A Dynamic Analysis of Daylight Availability in Dense Urban Residential Areas:
A Cross-region Study in China

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ABSTRACT: Daylight utilization in cites is receiving increasing attention from urban planners and developers, architects, and engineers, especially in China. This article aims to study the daylight availability in highly dense residential areas across China with respect to current planning regulations. Using a method of climate-based analysis, frequencies of vertical daylight illuminance at building south façades in three urban layouts have been assessed according to five typical locations, one of which represents one daylight climate zone. Key findings are as follows: 1) Given the daylight availability, these layouts were proved as suitable for only two southern locations, but not appropriate for others. 2) Current regulations, focusing on ground floors in these layouts, would lead to excessive daylight illuminance and solar gain received at the higher façade. It is necessary to achieve a balanced level of daylight availability across various positions of building façade through an effective approach. 3) Under a situation of the highest building density allowed by current regulations, urban layouts (building forms) might not be able to take substantial effect on the overall daylight availability in buildings.
KEYWORDS: Daylight availability, Dense residential area, Daylight climate zone, Dynamic simulation, China

1. INTRODUCTION

Daylight utilization in urban areas is receiving increasing attention from urban planners and developers, architects, and engineers [1, 2]. China currently has two building regulations relating to daylighting planning: 'Standard for daylighting design of buildings (2013)' [3] and 'Standard for urban residential area planning and design (2018)' [4]. The first specifies daylight factors in terms of various functional spaces as the evaluation index for daylighting design, while the second quotes a minimum requirement of sunlight hours (calculated using sunpath diagram) in residential buildings. With the rapid urbanization in China, a great number of dense urban areas have recently emerged with high-rise buildings and narrow open spaces, resulting in very poor daylighting conditions [2]. However, with this new situation, it can be found that methods mentioned in two regulations [3, 4] are not able to help to achieve practical design and planning solutions, especially based on the response to local climates [2].

Several studies of planning regulations have been implemented in high dense cities in China. Ng [5] discussed daylight planning in terms of existing rules and policy in Hong Kong and found that these regulations had been applied 'out of context' with higher tower-like buildings. Other studies [6, 7] argued that the old version of the planning regulation [4] has very low potential to support practice due to the lack of detailed descriptions or adequate quantitative items, and on the other hand it could be hard to apply it for locations dominant by non-clear sky conditions. In addition, in some areas of north China, this regulation resulted in excessive land waste [8]. These studies did not move beyond theoretical discussions and it seems that they might lack solid practical proofs to justify how to effectively improve the daylighting planning at an urban scale.

Some investigations provided in-depth analysis of application of the regulations [3, 4] relating to daylighting at specific Chinese locations. At a city of east China, a study [9] found that some high-rise residential buildings still got poor daylighting condition, even though they have been properly planned based on the regulation [4]. Using a dynamic analysis method, Lu and Du achieved more practical analyses according to daylight availability in a highly dense residential area in north-east China with a cold climate [2]. It seems that a cross-region study would be beneficial due to facts that planners could understand the limitations of current planning methods and thus more practical design activities could be effectively implemented.

This article presents a climate-based simulation analysis for daylight availability in five Chinese locations, each of which represents one of the five daylight climate zones in China [3]. Planned based on current regulations, three typical urban layouts (residential area) with high density were assessed. This study aims to find out the feasibility of daylighting planning at an urban scale and the possibility to produce new design guidelines and strategies for achieving an effective daylighting planning at an urban scale in current China cities.

2. METHODS

2.1 Daylight climate zones and locations

As shown in Figure 1, five daylight climate zones in China [3] have been defined according to annual average total illuminance E_q (klx). They are zone I ($E_q \geqslant 45$), zone II ($40 \leqslant E_q < 45$), zone III ($35 \leqslant E_q < 40$), zone IV ($30 \leqslant E_q < 35$), and zone V ($E_q < 30$). This study selected five locations, each of which is the representative in one of these zones. The locations are: Lhasa (zone I), Yinchuan (zone II), Beijing (zone III), Guangzhou (zone IV), and Chengdu (zone V).

