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Correlative Impact of Shading Strategies on Sky Exposure and Cooling Performance at Pedestrian-level in Street Canyon

Case study on Traditional Shophouse Neighbourhoods in Hot-Humid Zone

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ABSTRACT: Shading strategies in street canyon are essential for reducing sky exposure and optimizing outdoor thermal environment, especially in the hot and humid climate zone. However, over shading might damage the thermal dissipation potential in a street canyon. Traditional shophouse neighbourhoods (TSNs) in southern China is a good reference on climate-adapted urban morphology since they integrate multiple shading strategies properly. In this paper, the correlative impact of four shading strategies of TSNs on sky view factor (SVF) and pedestrian-level thermal comfort are investigated, including aspect ratio of canyon, axis orientation, proportion of arcade, and tree coverage area. The concept of physiological equivalent temperature (PET) load is applied on assessing the cooling performance in different experimental case. The results illustrate that: the cooling performance of the streets with border tree in high SVF are better than the streets only shading by building geometry; the cooling effect of shading facilities is getting weak in street canyon with low SVF (SVF < 0.1 on the middle of pedestrian area). Furthermore, a proper value range of the above four shading strategies is given for guiding climate responsive street canyon design.

KEYWORDS: Urban microclimate, Parametrical simulation, Pedestrian-level thermal comfort, Correlated assessment

1. INTRODUCTION

The characteristic of urban morphology relates with the local microclimate directly[1]. As an element of urban morphology, shading facilities are necessary in street canyon for achieving a comfortable outdoor environment especially in warm climatic zone where suffers a long and unbearable hot summer season[2]. Shading facilities are served as preventing solar radiation and adjusting the level of sky exposure. According some contrastive studies, the cooling performance and correlative impact between shading strategies are different[3-5].

However, over shaded or too deep canyon might also lead to aggravate urban thermal environment, since the lower sky exposure would damage the thermal dissipation potential of urban in nighttime as well[6, 7]. A negative correlation between sky exposure and intensity of Urban Heat Island (UHI) has been verified[8]. Thus, it is important to balance the needs of shading and performance of cooling in the process of street canyon design.

A kind of compact and climate-adapted Traditional shophouse neighbourhoods (TSNs) can be found in many old city quarters of southern China and Southeast Asia (Fig. 1), where are located in the hot-humid climate zone. Multiple shading facilities are integrated in these TSNs, including greening, semi-open arcade, and high aspect ratio, to achieve comfortable thermal environment for residential and pedestrian, which is a proper reference for urban design on responding climate.

Authors has already reported the correlative impact between shading strategies and neighborhood configurations on pedestrian-level thermal comfort (PTC) in the street canyon of TSNs [9, 10]. This research is a further study based on the microclimatic simulation result from the former papers. By means of relating the value of sky view factor and thermal environment on pedestrian level, the correlative impact of shading strategies in street canyon on sky exposure and cooling effect can be investigated.

Fig. 1. Aero and street view at a Traditional Shophouse Neighbourhood in Guangzhou, China

2. METHOD

2.1 Parametrical simulations

In the context of ideal street canyon, four main shading strategies of street design are studied, which are aspect ratio of canyon (CHW), axis orientation (AO), aspect ratio of arcade (AHW) and tree coverage area (TCA). Those streets are in a fixed length (200m) and height (12m). The pedestrian area with 3m width is set beside both sides of road. As shown on Fig. 2, three groups of street canyon for experiment (G1 to G3) are generated following the spatial scale ranges of TSNs in South China, details can be found in Yin, Lang [9].

The CHW is varied via adjusting the width of road. According to the site survey on relating canyon type in cities of Southern China, the CHW in three groups are different. In G1, CHW is varied from 1.00 to 3.00; in G2 is 0.67 to 1.67; in G3 is 0.33 to 1.33. Regarding the AHW in G2, the height of arcade is fixed at 4 m same as that of ground floor. The AHW is changed from 0.67 to 2.67 via varying the width of arcade. The variation of TCA in G3 is generated by increasing crown diameter of border trees in both sides, and the range is from 22% to 89%. In each value range, five cases are selected with equally interval.

In all above cases, four AOs are investigated which are east to west (EW), southeast to northwest (SE-NW), south to north (SN), and southwest to northeast (SW-NE). In a total, 216 street canyons have generated as experimental case in this research.

These models are named as variable followed value, such as the CHW300 in G1 is alluding to the alley with CHW in 3, and the TCA089 is pointing the canyon with TCA in 89% in the G3. The predicted points locate at both the middle of pedestrian area and road.

