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The influence of exterior obstruction on the integrated evaluation of daylight utilization during initial design stage

Jingting Sun[a,b,*],Zhengrong Li[a], and Fu Xiao[b]

[a]Tongji University, School of Mechanical Engineering, HVAC & Gas Institute, Shanghai 200092, China
[b]Hong Kong Polytechnic University, Department of building services engineering, Hong Kong SAR (Zip-code free), China

Abstract

This paper presents a concise parametric study to investigate the influence of external obstruction on the evaluation of daylight utilization during design stage. A generic building located in Hong Kong has been established with dimmable controlled lighting system and interior shade. Multiple simulations under different external obstruction patterns are conducted with simulation engine EnergyPlus. Metrics on daylight availability, together with energy performance of both lighting and air conditioning system are analyzed. The result indicates that the ground floor is the most vulnerable to the existence of exterior obstruction and building zones of different orientation are affected in different ways. Further analysis also shows the impact from obstruction is not necessarily negative for daylight utilization cases. An overall assessment of this impact requires an integrated evaluation including both lighting and air conditioning system. These all demonstrate the necessity of taking exterior obstruction into consideration during the design stage.

Keywords: Energy efficiency; Daylight availability; Cooling and heating load; Exterior obstruction; Sensitivity analysis

1. Introduction

After a long time being applied in built environment domain as an additional benefit for its positive effect on occupant's psychology, productivity and visual comfort [1-3], daylight has also become a source of energy efficiency

* Corresponding author. Tel.: 86-15000750967.
E-mail address: jingting.sun@connect.polyu.hk

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Nomenclature

WWR	Window to wall ratio
TMY	Typical Meteorological Year
θ_{obs}	The external obstruction angle
H_{obs}	The height of external obstruction, m
D_{obs}	The road width, m

recently by taking advantage of the exterior illumination as a supplement or replacement for indoor artificial electrical lighting. A reduction of 25% to 60% on lighting electricity consumption could be achieved via the application of daylight-linked lighting control system [4-6]. To further explore the potential of daylight utilization in energy efficiency, it is essential to evaluate the availability of daylight utilization technique at the initial design stage of building construction. As the utilization of daylight could also be at a risk of excessive solar heat gain, the evaluation should consider the twofold effect from both visual and thermal aspects of indoor environment.

As the information is limited during the preliminary design stage, simulation tool has been applied frequently as an indispensable assistance in decision-making. Conventionally, only the building or the building complex in the project would be considered in the simulation. Ignoring the existence of exterior obstruction simplified the simulation task. However, it is severely different from the reality. For urban environment characteristic of densely constructed districts, buildings could be heavily shaded by ambient obstructions. Moreover, during the long lifespan of building, the ambient environment of building is subject to change. With urban growth and new land use planning, the ambient environment of the building could shift from broad to being shaded by new constructions. These all raise the concerns about the long term performance of daylight-utilized techniques.

In such context, this study conducts a parametric analysis via simulating with variations on layout and tilt angles of the exterior obstruction. Simulation engine EnergyPlus is called for the capability on both thermal and daylight aspects. Compared with other simulation tools which are specifically developed for daylight-related performance simulation, such as Radiance and Daysim, EnergyPlus could seamlessly connect the thermal and daylight modeling of building performance while still maintaining an acceptable accuracy on daylight modeling.

This methodology contains three major steps: first, a generic building is established as geometry model. Next, different combinations of road width and obstruction angle are generated on behalf of different obstruction patterns. Finally multiple simulations are conducted and results are collected for analysis.

2. Method

One generic building of five floors with no external obstruction was established as the base case model to deploy parametric study. The dimension of building floor dimension was depicted with Figure 1. Following the conventional zoning strategy, each floor of the building was divided into one core zone and four perimeter zones corresponding with four main orientation: south, north, east and west. The interior wall between two adjacent perimeter zones was adiabatic and therefore four perimeter zones were on behalf of building zones with different orientations.

For each perimeter zone, window to wall ratio (WWR) was 0.4. Side windows were equipped with interior shade. The interior shade would be activated when the incident radiation was over 300W/m^2. One daylight reference point was placed within each perimeter zone at the spot as showed in Figure 2. The target illuminance value at daylight reference point was set as 500lux. Indoor electrical lighting provided continuously dimming response to the illuminance level at the daylight reference point. When the illuminance introduced by daylight exceeds 500lux at the daylight reference point, the electrical light would be completely off.

