device is higher than the other window type, and the A03's inner light guiding device will reduce the sDA value by 5.2% to 7.3%, which is not conducive to the improvement of natural daylighting. The north-oriented window features the best ASE value. Regardless of the light guide device, the ASE value is always kept at 0%, lower than the standard value of 10%. What follows is the A05 with the double-sided light guide plate installed in the south and east orientations. It has an ASE value of 7.7% lower than the standard value of 10%, which is within the range of sound performance.

Take the sDA300lux value of 55% as the standard, the double-window type A01 without sunshade can reach a daylighting depth of about 4m in the north orientation, 3.5m in the east and west orientations, and 3.2m in the south orientation. The A05 installed with double-sided light-guide device features the daylighting depth of about 2.4m in the east and north orientations, and about 3m in the south and west, indicating that the installation of double-sided light device tends to lower the amount of daylighting, especially for the north orientation. For the purpose of sound daylighting, the installation of light guide sunshade device is not recommended for the double window type unit.

Table 4: Dynamic lighting simulation results of all orientation of double window

Orientation		A1	A2	A3	A4	A5	A6	A7	A8
East	sDA(%)	32.8	31.6	26.3	27.9	19.0	19.0	19.4	19.0
	ASE(%)	17.8	16.2	13.4	13.4	7.7	7.7	7.7	7.7
West	sDA(%)	33.2	29.6	25.9	26.3	20.2	19.0	20.2	20.2
	ASE(%)	20.2	16.2	15.4	14.2	9.3	9.3	9.3	9.3
South	sDA(%)	28.7	28.7	22.7	27.5	19.8	19.0	20.2	19.8
	ASE(%)	18.6	15.0	14.2	12.1	7.7	7.7	7.7	7.7
North	sDA(%)	36.4	33.6	31.2	32.0	23.1	21.9	24.3	22.3
	ASE(%)	0	0	0	0	0	0	0	0

(2) Ribbon-window type
Compared with the B01 and B02 of each orientation, except the sunshade of the south-oriented window, the sDA value will be reduced by 2% to 6% when there is a sunshade device, and the north-oriented window without the sunshade device features the highest sDA value, which is 59%. But the standard value of 55% still fails to be reached, requiring the daylighting to be improved. The north-oriented window features the best ASE value, all below the standard value of 10%. What follows is the B02 with sunshade in the south, and its ASE value is 18.2%. The ASE values of the west-oriented windows are all relatively high. The installation of a sunshade device can reduce the ASE value of each orientation by 3.3% to 4.4%.

In comparing the B01 to B05 of each orientation, the sDA value of the B01 without sunshade device is higher than the other window type, and the north-oriented g non-shading sDA value is optimally 59%. In addition to the south, the light guide will reduce the natural light in the indoor space, while the south-oriented outer light guide B04 will increase the sDA value by 6.1%.The north-oriented window features the best ASE value. Regardless of the light guide device, the ASE value is always kept at 0%, lower than the standard value of 10%. What follows is the B05 with the double-sided light guide plate installed in the south and east orientations. The ASE value of 10.5 is close to the standard value of 10%, and it can be achieved with a slight improvement.

Take the sDA300lux value of 55% as the standard, the ribbon-window type B01 without sunshade can reach a daylighting depth of about 5.7m in the north orientation, 5m in the east and west orientations, and 4.5m in the south orientation. The B05 features the daylighting depth of about 5.5m in the north orientations, and about 4m in the south and west, indicating that the installation of double-sided light device tends to lower the amount of daylighting, especially for the north orientation.

Table 5: Dynamic lighting simulation results of all orientation of ribbon window

Orientation		B1	B2	B3	B4	B5	B6	B7	B8
East	sDA(%)	51.8	49.0	47.8	49.0	47.8	46.6	47.8	46.6
	ASE(%)	33.2	28.3	27.9	31.6	25.5	25.5	25.5	25.5
West	sDA(%)	51.4	49.4	49.0	51.4	47.8	46.6	48.2	47.8
	ASE(%)	36.4	32.0	30.4	32.4	27.1	27.1	27.1	27.1
South	sDA(%)	42.9	45.7	45.7	49.0	44.5	46.6	47.0	44.5
	ASE(%)	21.5	18.2	15.8	10.5	10.5	10.5	10.5	10.5
North	sDA(%)	59.0	53.0	53.4	53.8	51.0	50.2	53.0	51.0
	ASE(%)	0	0	0	0	0	0	0	0

4. Dynamic daylighting simulation of unit type office space: double-sided window opening

According to the above simulation results, if only one side within the single space can be used for daylighting, the sDA must be more than 55% and the ASE be less than 10% simultaneously. It is almost impossible to meet these two requirements at the same time, except for the north-oriented window opening, because when the window is opened on one side, the indoor illuminance gradient changes too much, leading the high illuminance to be concentrated in the near-window area. Therefore, the second stage of the daylighting simulation in this study is to test the double-sided window opening, to increase the indoor daylighting amount and improve the indoor uniformity of light and the indoor daylighting conditions.

Considering the design of building daylighting and energy consumption, in the simulation setting of double-sided window opening, the east-oriented and west-oriented window types are the double windows with small aperture opening ratio, and adopt double-sided light guiding device; south-oriented window type is the ribbon window, and the light guiding sunshade type is a double-sided lighting device; the north-oriented window type is a ribbon window, and no light guiding sunshade device is installed. The overall simulation results are shown in the table below.