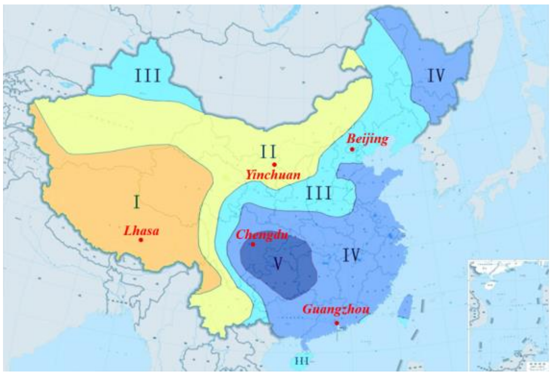

Figure 1: Daylight climate zones (I-V) and five Chinese locations.

2.2 Urban layouts studied

At each location, three typical urban layouts in residential areas were studied (Figure 2 & Table 1). Layout 1 and Layout 2 have square buildings (27 × 27 × 72 m) and rectangular buildings (13 × 60 × 36 m) respectively, while Layout 3 includes both two building types. The three layouts are used because they are currently typical urban layout forms applied in residential areas of most big Chinese cities [10]. Table 1 presents building distances in terms of locations and three layouts. The building dimensions and distances were defined to achieve the highest building density according to both national and local planning regulations [4, 11-17], with respect to the residential building design requirements of health and wellbeing, building structure, fire safety, etc.

Table 1: Building distances in three layouts.

Location	Building distance (m)							
	Layout 1		Layout 2		Layout 3			
	L1	L2	L1	L2	L1	L2	L3	L4
Lhasa	13	96	13	48	13	13	96	48
Yinchuan	13	119	13	58	13	13	119	60
Beijing	13	120	13	61	13	13	120	61
Guangzhou	22	45	13	38	13	22	45	27
Chengdu	22	36	16	30	16	22	36	30

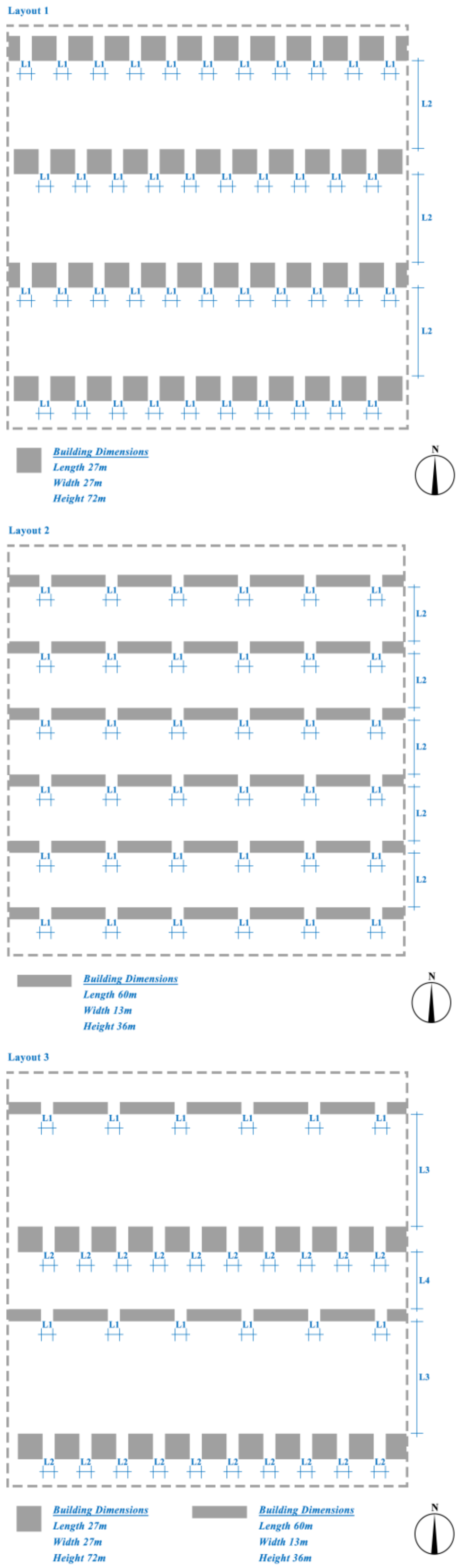

Figure 2: Three typical urban layouts studied.