Typical meteorological year (TMY) of Hong Kong was used as the weather input file. For tropical cities like Hong Kong, space cooling is almost required along the whole year. Air conditioning mode in the simulation only considered cooling and the cooling set point of indoor air temperature was set as 25℃. The occupant hours followed the conventional mode of typical office building and was set from 8am to 6pm on weekdays. Space cooling would start 1h ahead the occupancy (7am) to avoid occupants' discomfort at arrivals. Other detailed information about building physical parameters and interior shade parameter were summarized in Table 1.

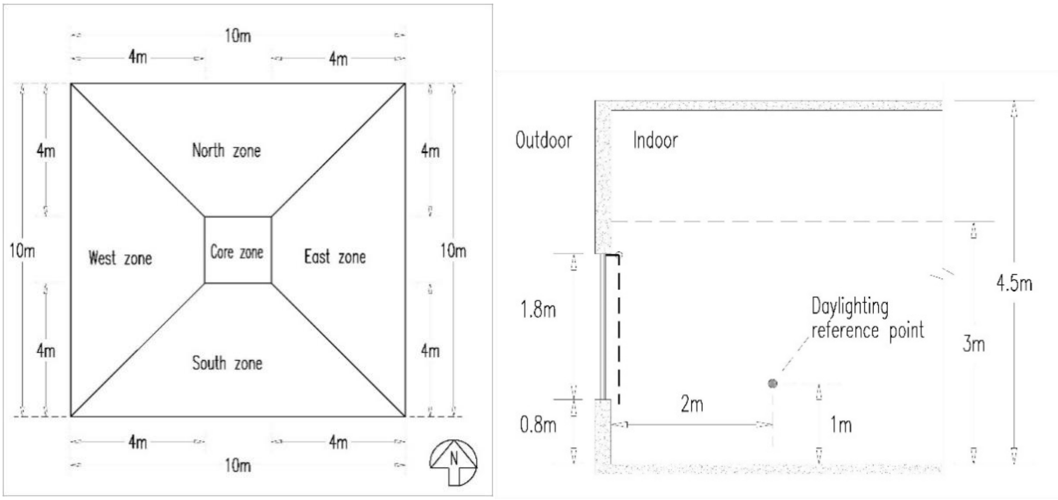

Fig.1. & 2. The layout of the floor and the position of daylighting reference point within perimeter zone

The external obstruction angle of the ground floor (1st floor) was applied to measure the shading effects of exterior obstruction. Defined as the angle between the horizontal line at the window sill level and the line connected with the highest point of the obstruction facing the building [7], the external obstruction angle (θ_{obs}) was set to vary from 0 degree to a maximum value of 87 degree with an increment of 10 degree [8]. For the case with θ_{obs}=0, the existence of obstruction was considered no effect on the building and the corresponding case was used as base case. The road width between obstruction and the building varies from 10m to 30m with an increment of 5m. The height of external obstruction (H_{obs}) was deduced from the chosen external obstruction angle (θ_{obs}) and the road width (D_{obs}) with the following equation:

$$H_{obs} = \tan(\theta_{obs}) \times D_{obs} \tag{1}$$

Table 1. Building physical and interior shade parameter

Building		Interior shade	
Parameter	Value[Unit]	Parameter	Value[Unit]
U-value (exterior wall)	2.0W/m^{2}k	Solar transmittance	0.05
		Visual transmittance	0.05
Solar heat gain coefficient (double low-e glazing)	0.2	Infrared hemispherical emissivity	0.9
Visual transmittance (double low-e glazing)	0.9	Visual reflectance	0.75
Lighting load	20 W/m^2	Solar reflectance	0.75
Occupant load	4 m^2/person	Thickness	0.01m
Equipment load	20 W/m^2	Conductivity	1 W/m·k

50 combinations of road width and obstruction was generated for each main orientation. Therefore 200 simulations were carried out. Some of obstruction layouts were shown in Figure 3.