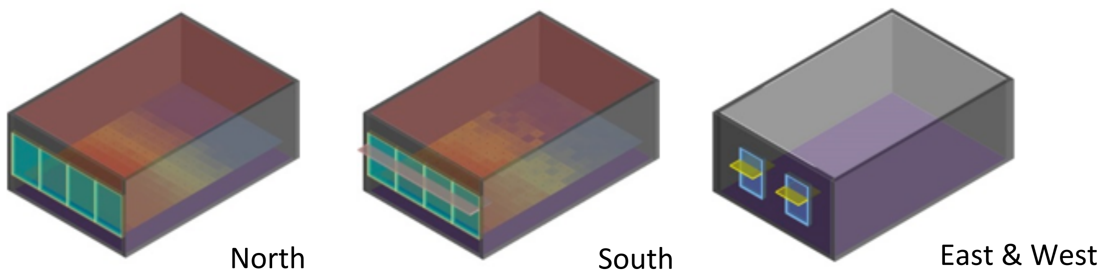


Figure 6: Opening settings of double-sided window simulation

Table 6: Dynamic lighting simulation results of double-sided window

Model scale : 9m(W)*6m(D)			
Window orientation	Window-to-wall ratio (WWR)	sDA(%)	ASE(%)
South & North	18	100	25
East & West	8	21	17
East & North	13	100	9
East & South	13	83	37
West & North	13	100	9
West & South	13	85	38
Model scale : 6m(W)*9m(D)			
Window orientation	Window-to-wall ratio (WWR)	sDA(%)	ASE(%)
South & North	13	100	10.5
East & West	16	92.7	68.8
East & North	15	84.6	19
East & South	15	69.2	31.2
West & North	15	88.7	22.3
West & South	15	72.5	32.8

In general, except for the "East & West"-oriented window opening unit with a width of 9m and a length of 6m, the sDA values of the unit-type double-sided window are mostly above the standard value of 55%, and most of them fall into the category of good daylighting. For the "East & West"-oriented window opening unit with the width of 9m and the length of 6m, the sDA value is only 21%, falling into the category of poor daylighting. The ASE values of the unit type double-sided window opening are mostly above the standard value of 10%, making it the daylighting space prone to glare. The "East & North" and "West & North"-oriented window opening with the width of 9m and length of 6m all feature the ASE values of 9%, below the standard value, making it the daylighting space not prone to glare.

The analysis of dynamic daylighting is conducted on the window opening orientation. Regardless of the combination of space dimensions, the sDA value and the ASE value of the "East & North" orientation are better than the other combinations, followed by the "South & North"-oriented window. The combination of "West & South", "East & South" and "East & West" shows higher ASE value than other combinations.

In terms of space size, a combination of 9m wide and 6m deep is recommended. This space combination shows a ribbon window type for the north-south-oriented window style, and the east-west-oriented window style features the double window type, and the sunshade lighting style is a north-oriented sunshade device, while the south and east-west orientations are installed with the double-sided sunshade light guiding plate.

Since the north-south-oriented double-sided window style can make the sDA value easily reach the standard value of 55%, and the ASE value is relatively lower than other space combinations; the east-west-oriented window style makes the sDA value lower, but can effectively reduce the ASE value, making the ASE value closed to or below the standard value of 10%.

Conclusion and Suggestion

1. The main influence factor of sDA

The window opening area has the greatest influence on the sDA value. What follows is the sunshade light guiding form, but the material reflectance relatively exerts no effect. In a double-window type space, the use of a sunshade light guide reduces the sDA value, but in a ribbon window type space, the sunshade light guide device can increase the sDA value. In addition, the reflectance of the ceiling increases the depth of natural light reflected into the room, while the reflectance of the wall material slightly increases the sDA.

2. The main influence factor of ASE

The sun light guiding device can effectively prevent the occurrence of glare, especially the use of the double-sided light guiding sunshade device can reduce the ASE to below 10%, which is the most important influence factor for ASE. The window opening area has only a slight effect on the ASE, but in a unit space with a small surface, the narrow opening of the window will instead increase the illumination at the window edge, triggering the rise of ASE.

3. Effect of sun light guiding device on space daylighting
The sunshade device is installed for the purpose of reducing the ASE value.The sunshade device needs to be installed in the south-oriented, west-oriented and east-oriented window opening, and there is no need to install the sunshade device in the north-oriented window.

In order to increase the sDA value and decrease the ASE value, a light guide device is required as an improvement method. Regarding the internal light guide plate, the outer light guide plate and the double-sided light guide plate, the external light guide plate can increase the sDA value the most, and the double-sided light guide plate has the best effect of lowering the ASE value. Clients can select the appropriate light guide device based on the demands.

4. Discussion on dynamic daylighting performance of window opening type and window opening orientation
When the window is opened on one side, the ribbon window type has better daylighting performance than the double window type. Especially if the façade of ribbon window type can be matched with the continuous horizontal outer sunshade, it can not only reduce the direct sunlight exposure of the window, but also increase the amount of natural light in the room.

When the window is opened on two sides, the daylighting design should be combined with the external sunshade light guide device to increase the sDA value and reduce the ASE value. The best window opening orientation is the "South & North" space combination, and the worst window opening orientation is "East &West".

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