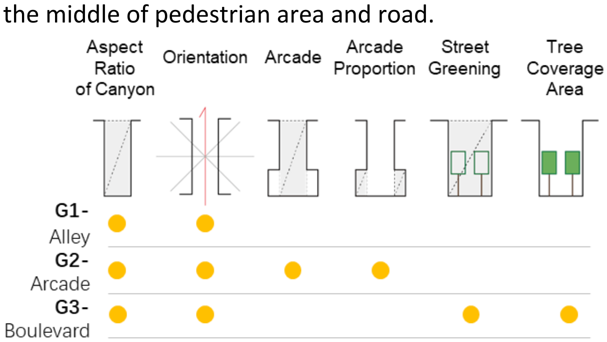

Fig. 2. Parameters investigated in three groups

2.2 Assessing Index for Sky Exposure

The Sky View Factor (SVF) is adopted to assess the level of sky exposure on a predict point. SVF represents the ratio at a point in space between the visible sky and a hemisphere centered over the analyzed location[11]. The range of SVF is varied from 0 to 1. At the point with SVF=0, the sky is blocked entirely by obstacles. In this research, the crown of tree is set as a solid volume and 15 m height in calculating SVF.

2.3 Assessing Index for Cooling Performance

The physiological equivalent temperature (PET) is applied to evaluate the PTC. The concept of PET load (PETL) is applied in this research, which means the part of PET over no thermal stress[12]. Thus, the cumulative PETL (cPETL, i.e., the sum of PETL) can present the thermal stress load on the attendance of a person at a specific point during a certain period, as in the Equation (1).

In this research, the value of no thermal stress perception (BC) is set as 30 ◦C, which is the neutral PET in hot-humid climate zone according to relating research[13]. The cPETL is the sum of PETL at a predicted point from 8 to 20h, when is the main period for outdoor activities. For comparing the cooling effect between different cases, the ΔcPETL is adopted, which is calculated as the Equation (2). The OcPETL (◦C) is the cumulative PET load of the point in the base case, which is the alley with CHW=1 (CHW100). The PcPETL is other street canyons with the same AO of the base case. Thus, higher ΔcPETL means better cooling performance and vice versa.

$$\mathrm{cPETL} = \sum_{h=8}^{20} (PETL_h - BC) \tag{1}$$

$$\Delta\mathrm{cPETL} = O_{cPETL} - P_{cPETL} \tag{2}$$

where PETLh (◦C) is the PET load in h time; PcPETL (◦C) is the cumulative PET load of the point in predicting street canyon; OcPETL (◦C) is the cumulative PET load of the point in reference street canyon, which is an alley without any shading facility and its CHW is 1.

2.3 Boundary Conditions for ENVI-met

The ENVI-met 4.3 (released in Dec. 2017) [14] is used for both calculating the value of SVF and simulating the PTC in each generated cases in Chapter 2.1. The PET is calculated via Biomet which is a post processing program in the suite of ENVI-met.

The Tab. 1 indicates the boundary conditions for parametrical microclimate simulation. The data of Ta and RH come from a weather station on the roof of TSN in Guangzhou on 30th July 2017, more details can be found in a former research by authors. The variations of Ta and RH in a day are set as forced file in hourly for simulating in ENVI-met. The Ta reached its peak at 1600H and the lowest value at 0200H, which is 38.7°C and 27.1°C respectively, while the RH lied in the valley bottom, 48.5% and get the top at 0700h, 90.1%. The Solar adjustment factor of ENVI-met model is set as 0.78 to fit the Global Horizontal Irradiance from measured point.

Tab. 1 Climate data input for simulations with ENVI-met

Size and resolution	100x100x50m X=1m, Y=1m, Z=2m
Date	30.07.2017
Duration	4:00 am- 8:00 pm
Ta	38.7°C - 27.1°C
RH	48.5% - 90.1%.
Solar adjustment factor	0.78, max 847 W/m^2
Wind Velocity and Wind Direction at 10m	1.5 m/s, 135°
Specific humidity at 2500 m[1]	13.0 g/kg
Soil initial temperature[2]	305K (0-20 cm)/ 307K (20-50 cm)/ 306K (<50 cm)
Soil wetness[2]	30% (0-20 cm)/ 40% (20-50 cm)/ 50% (<50 cm)
Building	Wall: Thermal resistance=0.5 (m^{2}K)/W, albedo=0.4 Roof: Thermal resistance=1.0 (m^{2}K)/W, albedo=0.45
Surface Albedo	Asphalt=0.2/ Concrete=0.8/ Grey tile=0.5

[1] this variable acquired from Barsi [15]
[2] this variable acquired from Yang, Zhao [16]

3. RESULT AND CONCLUDSION

The SVF and PTC on the middle of the road and pedestrian area are compared for investigating the correlation between sky exposure and cooling performance.