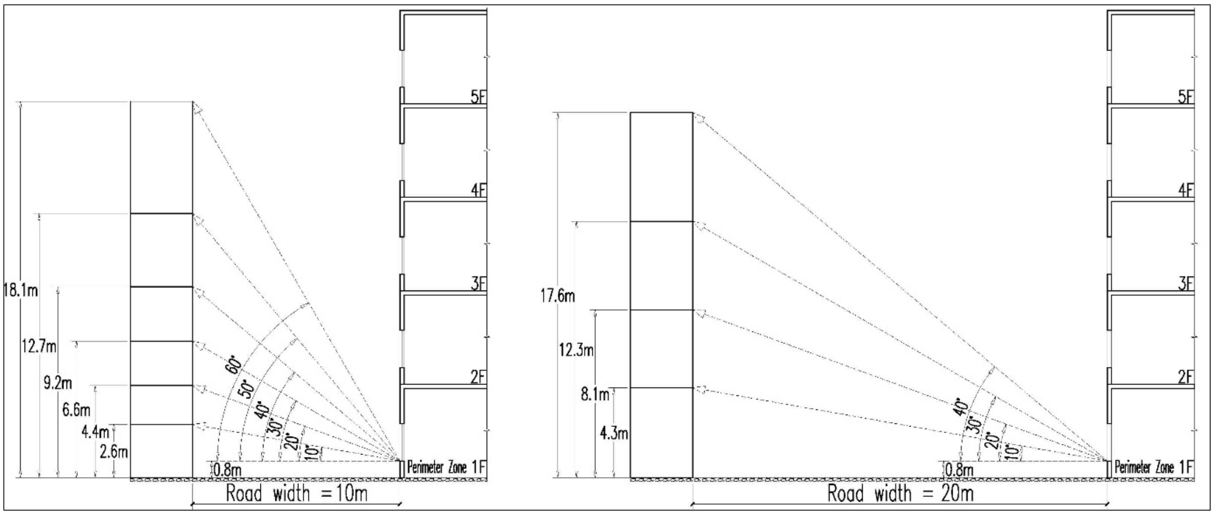

Fig.3. Some of obstruction layouts

3. Results

Data about the operation status of shading device, the daylight illuminance at reference point, energy performance of both lighting and air conditioning systems are extracted from simulations. The deviation from base case of each floor under various occasions are first analyzed. For all the metrics, the ground floor (1st floor) is the most vulnerable to the existence of exterior obstruction. This result also fits the common knowledge. Middle floors (2nd, 3rd, 4th floor) as well as the top floor (5th floor) follow a similar pattern when the existence of obstruction could cause an effect. Deviation of daylight exceeding hour value among all floors with obstruction from western orientation is listed in Table 2 as an example of daylight distribution along the height of the building. As the impact is the most significant for the ground floor, the following result demonstration and discussion mainly use the data of the ground floor for length reason. The effect of obstruction from different orientation is studied under the corresponding perimeter zone of the ground floor.

Table 2. Deviation of daylight exceeding hour value among all floors with obstruction from western orientation (compared with the base case)[%]

OB*	Road width=10m					Road width =20m					Road width =30m				
	1F	2F	3F	4F	5F	1F	2F	3F	4F	5F	1F	2F	3F	4F	5F
10°	1.0	—	—	—	—	0.9	—	—	—	—	0.8	—	—	—	—
20°	1.7	—	—	—	—	1.2	0.4	—	—	—	0.6	0.8	—	—	—
30°	2.4	0.5	—	—	—	2.1	1.1	0.3	—	—	0.9	1.1	0.3	0.2	—
40°	0.9	2.0	—	—	—	2.2	2.3	1.3	0.7	—	0.5	1.4	0.7	0.7	0.3
50°	3.6	4.0	1.0	—	—	4.2	2.9	1.5	1.6	0.7	1.9	1.2	0.6	—	0.9
60°	6.2	4.1	0.8	1.9	—	6.4	5.7	4.7	3.4	2.1	3.4	3.1	2.8	2.1	1.6
70°	8.3	7.6	6.5	4.8	1.8	8.1	7.8	7.4	7.1	6.6	4.7	4.6	4.4	4.2	4.1
80°	9.3	9.3	9.3	9.2	9.0	8.9	8.9	8.9	8.9	8.9	5.6	5.6	5.6	5.6	5.6
87°	9.3	9.3	9.3	9.3	9.3	8.9	8.9	8.9	8.9	8.9	5.6	5.6	5.6	5.6	5.6

Remarks: OB* is the abbreviation of obstruction angle.

Annual activated time faction of shading device of four main orientation under different road width and obstruction angles are compared and depicted with line chart in Figure 4. The results indicated that the shade within northern perimeter zone has been seldom activated under all obstruction patterns. Shades within the other three perimeter zones become less activated as the increasing of obstruction angle. This trend is more obvious under cases with smaller road width. When road width is 10m and obstruction angle is 87 degree, the activated time fraction of southern shade falls from 21% (the base case level) to 10%. For eastern and western perimeter zones, the fall is 15% to 5% and 19% to 6% respectively.