2.3 Daylight availability and simulation

As mentioned in a previous study [2], there is a linear relationship between external vertical illuminance at centre external window of building (Ev) and indoor average daylight illuminance at the working plane (IAI). Thus, an equation can be used to describe this relationship as follows:

$$Ev = K \times IAI \quad (1),$$

where K is the coefficient factor, which is related to locations and climates. According to the method in the reference [2], the K value was achieved based on the regression analysis using local weather data. In this study, K values were used as 8.0 (Lhasa, Yinchuan, and Beijing), 9.0 (Guangzhou) and 9.5 (Chengdu). In addition, the daylight availability in these layouts was indicated by the external vertical illuminances at the centre south façade of square or rectangular buildings. As discussed in a study [18], when only receiving the daylight from windows, the range of 100 lx to 3000 lx for IAI can be interpreted as a condition of 'useful daylight', while the ranges of > 3000 lx and ≤ 100 lx will be treated as 'excessive daylight' and 'inadequate daylight' respectively. Thus, with respect to the ranges of IAI, Ev ranges were categorized using the Equation (1) at different locations as follows: 1) proper external vertical illuminance (PrVI) with (K×100 lx < Ev ≤ K×3000 lx); 2) excessive external vertical illuminance (ExVI) with (Ev > K×3000 lx); 3) poor external vertical illuminance (PoVI) with (Ev ≤ K×100 lx).

In the three layouts (Figure 2), the centre south façade of the buildings located in the middle was adopted as the studied position, due to a fact that the highest level of obstruction (worst daylight conditions) was found here. At this façade position, external vertical illuminance (Ev) was calculated using Daysim/Radiance and the method mentioned in a reference [2]. The annual occurrence (frequency) of the vertical illuminance (6:00 - 18:00) in each Ev range can be used to justify the potential of daylighting in buildings. A higher frequency of PrVI indicates a 'good' outdoor vertical illuminance that would result in a proper indoor illuminance across the working plane. If the frequency of ExVI has a higher value, the external façade surfaces will receive excessive solar gain and daylight illuminance, which means a higher risk to get visual discomfort and overheating problems in the indoor spaces. In addition, for PoVI, the higher is its frequency, the lower possibility is found to apply daylighting in the room.

3. RESULTS

This section presents frequencies of different ranges of vertical illuminance at south façades in terms of locations and three typical façade positions. Heights of these positions are: square building (s): 2.1 m (ground floor), 34.55 m (middle floor) and 69.95 m (top floor); rectangular building (r): 2.1 m (ground floor), 16.55 m (middle floor) and 33.95 m (top floor).

3.1 Daylighting availability: ground floor

Figure 3-5 show frequencies of PrVI and ExVI at ground floor in three layouts. It can be found that the three layouts could lead to relatively higher daylight availability at the ground floor for all locations (higher frequency of PrVI). Guangzhou has the highest PrVI frequency (over 71.65%), while Lhasa and Yinchuan have lower frequency of PrVI (still over 40.11%). However, ExVI frequencies of Lhasa and Yinchuan are both around 30%, which means at the two locations there are higher risk to get excessive solar gain and daylight illuminance, even at ground floor. On the contrary, Chengdu and Guangzhou have very low risk to get excessive solar gain (ExVI frequencies ≤ 7%). Beijing has PrVI frequency of over 55%, while its ExVI frequency is slightly lower than that of Lhasa and Yinchuan.

For Layout 1, the difference between PrVI frequency and ExVI frequency ranges from 14.12% (Yinchuan) to 68.90% (Guangzhou), whilst Yinchuan and Guangzhou see the differences of 11.08% and 64.61% for Layout 2 respectively. In Layout 3, these frequency differences have one range from 11.44% (Yinchuan) to 68.47% (Guangzhou) for square buildings, and another range from 8.58% (Lhasa) to 68.75% (Guangzhou) for rectangular buildings. Therefore, Guangzhou has higher possibility to achieve useful daylighting utilization under national and local regulations.

For one specific location, generally, PrVI frequencies of square and rectangular buildings are similar (absolute difference ≤ 3.67%). This finding could be reasonable since based on current regulations a similar level of obstruction could be found at the ground floor and thus the 'good' daylight condition will receive lower impact of urban layouts.

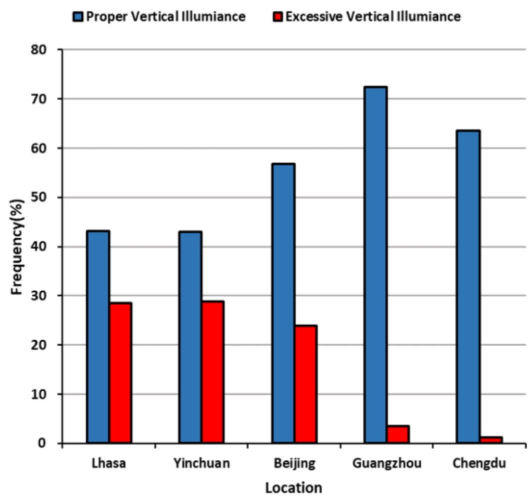

Figure 3: Frequencies of Ev ranges (Layout 1; ground floor).

