A dynamic analysis of Photosynthetically Active Radiation (PAR) availability to achieve a biophilic office building in three highly dense Chinese cities

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Abstract

The application of plants has been established as one of the most important biophilic solutions in an office building. Access to Photosynthetically Active Radiation (PAR) is critical for sustaining plant growth in an indoor space. Using advanced ray-tracing simulation and various weather data, this study presents a dynamic analysis of PAR availability and distributions in a Chinese open-plan office building, taking into consideration positions, orientations, obstructions, and locations. The results could be developed into design guidelines for the establishment of a biophilic office building with a high potential to bring indoors a 'green nature' for building occupants.

Highlights

- A biophilic office achieved using indoor plants
- A novel PAR metric applied for indoor planting
- PAR availability simulated using raytracing package
- Effects of environmental factors on PAR availability

Introduction

Biophilic offices (Aristizabal et al., 2021), are an emerging design concept in the workplace, and are increasingly being applied to improve office workers' connectivity to the natural environment through direct nature, indirect nature, space and place conditions, and climate. As suggested in a biophilic design guidance (Browning et al., 2014), the application of plants has been established as an important and easily achieveable biophilic solutions in buildings. In a longitudinal study of biophilic open-plan offices (Gray & Birrell, 2014), indoor plants had enhanced occupants' performance and satisfaction.

The benefit of indoor plants in office buildings has been well recognized over decades, including removing pollutants/CO_2 and improving air quality (Gubb et al., 2019), increasing relative humidity through transpiration (Deng & Deng, 2018; Gubb et al., 2019), reducing building energy consumption (Gubb et al., 2019), and promoting psychological wellbeing (Bringslimark et al., 2009). Twenty-eight ornamental green plants commonly used in indoor spaces were tested for their ability to remove five volatile indoor pollutants (Yang et al., 2009). The variation in removal efficiency among these plants indicated that multiple species were needed to achieve the maximum improvement of indoor air quality (Yang et al., 2009). However, Cummings and Waring (2019) did not support that indoor plants improve indoor air quality according to airborne volatile organic compounds removal. A quasi-experiment study in several offices (Fjeld, 2000), suggested that indoor foliage plants can reduce office workers' discomfort caused by mucous membrane symptoms, such as dry and hoarse throat. Thus, it seems that this outcome was achieved due to the increased air humidity through indoor planting. The effect of indoor plants on office workers' psychological performances has been broadly investigated (Fjeld, 2000; Bringslimark et al., 2007; Bringslimark et al., 2009). It has been preliminarily identified that indoor plants can provide psychological benefits such as stress-reduction and increased pain tolerance.

Studies of daylighting application in office buildings generally target three aspects - occupants, plants, and energy (SLL, 2015). The wall, floor, and tables in an office can be used as possible positions to place plants of various types and sizes (Gray & Birrell, 2014). To maintain plant growth within the indoor workplace is one of key objectives for sufficient daylight level needs in office buildings (SLL, 2015). Plants require plentiful amounts of natural light to support fundamental photosynthesis processes, and maintain normal growth (Langhans & Tibbitts, 1997). It is recommended that typical needs of common plants lie in the range of 700 to ~2000 lx for twelve hours a day and that top lighting is more desirable as a direction-giver (Littlefair & Aizlewood, 1998). Therefore, daylighting in an office building has been regarded as one of the most difficult environmental factors to predict and control on the basis of plant maintenance for the interior (Littlefair & Aizlewood, 1998). In many office buildings, supplementary electric lighting will have to be used to sustain the planting (Langhans & Tibbitts, 1997; Littlefair & Aizlewood, 1998). However, the use of electric lighting would not just increase energy consumption, but also bring in undesirable negative effects on a biophilic space, where man-made environmental factors and relevant control measures should be minimized or even avoided (Browning et al., 2014).

For the planting in a controllable facility (e.g. chamber, greenhouse), the light levels required by plants can be measured by illuminance (unit: lux) or Photosynthetically Active Radiation (PAR, unit: W/m^2 or $\mu mol/m^2/s$) (Van Patten, 1995; Langhans & Tibbitts, 1997). The concept of illuminance was developed based on the human visual system (Baker et al., 1993), and it was also applied by horticultural scientists to indirectly indicate how much light is required by the plants (Baker et al., 1993). Photosynthetically Active Radiation (PAR), the spectral range (wavelength) of solar radiation (400 to 700 nm) that photosynthetic organisms use in the process of photosynthesis, is a direct metric of energy critically required for sustaining plant and vegetable growth (Langhans & Tibbitts, 1997). PAR varies seasonally and changes based on time of day and site latitude (Langhans & Tibbitts, 1997). Investigating the availability of PAR is necessary when planning an indoor planting scheme and the relevant facilities for growing the plants (Du & Sharples, 2020).