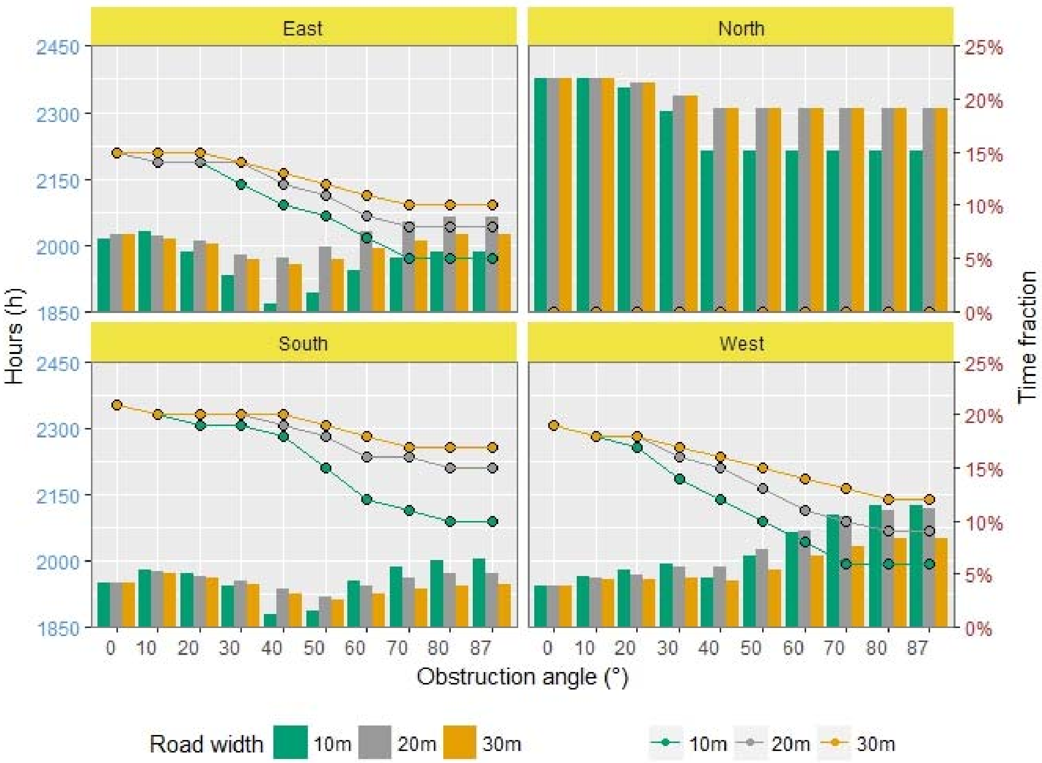

Fig. 4. Annual hours of Daylight Illuminance Exceeded 500 lux and activated time fraction of shade device (the ground floor)

Annual hours of daylight illuminance exceeding 500lux at the daylight reference point (mentioned as "exceeding hour value" in the rest part of this paper) is also illustrated as the bar plot in Figure 4. Higher value suggests a higher level of fully replacement of daylight on electrical lighting. For northern perimeter zone, the existence of obstruction decreased the exceeding hour value with a maximal fall of 7% and the exceeding hour value become stable after obstruction angle exceeding 40 degree. For eastern and southern perimeter zones, the exceeding hour value first decreases as obstruction angle increasing and then reaches their minimal level when obstruction angle reaches 40 degree. For western perimeter zone, exceeding hour value fluctuates slightly before obstruction angle reached 40 degree and then increases. It is interesting to find that exceeding hour value of western perimeter zone reaches its maximal level road width of 10m and obstruction angle of 87 degree, which is seemed as the most heavily shaded case.

Annual electricity consumptions of lighting system, air conditioning system and the integrated amount of these two systems could be found in Figure 5. The electricity power consumption of air-conditioning system is calculated with space cooling load by dividing an overall coefficient of 3. It is noted that, practically, the load of air conditioning system should also consider the fresh air rate. However, the load of fresh air rate could only be influenced by variables such as indoor occupancy, average air change rate, outdoor air temperature/humidity and the state point of fresh air. For the cases within this study, the fresh air load is constant and would not be influenced by obstruction patterns. Therefore, the load of fresh air rate is not considered under the space cooling issue.