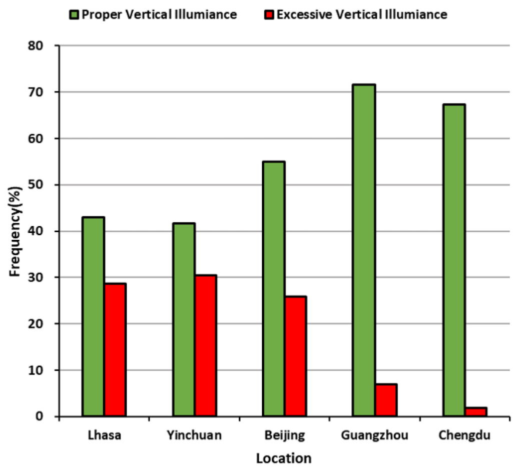

Figure 4: Frequencies of Ev ranges (Layout 2; ground floor).

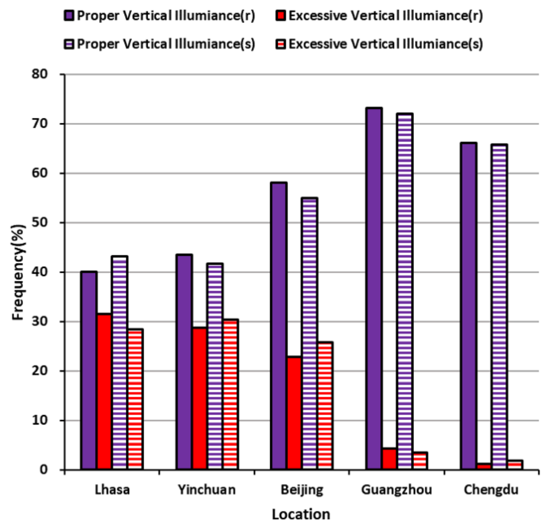

Figure 5: Frequencies of Ev ranges (Layout 3; ground floor).

3.2 Daylight availability: middle floor

Figure 6-7 present frequencies of two Ev ranges at middle floor in three layouts.

Apparently, the three layouts can still lead to relatively higher PrVI frequencies at the middle floor. Lhasa and Yingchun have much lower PrVI frequencies than Guangzhou and Chengdu. In addition, ExVI frequencies have become higher at the middle floor. A higher level of solar gain and daylight illuminance will thus be found at middle floor for all locations, especially at Yinchun and Lhasa. In Yinchuan, ExVI frequencies are generally higher, with the lowest value of 33% found at rectangular buildings in Layout 3. Lhasa sees that frequencies of PrVI and ExVI are very closed, and that 31% is the lowest ExVI frequency (rectangular buildings in Layout 3). These would clearly indicate that Lhasa and Yinchuan will have to deal with very high risk of overheating and visual discomfort at middle floor.

Compared with the ground floor, the middle floor sees increased ExVI frequencies for most buildings. For Layout 1 and Layout 2, the increase of ExVI frequency at Lhasa and Yinchuan have achieved over 6%, while Chengdu has a lower increase of around 2%. For Layout 3, the trend tends to be more complex. The increases of ExVI frequency at rectangular buildings are generally lower than square buildings. For rectangular buildings in Layout 3, Yinchuan has higher increase, but Lhasa does not have change. Square buildings see Lhasa and Yinchuan receive the highest increase, while the lowest increase is found at Chengdu. Thus, the daylight availability is significantly affected by the façade position in Lhasa and Yinchuan. The effect tends to be less in Chengdu.

At middle floor, there are no big differences of PrVI frequencies between Layout 1 and Layout 2 (< 0.4%) at all locations. This means that the layouts (with one type of building) will not significantly affect daylight availability at middle floor. For Layout 3 (mixed layout), rectangular buildings generally have higher PrVI frequencies than square buildings. Differences of PrVI frequency between rectangular and square buildings decreases with the decrease of E_q at five locations.