3.1 SVF

The Fig. 3 indicates that the SVF in different groups. In G1, the SVF presents positive correlation between the point on road and pedestrian, whose R-squared is over 0.9. The value of SVF on road is varied from 0.13 to 0.53, while on pedestrian is from 0.15 to 0.44.

Similar positive correlations are illustrated in the street with arcade in G2. In general, the SVF on the pedestrian is getting lower with the AHW decreasing. Besides the AHW067, the other 4 streets present linear correlation between the point on road and pedestrian with the same slope, which is much slower than it in G1. The SVF on road changes from 0.30 to 0.67, and on pedestrian area varies from 0 to 0.3. The SVF on pedestrian approach 0 when the SVF on road lower than 0.6 in the AHW067, while the SVF on pedestrian is closing 0 when the road's SVF is 0.3 in the AHW 100 as well.

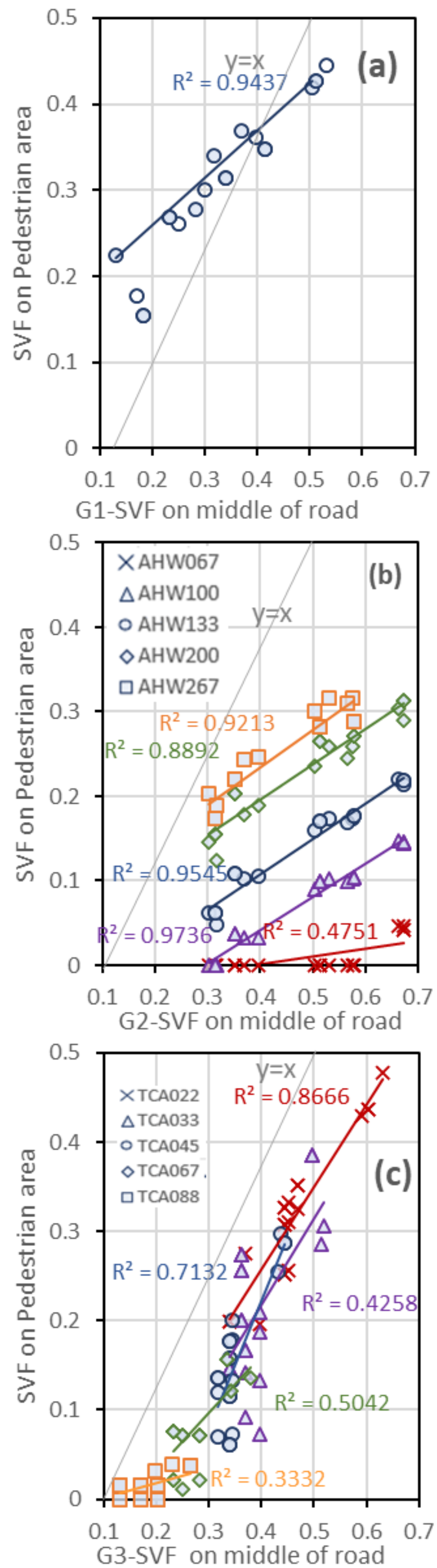

Fig. 3 The correlation between SVF on middle of road and pedestrian area in three groups. (a) is the group of alleys with shading facility; (b) is the group of arcade streets; (c) is the group of boulevards.

Regarding the street with trees, the correlation between the SVF on the middle of road and pedestrian presents less linear relations than that in G1 and G2. Though the R-squared value in all streets are rather lower, the street with less tree coverage area presents high linear correlation. The R-squared in TCA022 is 0.87, while in TCA088 is only 0.33. The SVF in most of its canyons are closing 0 on pedestrian area. In G3 the value of SVF on middle of road varies from 0.13 to 0.63, and on pedestrian area changes from 0 to 0.47. With the tree coverage area increasing, the response of SVF on pedestrian area is getting insensitivity and presenting mild slope on its fitting line. For example, the SVF on pedestrian area in TCA022 varies from 0.2 to 0.48, while in TCA088 is only from 0 to 0.05. The SVFs are raised markedly when its TCA less than 33%.