Using advanced ray-tracing simulation and various weather data, this study presents a dynamic analysis of PAR availability and distributions in a Chinese open-plan office building, taking into consideration positions, orientations, obstructions, and locations. The results could be developed into design guidelines for the establishment of a biophilic office building with a high potential to bring indoor a 'green nature' for building occupants.

Methods

Locations and climates

Three Chinese locations with different climates were selected in this study (MHUD, 2013) - Beijing (39.9° N, 116.4° E), Shanghai (31.23° N, 121.47° E), and Guangzhou (23.13° N, 113.27° E). Beijing (BJ) has a continental climate with a cold winter and a hot and humidity summer. Both Shanghai (SH) and Guangzhou (GZ) have a humid subtropical climate with a hot, muggy and rainy summer. Guangzhou can see a very mild winter, while a relatively cold winter is found in Shanghai. Total annual sunshine hours of Beijing, Shanghai, and Guangzhou are 2478, 1978, and 1773, respectively. Beijing has 25% and 40% more sun shining hours than Shanghai and Guangzhou respectively, indicating a much higher level of solar/daylight availability.

Open-plan office model

For each location, one typical office building (MHUD, 2006) with the same open-plan office room at each floor was digitally modelled (perspective view in Figure 1).

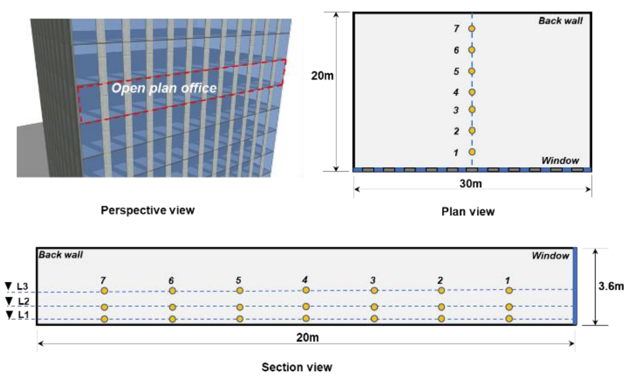

Figure 1: Open-plan office room studied (perspective, plan, and section views).

The analysis was conducted in one room located at the middle floor of the building (no reflected light received from the ground). The room has a dimension of 30×20×3.6m and only one side has a double-glazed window wall. The reflectances of ceiling, wall, and floor were 0.8, 0.6, and 0.3, respectively, whilst solar and visual transmittances of the window (clear glazing) were 0.42 and 0.67, respectively. In the plan view in Figure 1, seven points (No. 1-7) were defined for the evaluation of PAR availability, which were evenly distributed across the room centre from window to back wall. Thus, the distance between two adjacent positions was 2.5 m. In addition, as shown in the section view, three levels (L1, L2, L3) were adopted as the vertical positions for the seven points - L1 (0.1 m above floor, near floor), L2 (0.8 m above floor, table surface), L3 (1.6 m above floor, high shelf), representing possible positions to place plants in an office.

Four orientations were studied in terms of the normal direction of glazed wall, including south (S), east (E), north (N), west (W). In addition, four types of external obstruction were included in the analysis to simulate the effect of various surroundings in highly dense cities, such as no obstruction (OA0: obstruction angle = 0°), light obstruction (OA25: obstruction angle = 25°), medium obstruction (OA45: obstruction angle = 45°), heavy obstruction (OA65: obstruction angle = 65°). The surface reflectance of these obstructions was set as 0.4.

PAR & lighting metrics of indoor plants

Generally, PAR is quantified in terms of Photosynthetic Photon Flux Density (PPFD, $\mu mol/m^2/s$) (Langhans & Tibbitts, 1997). Table 1 gives the light and PAR requirements of indoor plants, while typical indoor plants applied in an office are listed in Table 2.

Table 1: Light and PAR requirements of indoor plants.

	foot-candles [a]	lux [b]	PPFD ($umol/m^2/s$) [c]
Low-light plants	50--250	538--2690	10.2--51.11
Medium-light plants	250--1000	2690--10760	51.11—204.44
High-light plants	≥1000	≥10760	≥204.44

a: The lighting requirements for indoor plants were achieved from the reference (Trinklein, 2016). b: Conversion from footcandle to lux: 1 footcandle = 10.76 lux. c: Conversion from lux to PPFD with the sunlight: 1 lux = 0.019 PPFD (Langhans and Tibbitts, 1997).

Table 2: Typical indoor plants which can be applied in an office building (Weisenhorn and Hoidal, 2020).