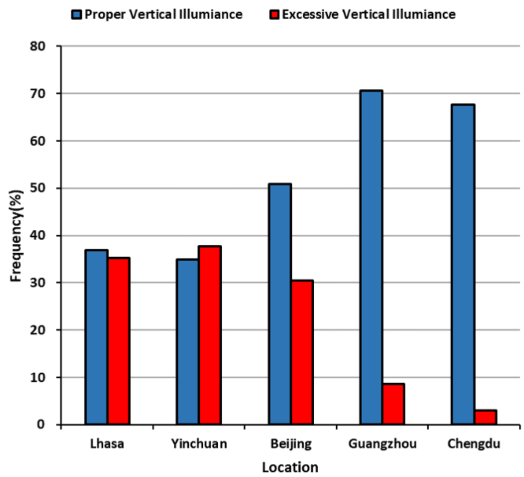

Figure 6: Frequencies of Ev ranges (Layout 1; middle floor).

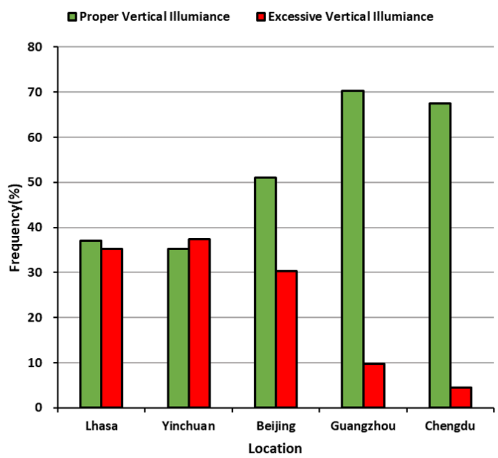

Figure 7: Frequencies of Ev ranges (Layout 2; middle floor).

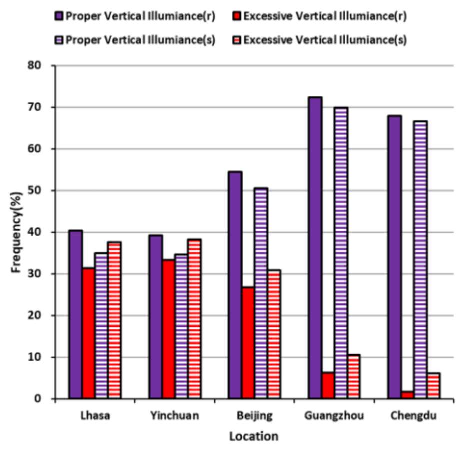

Figure 8: Frequencies of Ev ranges (Layout 3; middle floor).

3.3 Daylight availability: top floor

Frequencies of two Ev ranges at top floor in three layouts can be found in figure 9-11.

It can be found that only at three locations (Beijing, Guangzhou and Chengdu), the three layouts can lead to higher PrVI frequencies at top floor (above 45%). In addition, Lhasa and Yingchun can see higher ExVI frequencies (≥ 35%), which are larger than their PrVI frequencies. For Beijing, Guangzhou and Chengdu, even though ExVI frequencies are still lower than PrVI frequencies, values of the former have significantly increased with positions moving to top floor. It is normal to agree that the top floor of buildings has highest risk of excessive solar gain and daylight illuminance.

Compared with middle floor, the decreases of PrVI frequency at top floor are larger in Lhasa and Yinchuan, but less clear in Guangzhou and Chengdu. The trend is similar to that of the middle floor, which can again enhance the fact that the daylight availability receives higher impact from the façade position in Lhasa and Yinchuan than Guangzhou and Chengdu.

At top floor, differences of PrVI frequency between Layout 1 and Layout 2 are insignificant (lower than 0.5%). Similar to the middle floor, the daylight availability at top façade will not be clearly influenced by the layout (with the same building in). In addition, for Layout 3, square buildings generally receive lower PrVI frequencies than rectangular buildings at all locations. The absolute differences of PrVI frequency between the two buildings are above 2.19%.

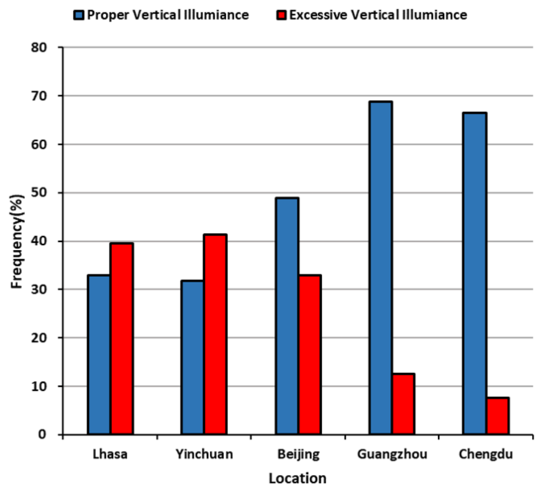

Figure 9: Frequencies of Ev ranges (Layout 1; top floor).