3.2 ΔcPETL

The OcPETL (℃) is the cumulative PET load of the point the alley without any shading facility and its CHW is 1,which is varied from 121.3 to 142.4 ℃ according to its orientation. With the CHW increasing, the cPETL of the predicting point is reducing and its corresponding ΔcPETL is higher. As shown in Fig. 4, the highest ΔcPETL in G1 is 50.3 ℃ and the average is 18.4 ℃. The inter quartile range (IQR) of G1 is from 4.1 to 29.4 ℃, which is the lowest range comparing with that in G2 an G3.

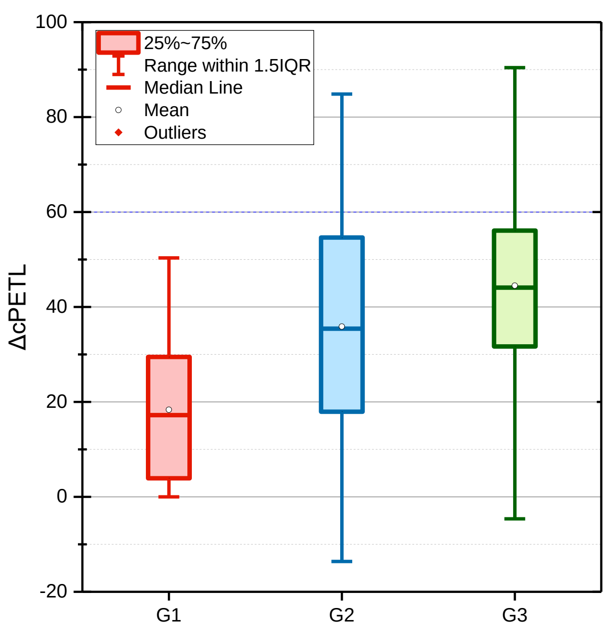

Fig. 4 The box-plot of ΔcPETL on the pedestrian area in different street type, G1 is alleys, G2 is street with arcade for pedestrian, G3 is street with boulevard.

In most of arcade streets, pedestrian area is comfort than in alleys. The average value in G2 is 35.9℃ and in G1 is 19.5℃. The AHW200 with CHW in 0.33 and N-S orientation shows the worthiest thermal environment with ΔcPETL=-13.6℃. The maximum ΔcPETL is 84.8℃ in the AHW067 with CHW=1.67. The span of its IQR is longest among the three groups, from 18.0 to 54.6℃.

The streets with trees illustrate the best performance on reducing PET load and the average ΔcPETL is 42.5℃. Though the third quartile only slightly over it in arcade street with 56.0 ℃, the first quartile is fast double as it in G2 with 31.8 ℃. The average of ΔcPETL in G3 is fast 44.5 ℃ and higher than the third quartile in G1. The minimum ΔcPETL is only -4.6 ℃ just few lower than it in the reference street canyon.

3.3 Correlation between SVF and ΔcPETL

As shown on Fig. 5, the correlation of SVF on road and pedestrian area with the ΔcPETL on pedestrian area are presented, respectively. In general, the ΔcPETL in all streets is reducing with the SVF raising. The alleys always present worse outdoor thermal environment comparing other two street types when they share the same SVF on the middle of road, expect the street in extremely deep canyon. For example, the lowest SVF on the middle of road in G1 and G3 are 0.13, but the ΔcPETL in some street with trees even lower than it in alleys. Differing from the linear correlation between the SVF on the middle of road and the ΔcPETL on pedestrian area in G1, the PTC in the street with arcade and tree shows weak relationship with the SVF on the middle of road, such as the ΔcPETL varied significantly from -13.6 to 80.4 ℃ in G2 when its SVF on the middle of road is around 0.66. The range of ΔcPETL of boulevards in a certain SVF is about 60 to 70 ℃, as the shading facilities impact the PTC in those streets on pedestrian area.

Regarding the correlation between SVF and ΔcPETL on pedestrian area, a linear relationship only present in G1. In other two type of street, the span of ΔcPETL is relative significant, especially in the street with high SVF. For example, the difference of ΔcPETL between cases in arcade street with SVF in about 0.3 is over 85 ℃, in 0 is around 60 ℃. Such range in G3 is smaller, which is around 60 ℃ in different SVF. When the SVF is less than 0.3, the ΔcPETL in G1 is closing worst case in G3 but is higher than majority streets with arcade. For example, the highest ΔcPETL of G1 in SVF=0.3 is 22.3 ℃, and the lowest ΔcPETL of G3 in the same SVF is 18.4 ℃, but its top value is fast 75 ℃. In G2, the lowest case is -13.0 ℃ and the best is 72.8 ℃.