Type	Name
Low-light plants	Chinese evergreen (Aglaonema), Cast iron plant (Aspidistra), Dumb cane (Dieffenbachia), Dracaena, English ivy (Hedera helix), Homalomena, Pothos (Epipremnum), Philodendron
Medium-light plants	Amaryllis (Hippeastrum), Elephant ear (Alocasia), Norfolk Island pine (Araucaria), Asparagus fern (Asparagus), Ferns, Rubber plant (Ficus elastica), Fiddleleaf fig and weeping fig (Ficus)
High-light plants	Cacti and succulents, Hibiscus, Culinary herbs, Ti plant (Cordyline), Gardenia (Gardenia), Jasmine (Jasminum), Orchids, Caladium

As given in Tables 1 and 2, three PPFD ranges for sustaining the growth of indoor plants were recommended: (i) low level (10.2-51.11 μmol/m^2/s); for example, Aglaonema, Dieffenbachia; (ii) medium level (51.11-204.44 μmol/m^2/s); for example, Ferns, Rubber plant; (iii) high level (≥204.44 μmol/m^2/s); for example, Jasmine, Orchids. A very low PPFD (<10.2 μmol/m^2/s) might not be able to sustain the healthy growth of indoor plants. Thus, a PAR metric in this study was applied based on these three PPFD ranges.

Numeric simulation

The PAR calculations in the office model were achieved using the following steps: 1) The daylight illuminance (lux) at specific positions was simulated using the lighting software DAYSIM/RADIANCE (Radiance, 2022) and the weather data of the three locations; 2) The illuminance (visual part of solar irradiance spectrum) was converted to PPFD (μmol/m^2/s) using the algorithm: PPFD = 0.019 × Illuminance (Langhans and Tibbitts, 1997). The daily analysis of PPFD was only considered within a daytime period of 7:00 - 18:00 (Littlefair & Aizlewood, 1998). The ambient settings for the RADIANCE simulations were: Ambient Divisions 1500; Ambient Bounce 7; Ambient Super-Samples 100; Ambient Resolution 300 and Ambient Accuracy 0.1.

In this study, the PAR availability was assessed using the annual percentage of time each office position was in the three PPFD ranges mentioned above. For the three cities, seven positions at three vertical levels (as shown in Figure 1) were studied.

Results

PAR availability at three vertical levels

Figures 2, 3 and 4 indicate the annual percentages of time of the three PPFD ranges for indoor plants at heights L1, L2, and L3 and three locations (for the south facing office with no obstruction).

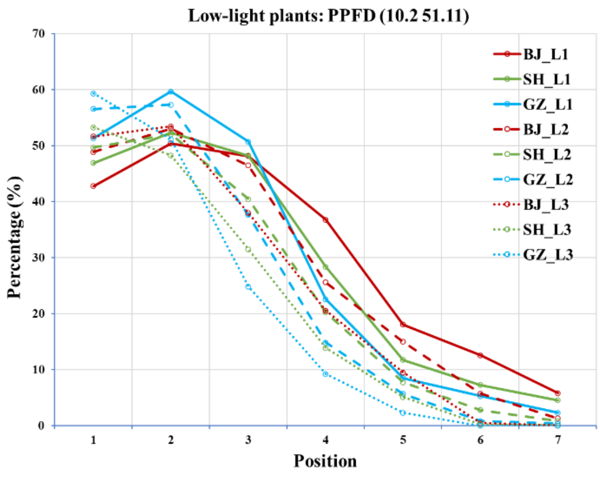

Figure 2: Annual percentage of time of PPFD (low-light plants) at three vertical levels and three locations (south facing and no obstruction).

In Figure 2, for the low-light plants (PPFD:10.2-51.11 μmol/m^2/s), PPFD percentages tend to decrease with distance from the window to the back wall. At each location, higher PPFD percentages can be found at the lower vertical level in the middle and back room areas (No.3-7) (L1 > L2 > L3), while the front room (No.1-2) shows the opposite trend (L3 > L2 > L1). Interestingly, for each vertical level, the location with a higher latitude has a higher PPFD percentage in the middle and back room areas (No.4-7) (BJ > SH > GZ), while the opposite trend is found in the front and middle room areas (No.1-3) (GZ > SH > BJ).

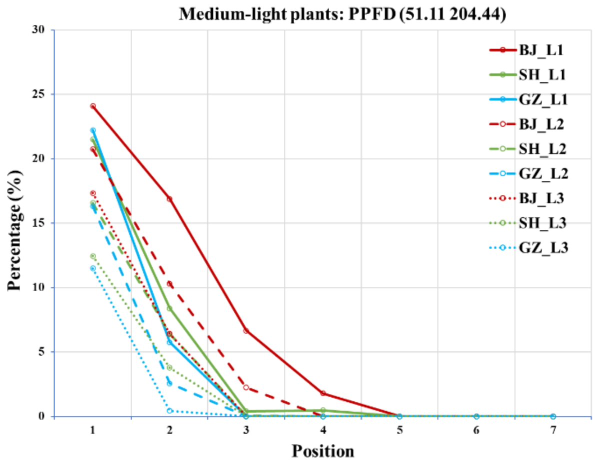

Figure 3: Annual percentage of time of PPFD (medium-light plants) at three vertical levels and three locations (south facing and no obstruction).