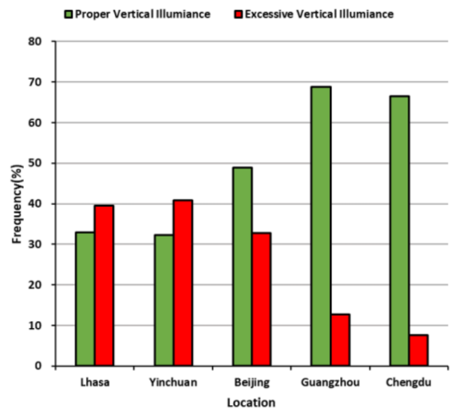

Figure 10: Frequencies of Ev ranges (Layout 2; top floor).

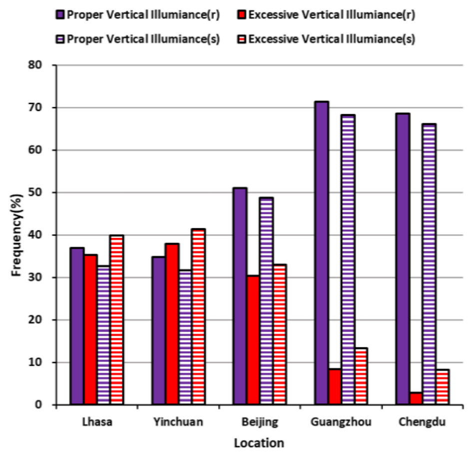

Figure 11: Frequencies of Ev ranges (Layout 3; top floor).

4. DISCUSSION AND CONCLUSION

Based on a climate-based analysis method, this study focuses on investigating the daylight availability of three urban residential layouts at five Chinese locations.

First, locations and climates play the most important role to achieve a proper daylighting utilization. In general, Guangzhou (Zone IV) and Chengdu (zone V) have the highest potential to achieve 'useful' daylighting due to the achievement of the highest PrVI frequencies and relatively lower ExVI frequencies, while Lhasa and Yinchuan (Zone I and II) have the highest risk to get problems of overheating and visual discomfort due to the higher ExVI frequencies. Beijing's has a medium potential for such 'useful' daylighting with the medium levels of PrVI and ExVI frequencies. These could indicate that the three layouts are very suitable for Guangzhou and Chengdu under current regulations but may not be appropriate for other locations. Without further modification of current regulations, it could be possible to give rise to environmental problems relating to land waste in some cities.

Second, during the early stage of urban design, it could be necessary to achieve a balanced level of daylight availability across the building façade, including lower, middle, and higher positions. The results have shown that the daylight availability in Lhasa and Yinchuan (Zone I and II) is much more sensitive to the façade positions than Guangzhou and Chengdu (Zone IV and V). Most planning regulations in China only focus on the ground floor, with the minimum requirement of sunshine hours at this position [4]. Without considering local climates and higher floor positions, there would be higher risk to get excessive solar gain and daylight illuminance for locations with high annual average illuminance (E_q).

Third, under the situation of the highest building density allowed by planning regulations [4, 11-17], urban layouts might not be able to take substantial effect on the overall daylight availability across the south façade in buildings. For the layouts using the same building type (Layout 1 and Layout 2), it has been found that daylight availabilities at three facade positions (ground, middle or top floor) are similar (Fig. 3-4, 6-7 and 9-10). However, for Layout 3 with two different buildings (Fig. 5, 8, 11), there are some differences found between square and rectangular buildings. Compared with square buildings, rectangular buildings would receive slightly higher levels of 'useful' daylighting at all locations. Thus, it seems that the type of buildings between adjacent rows may bring in some impacts to the daylight availability. According to most regulations [4, 12-15, 17], in general, the distance between two building rows is established based on the height of southern buildings without taking into consideration building forms. This could explain the insignificant differences of daylight availability between various urban layouts.

Limitation and future work: This study was implemented in three specific layouts. It would be interesting to check more parameters relating to the urban forms. Except for the south façade, other façades of buildings in the three layouts should be also studied. In addition, other typical orientations (e.g. south-east or south-west) might deliver various impacts on the daylighting utilization in these layouts.

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