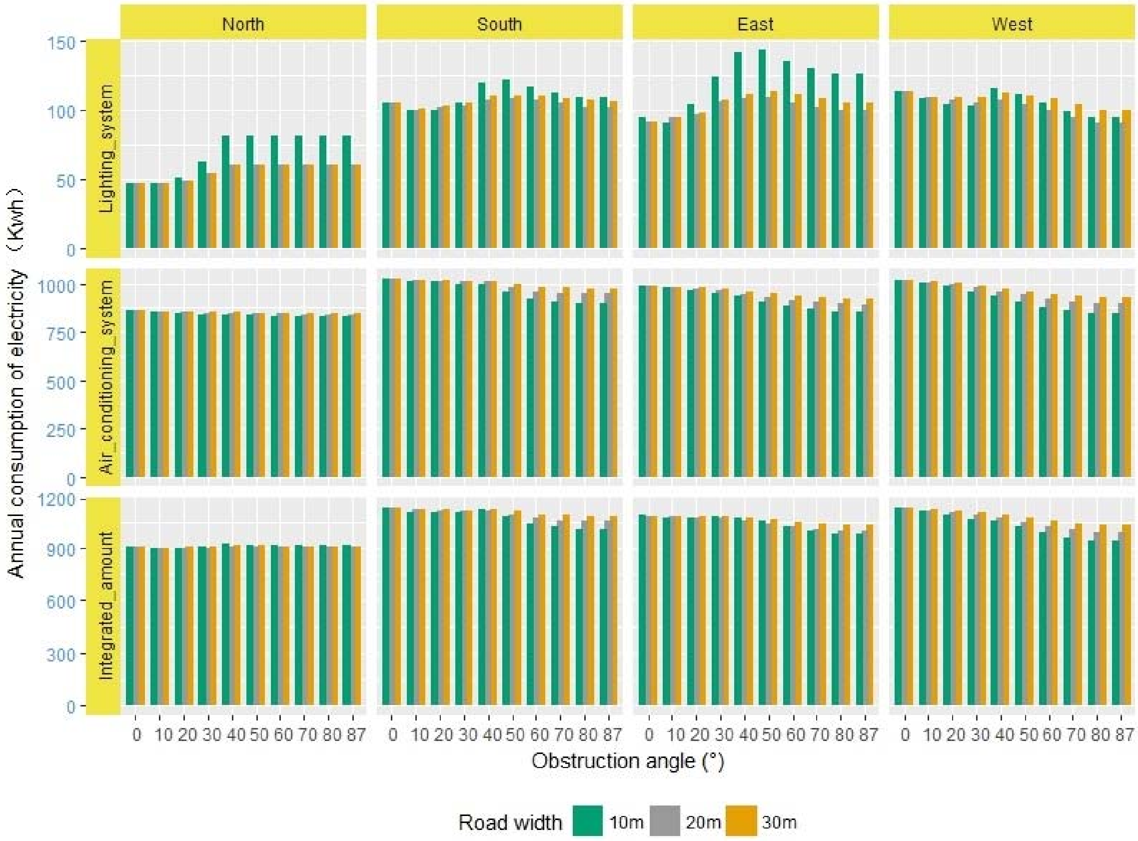

Fig. 5. Annual electricity consumption of lighting system, air conditioning system and the integrated amount of these two systems (the ground floor).

The first row of panels show the lighting electricity consumption within different cases. The existence of obstruction increases the lighting electricity of northern, southern and eastern perimeter zones. However, the western perimeter zone's lighting consumption is decreased. And all zones reach their maximal lighting consumption when obstruction angle is around 40 degree to 50 degree. Moreover, larger road width does not guarantee a less electricity consumption. A road width of 20m owns the lowest consumption value among all the three road width.

The second row of panels indicates the influence of obstruction pattern on electricity consumption of air conditioning system (AC). The AC consumption is obviously smaller than that of the other three perimeter zones and shows minor fluctuation under different obstruction patterns. For the other three perimeter zones, the space cooling load decreases with the increasing of obstruction angle. And the change is more significant under smaller road width. With a road width of 10m, the increase of obstruction angle from 0 degree to 87 degree lead to an 18% decrease in AC electricity consumption of western perimeter zone. The number is 14% in eastern perimeter zone, and 12% in southern perimeter zone.

The integrated electricity consumption of lighting and air-conditioning systems, which are the top two energy user within building energy systems, is also evaluated and drawn in the third row of panels. The integrated consumption of northern perimeter zone shows insignificant variations in the northern perimeter zone. For the other three perimeter zones, the integrated electricity consumptions decreases with the increasing of obstruction angle. This trend is the most obvious in western perimeter zone. Eastern and southern perimeter zones follow the similar trend and even coincide in certain range. For southern perimeter zone, the fluctuation is larger than 10%.