For the medium-light plants (PPFD: 51.11-204.44 μmol/m^2/s) in Figure 3, PPFD percentages drastically drop with distance from the window to the middle of the room (No.1-4) while there are no PPFD percentages found at the rear of the room (No.5-7). Similarly, PPFD percentages at L1 are higher than those of L2 & L3, especially in the area near the window (No.1-2). At the same positions, Beijing can see relatively higher PPFD percentages than Shanghai and Guangzhou.

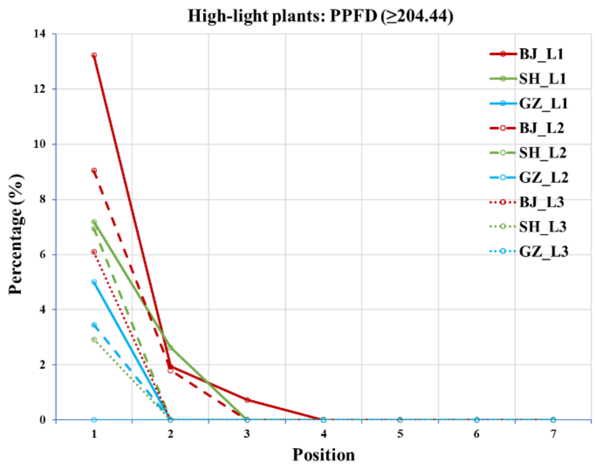

Figure 4: Annual percentage of time of PPFD (high-light plants) at three vertical levels and three locations (south facing and no obstruction).

As shown in Figure 4, the PPFD percentage varying trend of high-light plants (PPFD: ≥204.44 μmol/m^2/s) is similar to that of medium-light plants. In Beijing, only the position near the window (No.1) can get small PPFD percentages (6% ~ 14%), while other room positions have no values. Similar trends can be found at Shanghai and Guangzhou. However, all PPFD percentages at the two locations are lower than 8%, indicating that no big PAR availability is received in the PPFD range (≥204.44 μmol/m^2/s).

Table 3 shows the average PPFD percentages of the seven positions at three vertical levels and three locations. In general, L1 achieves lower average PPFD (<10.2) percentages at each location than L2 and L3, which means more annual working days to sustaining the growth of plants at the office floor. In addition, for each of the three PPFD ranges suitable for planting, Beijing can see relatively higher values than other two locations.

Table 3: Average PPFD percentages at three vertical levels and three locations (south facing, no obstruction).

Location	PPFD range (umol/m^2/s^2)	Average percentages of PPFD (%)		
		L1	L2	L3
BJ	<10.2	60.0	65.7	70.9
	[10.2 - 51.11)	30.7	28.0	24.8
	[51.11 - 204.44)	7.1	4.8	3.4
	≥204.44	2.3	1.5	0.9
SH	<10.2	65.7	70.9	75.5
	[10.2 - 51.11)	28.5	24.8	21.8
	[51.11 - 204.44)	4.4	3.3	2.3
	≥204.44	1.4	1.0	0.4
GZ	<10.2	66.6	72.1	77.3
	[10.2 - 51.11)	28.6	24.7	21.0
	[51.11 - 204.44)	4.0	2.7	1.7
	≥204.44	0.7	0.5	0.0

Effect of orientation on PAR availability

Figures 5, 6 and 7 give percentages of three PPFD ranges with four orientations at Beijing, Shanghai, Guangzhou, respectively (L1, no obstruction). As displayed in Figure 5, in Beijing, the range of PPFD (10.2 - 51.11) can generally achieve much higher percentages with each orientation than the range of PPFD.

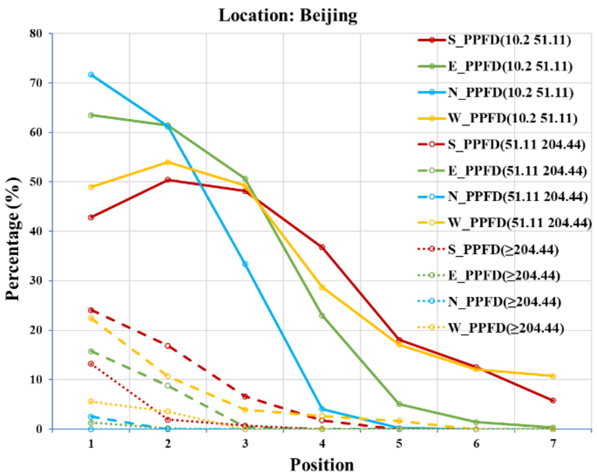

Figure 5: Percentages of PPFD with four orientations in Beijing (L1, no obstruction).