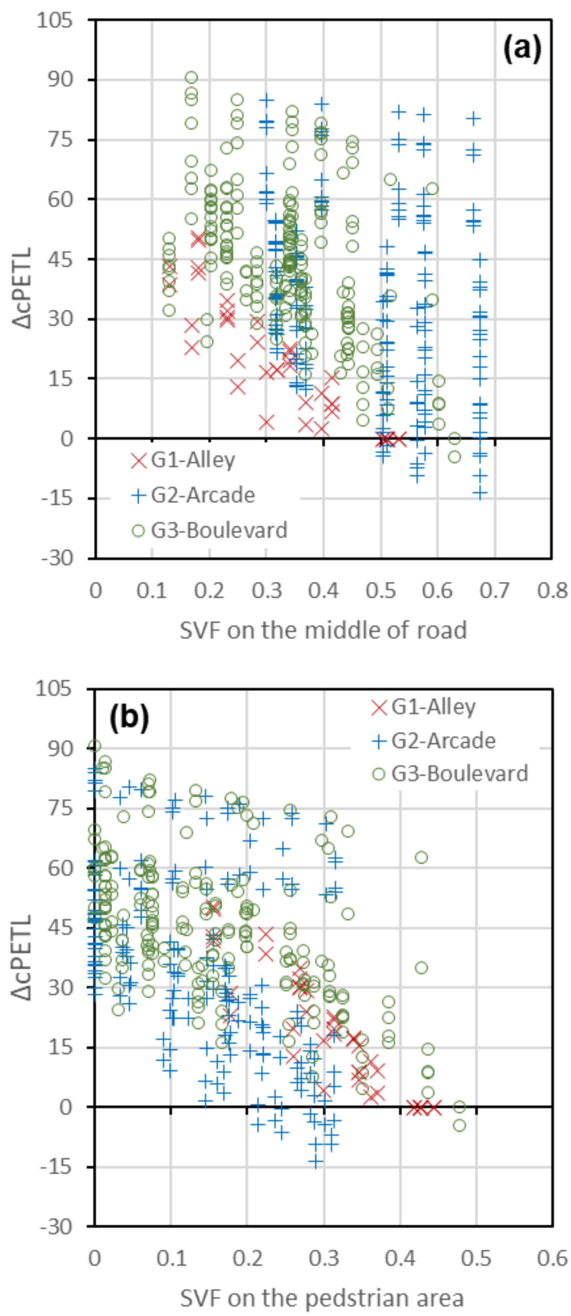

Fig. 5. The correlation between SVF and ΔcPETL of the point on the middle of road(a) and pedestrian area(b)

When the SVF higher than 0.21, the ΔcPETL in some street with arcade is lower than 0, but in G3, the threshold is postponed until the SVF over 0.47. This illustrates that the cooling capacity of tree coverage is better than it of building geometry. Only few arcade street's PTC is approaching that in boulevard with the same SVF, and most cases in G2 are worse than G3. When the SVF of G2 and G3 is lower than 0.05, the range of ΔcPETL of both two groups are similar, about 30 to 90 ℃. Meanwhile, the orientation plays an important role in G2, since some cases have much better cooling performance than others in the same SVF. The most significant gap can be found In the AHW267 with SVF about 0.3. The ΔcPETL in E-W orientation changed from 55 to 61 ℃, while in other orientation is from -13.6 to 34.9℃. However, the difference in G3 is rather small and the best orientation is N-S orientation.

4. CONCLUSION

Some conclusions can be summarized as following:

- Regarding the impact of shading facilities on sky exposure, the CHW presents an inverse relationship with SVF in all groups but in different tendencies. The SVF of point in arcade and under tree coverage increase much slower than it in alley with the road getting wider. It indicates the resistant capacity of arcade and trees on decreasing the sky exposure for pedestrian. Differing with a similar relating tendency in different AHW, boulevards illustrate variant trends between the SVF on middle of road and pedestrian area. With the TCA getting higher, the relationship is inconspicuous and insensitivity.
- The cooling performance in the street with arcade and tree is similar since both of them still present high ΔcPETL in the street with open sky exposure. The maximum and third quartile of ΔcPETL in G2 and G3 are closing. Most of the points at pedestrian area in G1 are lower than that in G2 and G3. However, over half of canyons in G3 have better thermal environment comparing street with arcade, even in shallower canyon. This indicates that the greening has the best cooling performance among all shading facilities.
- In the aspects of the correlation between SVF and ΔcPETL, the boulevards present the best cooling performance in high sky exposure canyon on pedestrian area, while in the pedestrian area with low SVF the cooling effect of arcade and greening are closing. Meanwhile, the impact of orientation is relative faint in the point of low sky exposure. The tree coverage has better resilience on preventing the raise of PET load in high sky exposure. The negative of ΔcPETL in G3 only appears out until the SVF over 0.47. The cooling performance in arcade is limited according to orientation, as its negative of ΔcPETL comes out at the SVF over 0.21 while the threshold for alley is over 0.4. When the SVF on pedestrian area too lower, the cooling impact of shading facilities is difficult to detect or even worse than that in higher SVF.

To avoid too deep canyon and over shading in arcade, the SVF in the middle of arcade can over 0, when its SVF at middle of street is higher than 0.3 but lower than 0.5, and its AHW is around 1 to 1.33. In the aspect of boulevard street, the TCA is suggested higher than 33% but lower than 67%, and the SVF on middle of road is over 0.2. Based on the above guidance, the need of shading from pedestrian is satisfied, meanwhile, the thermal dissipation of urban is ensured as well.

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REFERENCES

1. Oke, T.R., *Street design and urban canopy layer climate.* Energy and Buildings, 1988. **11**(1-3): p. 103-113.
2. Jamei, E., et al., *Review on the impact of urban geometry and pedestrian level greening on outdoor thermal comfort.* Renewable and Sustainable Energy Reviews, 2016. **54**: p. 1002-1017.
3. Ali-Toudert, F. and H. Mayer, *Effects of asymmetry, galleries, overhanging façades and vegetation on thermal comfort in urban street canyons.* Solar Energy, 2007. **81**(6): p. 742-754.
4. Lee, I., J.A. Voogt, and T.J. Gillespie, *Analysis and Comparison of Shading Strategies to Increase Human Thermal Comfort in Urban Areas.* Atmosphere, 2018. **9**(3): p. 91.
5. Morakinyo, T.E. and Y.F. Lam, *Simulation study on the impact of tree-configuration, planting pattern and wind condition on street-canyon's micro-climate and thermal comfort.* Building and Environment, 2016. **103**: p. 262-275.
6. Ojima, T., *Changing Tokyo metropolitan area and its heat island model.* Energy and Buildings, 1990. **15**(1-2): p. 191-203.
7. Taha, H., *Urban climates and heat islands: albedo, evapotranspiration, and anthropogenic heat.* Energy and buildings, 1997. **25**(2): p. 99-103.
8. Unger, J., *Connection between urban heat island and sky view factor approximated by a software tool on a 3D urban database.* International Journal of Environment and Pollution, 2009. **36**(1): p. 59-80.
9. Yin, S., W. Lang, and Y. Xiao, *The synergistic effect of street canyons and neighbourhood layout design on pedestrian-level thermal comfort in hot-humid area of China.* Sustainable Cities and Society, 2019. **49**: p. 101571.
10. Yin, S., et al., *Correlative Impact of Shading Strategies and Configurations Design on Pedestrian-Level Thermal Comfort in Traditional Shophouse Neighbourhoods, Southern China.* Sustainability, 2019. **11**(5): p. 1355.
11. Oke, T.R., *Canyon geometry and the nocturnal urban heat island: Comparison of scale model and field observations.* Journal of Climatology, 1981. **1**(3): p. 237-254.
12. Charalampopoulos, I., et al., *A methodology for the evaluation of the human-bioclimatic performance of open spaces.* Theoretical and applied climatology, 2017. **128**(3-4): p. 811-820.
13. Lin, T.-P. and A. Matzarakis, *Tourism climate and thermal comfort in Sun Moon Lake, Taiwan.* International Journal of Biometeorology, 2008. **52**(4): p. 281-290.
14. Bruse, M. *ENVI-met 4. A holistic Microclimate Modelling System*. 2018 15.04.2018 2018-08-27]; Available from: http://www.envi-met.info/doku.php?id=root:start.
15. Barsi, J. *Atmospheric Correction Parameter Calculator*. 2011-02-11]; Available from: https://atmcorr.gsfc.nasa.gov/.
16. Yang, X., et al., *Evaluation of a microclimate model for predicting the thermal behavior of different ground surfaces.* Building and Environment, 2013. **60**: p. 93-104.