4. Discussion

From the result, we can find that the effect of exterior obstruction are different in four orientations for the site location of Hong Kong.

As the northern perimeter zone receives little beam sunlight, the achievement of daylight utilization largely depends on diffuse illuminance. Meanwhile, incident solar radiation on the northern facade rarely exceeds the control threshold of the interior shading. Under the current control strategy, the shade of northern shade has been seldom activated, even for the case with no obstruction. Compared with other orientations under all circumstances, northern perimeter zone possesses a higher level of fully replacement for electrical lighting by daylight illuminance and a lower electricity consumption for lighting. As the obstruction angle increasing, the electricity consumption of lighting increases slowly while still at a low level and becomes stable after the obstruction angle reached 40 degree. The power consumption of air conditioning system is also slightly fluctuated as the obstruction patterns varied. From the integrated aspect of electrical consumption, the impact of exterior obstruction from northern orientation is marginal and could be ignored.

Opposite to northern perimeter zone, southern perimeter zone gets more exposure to direct sunlight. With current control strategy, the activation of southern interior shade is quite frequently and harms the admission of daylight. As a result, exceeding hour value of southern perimeter zone is the minimal among all orientations. This indicates that southern perimeter zone maintains a lower replacement level for electrical lighting. Although the direct sunlight would be inevitably shade by exterior obstruction, the interior shade would still be activated quite often until obstruction angle is above 40 degree. As the obstruction angle increasing, the electricity consumption of air conditioning system decreased. Integrated power consumption also follows the same trend.

Eastern perimeter zone also gets much exposure to direct sunlight. As the extent is less than southern perimeter zone, the shading is less activated. Eastern perimeter zone mainly receives direct sunlight in the morning. At that timing, beam illuminance is strong and solar radiation is not much. This indicates the daylight utilization could be quite efficient during the early hours of day time. When the obstruction angle is small, eastern perimeter zone could achieve a high level of replacement for electrical lighting. As the obstruction angle continues to increased, the illuminance level is harmed and the requirement for electrical lighting is increased. Annual electricity power consumption of lighting reaches its maximum as 143.8KWh when the obstruction angle is 50 degree. This consumption is more than 50% compared with the base case. After that peak, the increase of obstruction angle leads to less activation of interior shade and decreases the lighting requirement.

Western perimeter zone receives the direct sunlight mostly during afternoon. At that time spot, the sun altitude is small and solar radiation is strong. With the increasing of obstruction angle, solar radiation could be shade significantly. Benefit from the shading effect of exterior obstruction, solar radiation has been decreased and the interior shade is less activated. Daylight utilization is more efficient and the electricity power consumption of lighting system is decreased. Due to the above features of western orientation, the reduction of electricity consumption by air conditioning system is more obvious than other orientations. With a road width of 10m, the minimal case achieves a decrease of 18% comparing with the base case. Therefore, as the obstruction angle increasing, the lighting and air conditioning systems' electrical consumption are decreased simultaneously.

5. Conclusions

In this study, different combination of obstruction angle, road width between the building and obstruction height has been added to a generic building floor model to deploy a parametric analysis. The impact of external obstruction on the daylight availability, together with other concerned issues are explored. Several preliminary conclusions could be drawn as follows:

Firstly, obstruction from different orientation affect building in different ways. For north, the effect of exterior obstruction is marginal and could be ignored. However, for the other orientations, the effect is non-linear which indicates the necessity of detailed tradeoff with caution. Secondly, the evaluation of daylight related utilization should consider the overall effect of air conditioning and lighting system. For some cases, the existence of obstruction could cause a significant increase of lighting electricity and a decrease of air-conditioning system consumption at the same time. The overall energy consumption of these cases are only fairly fluctuated around the base case. If the evaluation only considers one aspect, conflicting conclusions could be resulted. Thirdly, the impact of exterior obstruction is not necessarily negative. Overall benefit of electricity consumption of building zones, except northern perimeter zone, could be found under large obstruction angle. Considering the shading device used in this study is interior shade. The activated status of interior shade would not affect much on the space cooling load. The benefit could be further by using exterior shading devices.

In conclusion, the impact of surrounding obstructions under various cases suggest it inappropriate to only consider the building in solo during the design stage. As the well performance of energy efficiency techniques usually depends on a sophisticated interaction between different elements, ignoring the existence of exterior obstructions could cause discrepancy between design and reality which could brought uncertainty. Therefore, it is important to take account the impact of exterior obstructions on the overall evaluation of daylight availability during the design stage.

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