(51.11 - 204.44) and the range of PPFD (≥204.44), especially at the front and middle room locations (No.1-5). The range of PPFD (51.11 - 204.44) can only see its percentage >8% at the front of the room (No.1-2) with south, east and west facing windows, while only the south-facing brings a relatively higher percentage (>10%) of PPFD (≥204.44) to the first position (No.1). For the PPFD range (10.2 - 51.11), south and west can deliver higher percentages than east and west in middle and back areas (No.4-7), while the opposite trend can be found in front room (No.1-2). Both south and west can achieve higher percentages than east and north for the PPFD (51.11 - 204.44) and PPFD (≥204.44).

In Shanghai (Figure 6), similar varying trends for the three PPFD ranges can be found at four different orientations. Facing north and east can lead to higher percentages of PPFD (10.2 - 51.11) than facing south and west in front room (No.1-2), while this trend is oppositely changed in middle and back locations (NO.4-7). Only the front positions (No.1-2) can see the percentages of PPFD (51.11 - 204.44) and PPFD (≥204.44). Both south and west positions can deliver higher percentages of the two PPFD ranges than north and east. Compared with Beijing, the PPFD percentage differences between four orientations tend to be smaller in Shanghai.

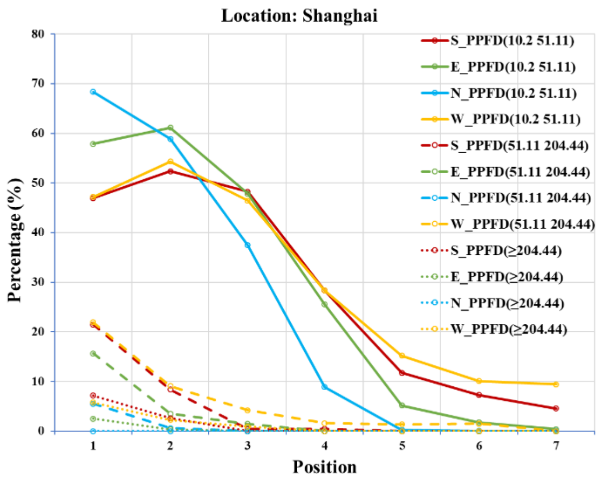

Figure 6: Percentages of PPFD with four orientations in Shanghai (L1, no obstruction).

Figure 7 shows how Guangzhou can achieve very similar percentage variations of the three PPFD ranges as Beijing and Shanghai. The front and middle positions (No.1-5) see higher percentages of PPFD (10.2 51.11) than other PPFD ranges. Compared with south and west, north and east can bring in higher percentages of PPFD (10.2 51.11) at the front positions (No.1-2), but lower percentages of PPFD (10.2 51.11) at the middle and back positions (No.4-7). In addition, Guangzhou sees relatively smaller PPFD percentage differences between four orientations than Shanghai and Beijing.

Table 4 presents the average PPFD percentages of seven positions at L1 and three locations, considering four orientations. In Beijing, facing south and west can receive lower average PPFD (<10.2) percentages than facing east and north, indicating that there are more annual working days to sustain the growth of plants with the former. For Shanghai and Guangzhou, facing west can result in the lowest average PPFD (<10.2) percentages, while the highest values can be found at north. When facing south, Beijing has the lowest average PPFD (<10.2) percentages than Shanghai and Guangzhou. However, facing east and west cannot see big differences of PPFD (<10.2) percentage between the three locations. Facing north, Beijing sees the highest average PPFD (<10.2) percentages.

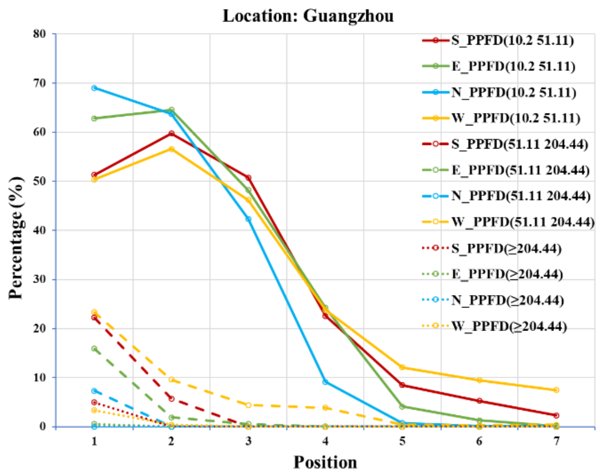

Figure 7: Percentages of PPFD with four orientations in Guangzhou (L1, no obstruction).

Table 4: Average PPFD percentages with four orientations at three locations (L1, no obstruction).

Location	PPFD range (umol/m^2/s^2)	Average percentages of PPFD (%)			
		S	E	N	W
BJ	<10.2	60.0	66.8	75.3	61.2
	[10.2 51.11)	30.7	29.4	24.4	31.6
	[51.11 204.44)	7.1	3.6	0.4	5.9
	≥204.44	2.3	0.2	0.0	1.3
SH	<10.2	65.7	68.1	74.3	62.9
	[10.2 51.11)	28.5	28.5	24.9	30.2
	[51.11 204.44)	4.4	2.9	0.9	5.7
	≥204.44	1.4	0.4	0.0	1.3
GZ	<10.2	66.6	67.9	72.5	63.9
	[10.2 51.11)	28.6	29.3	26.5	29.4
	[51.11 204.44)	4.0	2.6	1.1	6.1
	≥204.44	0.7	0.1	0.0	0.5

Effect of obstruction on PAR availability

Figures 8, 9 and 10 indicate the percentages of the three PPFD ranges with four obstruction angles (0°, 25°, 45°, 65°) in Beijing, Shanghai, Guangzhou, respectively (L1, south facing).

In Beijing (Figure 8), it can be clearly seen that PPFD (10.2 - 51.11) percentages are higher than the other two PPFD ranges with each obstruction angle, especially in front and middle positions (No.1-5). For PPFD (10.2 - 51.11), increasing the obstruction angle will increase the percentages at the position near window (No.1), while from the second position (No.2) to the back wall this trend has been reversed, i.e., a higher obstruction angle leads to a lower percentage. These percentages drastically drop towards the back of the room. For PPFD (51.11 - 204.44) and PPFD (≥204.44), the percentages can only occur in the front positions (No.1-3) and reducing obstruction angle will increase these values in these locations.

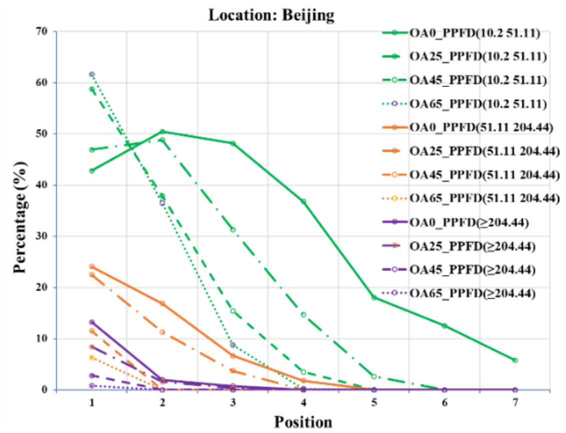

Figure 8: Percentages of PPFD with four obstruction angles in Beijing (L1, south facing).

In Figure 9 (Shanghai), similar variations of the three PPFD ranges can be found with each obstruction angle. Except for the PPFD (10.2 - 51.11) percentage at the position of No.1, higher obstruction angles will bring in lower percentages of the three PPFD ranges while these values tend to decrease towards the back of the room. However, at the position near the window (No.1), increasing the obstruction angle will give rise to a higher PPFD (10.2 - 51.11) percentage. For PPFD (51.11 - 204.44) and PPFD (≥204.44), the middle and back positions (No.3-7) cannot receive any percentages. Compared with Beijing, Shanghai sees a reduction of PPFD percentage difference between various obstruction angles.

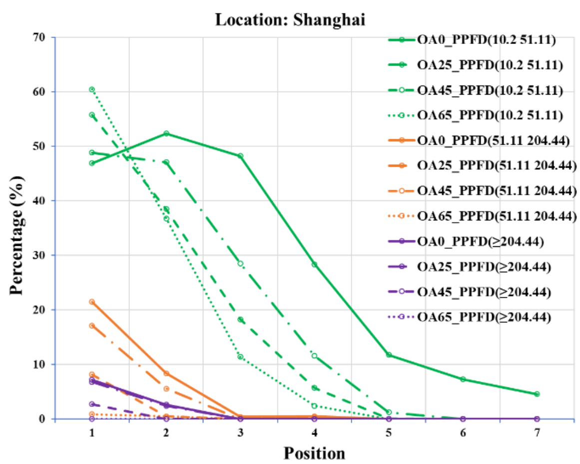

Figure 9: Percentages of PPFD with four obstruction angles in Shanghai (L1, south facing).

Like Beijing and Shanghai, Guangzhou (Figure 10) has the varying trends of three PPFD ranges as: for PPFD (10.2 - 51.11) and at most positions, reducing the obstruction angle can significantly increase the percentages; for PPFD (51.11 - 204.44) and PPFD (≥204.44), the same trend can be found just in the front area (No.1-3). Compared with Beijing and Shanghai, Guangzhou has a smaller difference of PPFD percentages between various obstruction angles.

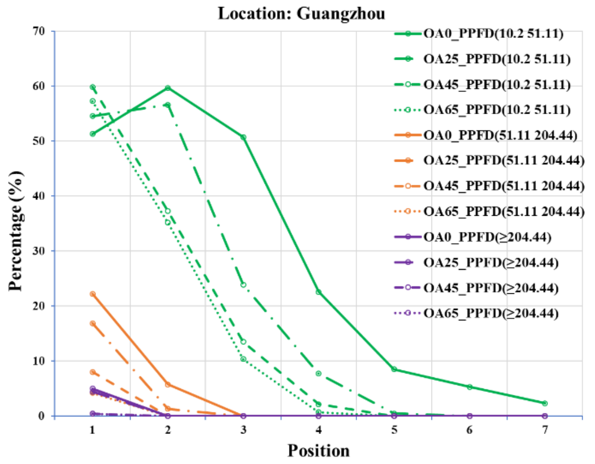

Figure 10: Percentages of PPFD with four obstruction angles in Guangzhou (L1, south facing).

Table 5 shows the average PPFD percentages of seven positions at L1 and three locations, considering four obstruction angles. In general, a higher obstruction angle will deliver a higher average percentage of PPFD (<10.2) at all locations, suggesting that increasing the obstruction angle can reduce the annual working days to sustain a healthy growth of plants in this office. The lowest average PPFD (<10.2) percentage of the three cities is found in the model without an obstruction (OA0) at Beijing. A clear difference for the PPFD (<10.2) percentages between Beijing and Shanghai or Guangzhou can only be found with lower obstructions (OA0 & OA25). For all obstruction angles, Shanghai and Guangzhou achieve similar percentages of PPFD (<10.2), which means similar PAR availability for planting.

Discussions

Given the results above, the effects of position (horizontal and vertical), orientation, external obstruction, and location on the PAR availability in this open-plan office are now discussed.

First, as shown in Figure 11, hemispherical images were produced in the area near window (No.1), the room centre (No.4), and the area near the back wall (No.7). Also, the three positions were assessed at three vertical levels (L1, L2, L3). Horizontally, for each vertical level, the sky components in these images apparently decreases from window to back wall while the components of the back wall increase. Thus, it is clear that the front area can receive the highest solar/daylight/PAR availability, whilst the lowest availability can be found in the area near the back wall. For the positions near the window (No.1), the higher distance above the floor can lead to a higher sky component. This may explain why, at the front of the room, the highest and the lowest solar/daylight/PAR availabilities were found at L3 (1.6 m above floor) and L1 (0.1 m above floor), respectively. At the positions in the room centre (No.4), the ceiling is the dominant component while the components of sky and back wall tend to be insignificant. The positions near the floor (L1) can receive more reflected light from the ceiling than the other two levels (L2 and L3), indicating that L1 has a higher solar/daylight/PAR availability than L2 and L3. For the positions near the back wall (No.7), the internally reflected component of the back wall tends to increase. As only a little light can be received at the back wall, a higher internally reflected component of the back wall would

Table 5: Average PPFD percentages with four obstruction angles at three locations (L1, south facing).

Location	PPFD range umol/m²/s²	Average percentages of PPFD (%)			
		OA0	OA25	OA45	OA65
BJ	<10.2	60.0	72.5	81.4	83.7
	10.2 -51.11	30.7	20.6	16.5	15.3
	51.11 - 204.44	7.1	5.4	1.6	0.9
	≥204.44	2.3	1.5	0.4	0.1
SH	<10.2	65.7	75.8	81.4	83.9
	10.2 -51.11	28.5	19.6	16.9	15.9
	51.11- 204.44	4.4	3.3	1.3	0.2
	≥204.44	1.4	1.3	0.4	0.0
GZ	<10.2	66.6	76.3	82.7	84.6
	10.2 -51.11	28.6	20.5	16.1	14.8
	51.11- 204.44	4.0	2.6	1.1	0.6
	≥204.44	0.7	0.6	0.1	0.1

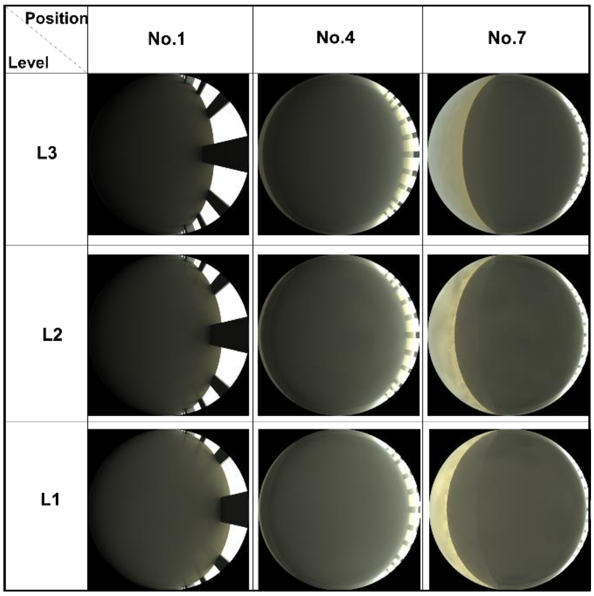

Figure 11: Hemispherical images at three positions (No.1, 4, 7) and three vertical levels (L1, L2, L3).

bring in a lower solar/daylight/PAR availability. In this area, a higher distance above the floor will lead to less internally reflected component of back wall. Thus, the positions at L1 have higher solar/daylight/PAR availability than L2 and L3. The component analysis of images can be used to explain the general variation of PAR cross the room and with three vertical levels.

Second, climate conditions can explain the PAR variations brought by orientation and location. As mentioned in Methodology, compared with Shanghai and Guangzhou, Beijing receives more annual solar radiation while it has a lower solar latitude (MHUD, 2013). These could give rise to higher solar gains received in the room, especially at the front area. For the three Chinese locations, windows facing south and west might receive higher solar gains than facing east and north.

Third, the increase of external obstruction can lead to more reflected light received at the front of the room. Compared with the direct light from the sky and sun, the light reflected from the obstruction might just increase the solar/daylight/PAR levels by a small magnitude, which can explian the increase of low-level PPFD (10.2-51.11 μmol/m^2/s) with the increased obstruction in the room positions near the window.

Conclusion

Based on the simulation analysis of PAR availability and distributions in an open-plan office model with four orientations, four external obstruction angles, and three locations, several key findings are discussed as follows.

Different from the daylighting metric applied for human visual function (Baker et al., 1993), the PAR metric (PPFD, μmol/m^2/s) recommended in this study could be more useful in terms of planning greenery systems to enhance biophilic aspects of office building. This metric adopted PAR thresholds (see Table 1) instead of illuminance levels to evaluate if plants can have a normal growth in an indoor workspace. This could be used to provide quick solutions for supporting landscape design (interior) in a straightforward way.

For this open-plan office building with one side being a glazed facade, low light level plants (PPFD: 10.2-51.11 μmol/m^2/s) could be applied in the front and middle areas, while only the area near the window (<2.5 m) has some possibilities to support medium-light plants (PPFD: 51.11-204.44 μmol/m^2/s) and high-light plants (PPFD: ≥204.44 μmol/m^2/s).

With a south facing orientation and no external obstruction, this open-plan office has the possibilities to use low-light / medium-light / high-light plants. For low-light plants, the high level position (1.6 m above floor) can receive higher PAR availability than a table surface (0.8 m above floor) and floor surface (0.1 m above floor) in the front area, while the middle and back areas indicate that the floor surface has the highest PAR availability. For medium-light and high-light plants, only the floor surface can receive proper levels of PAR.

For this open-plan office without obstruction, facing north and east can bring in higher PAR availability for low-light plants in the front area than facing south and west, while south and west are still the best orientations for low-light plants placed in the middle and back areas. For medium-light and high-light plants, facing south and east can bring in higher PAR availability.

For this open-plan office facing south, increasing the obstruction angle can increase the PAR availability for low-light plants in the front area, while decreasing this availability in the middle and back areas. For medium-light and high-light plants, increasing the obstruction angle can drastically decrease the PAR availability suitable for sustaining their health growth.

In general, Beijing can receive slightly higher PAR availability for the three types of plant than Shanghai and Guangzhou. There are no big differences of PAR availability between Shanghai and Guangzhou.

These results could contribute to design guidelines for the establishment of greenery systems in an office building to increase opportunities to create a biophilic office with the ‘green nature’.

Limitations and future work: First, this study only applied a simple window model of double clear glazing, while a solar-controlled glazing (coated glass) can be commonly found in modern office buildings. With a solar-controlled glazing, the conversion factor (1 lux = 0.019 PPFD) would be changed. Next, only an empty office room without shades was assessed. Considering the impact of shading systems and office furniture & facilities, the PAR/daylighting levels could be overestimated. Finally, this study only adopted one specific type of office room. The office configurations were relatively simple. More work will be continuously conducted on parameters including interior properties, shapes, glazing, façade configurations, obstructions.

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