Dynamic Evaluation of Daylight Availability in a Highly-dense Chinese Residential Area with a Cold Climate

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Abstract

Daylight utilization in urban areas is receiving increasing attention from urban planners and developers, architects and engineers. This study investigated the daylighting availability within buildings of a highly dense residential urban area under a cold climate in north-east China. Based on innovative simulations using climate-based daylight modelling (CBDM), three typical urban layouts have been assessed according to vertical daylight illuminance at the building facade. A comprehensive analysis of daylighting potential has been completed through various approaches including typical time (9am, 12pm and 3pm), yearly average daylight illuminance and a proposed external daylight metric based on the frequency. Several interesting relationships are found between daylighting potential, urban forms, and climate conditions. A number of design strategies and guidelines are produced to support early stage urban planning and design.

Keywords:

Vertical daylight illuminance; CBDM, Dynamic simulations; Highly-dense residential area; Cold climate

1. Introduction

Daylight (skylight and sunlight) has been considered as one of the most crucial environmental factors in terms of promoting energy efficiency, enhancing work productivity and improving human health and well-being in buildings [1, 2]. The availability of daylight has become a civil matter in some regions, which seriously concerns land developers, urban planners and building owners [3, 4]. In a densely built urban area, for example, obstructions by tall adjacent buildings can significantly reduce daylighting levels and solar gains at the ground and on facades [5]. Daylight availability and utilization potential in highly dense urban areas have increasingly attracted attention with increasing urbanization, in particularly in eastern Asia and a number of investigations on these topics have been implemented for more than 30 years [5].

The overcast sky, representing a 'worst' daylighting condition, has been adopted as the fundamental sky model for the evaluation of daylighting during the early building design and planning stage since Moon & Spencer introduced the concept in 1942 [6]. In an earlier study, a skylight indicator was first created to calculate vertical sky component (VSC) that primarily indicates incident daylighting level at window surfaces in cities [5]. The modified BRE (British Research Establishment) split-flux formulae [7] was further developed into a simplified daylighting design tool to estimate average daylight factor of rooms in high-density residential buildings in Hong Kong [8]. Three important variables of this tool are: vertical obstruction angle, horizontal obstruction angle and window glazing area. As a ratio of daylight illuminance on a vertical surface of a building to the unobstructed daylight illuminance on a horizontal surface, vertical daylight factor (VDF) includes three components: the light coming from the sky (VSC), the light reflected from obstructions and the light reflected from the ground [5]. In Hong Kong the VDF has been accepted as a metric within the building regulations used to specify daylight availability at window surfaces [9]. A minimum VDF standard of 8% and 4% is stipulated for habitable rooms and kitchens respectively [9]. These values were originally proposed from the results of a study based on an occupancy survey [10]. In addition, several new methods were studied to support daylight design and planning in the heavily obstructed environment of Hong Kong. Based on VDF fundamentals, the UVA (Unobstructed Vision Area) was developed to provide a consolidated relationship between unobstructed visionary areas that the windows 'see', building height and vertical daylight factor [10]. Other algorithms however focused on two direct approaches to calculate VDF at the windows [11, 12], which were both produced on basis of the split-flux formulae [7]. In Europe a recent study [13] extended the application of one model [12] to investigate the influence from surrounding buildings. This established a connection of daylighting conditions between the surface of window and the working plane in rooms in cities dominated by cloudy sky. In general, it could be pointed out that under overcast sky VDF has become an important daylighting indicator in densely built areas, regarding to its capability of supporting the practical design and planning [12].

Sunlight availability has been widely accepted as a significant and fundamental well-being requirement in houses and non-domestic spaces [5], and hence it is somewhat surprising that the overcast sky has such a dominate roll in daylighting analysis. Several algorithms were proposed to calculate mean daylight illuminance in rooms facing sunlit streets in 1995 [14]. The sunpath diagram, a simple solar tool, was generally used to analyze solar access or sunlight duration in buildings [15, 16]. However, an innovative tool, the BRE (British Research Establishment) Sunlight Availability Protractor, improved on the common sunpath diagram by adding a function of sunshine probability (statistic measured data on sunlight duration) [16]. The advent of Radiance (backward ray-tracing) [17] made it possible to carry out more complicated analyses of daylight and sunlight in a sophisticated urban environment. Compagnon [18] developed a simulation tool using Radiance as the platform to predict solar irradiation and illuminance levels across building envelopes of buildings at a relatively large urban scale. An early study using Radiance simulations found a stable linear varying trend between the vertical illuminance at the facade and the global horizontal illuminance in European urban canyons [19]. Furthermore, a daylighting study under a highly luminous climate found that the sunlight reflected from obstructions and ground makes the largest contributions to daylight levels at positions without direct sun shining [20]. Similarly, an investigation concerning solar gain and urban density showed the reflected light in dense urban canyons provides a substantial potential of electricity lighting energy savings at the lowest floors in a high latitude area [21]. These findings correspond well to the discussions on VDF distributions above and the conclusions of a recently developed study [22] of daylight illuminance calculation including sunlight in Hong Kong. More interestingly, a case study in Brazil [23] challenged local legislation and showed that daylight and sunlight availability can be very poor even though height and easements among buildings have been limited by regulations. Therefore, the daylight availability with the involvement of direct sun would still require more investigations in order to practically approach a satisfied solution, especially in a complex urban context.

Over the last three decades unprecedented high urban growth rates have occurred in China [24]. As a result, a large number of high-density urban areas have emerged with high-rise buildings and narrow open spaces and streets. This results in very poor daylighting conditions. China currently has two building regulations relating to daylight and sunlight respectively: 'Standard for daylight design of buildings' [25] and 'Code of urban Residential Areas Planning & Design' [4]. The first specifies basic daylight factors in terms of various functional spaces, while the second quotes a minimum requirement of sunlight hours in residential buildings. A preliminary investigation [26] of daylight availability was recently completed in a heavily dense residential area under a cold climate in China, with a focus on vertical daylight factor and sunlight hours across the building facades. Harbin, the city studied in this article [26], has a large number of heavily dense urban areas and a low daylighting availability due to its climate conditions [25]. Each urban layout studied has the highest possible plot density, which responses to the new trend of Chinese urbanization [24]. The suitability of the two standards [4, 25] in such an urban context has been discussed. However, the investigation [26] was completed based on two ideal and simple sky conditions: overcast sky (daylight factor) and clear sky (sunlight hours). Currently, the advent of CBDM (climate based daylight modelling) [27] has provided with a novel daylighting design and research approach to dynamically assess daylight systems under a more practical sky condition. Following the completed study [26], therefore, a new investigation was initiated in this article to assess the variations of vertical daylight illuminances at the building facade using the CBDM. Based on the local climate, a practical analysis of daylight availability in highly dense residential areas was presented to support early-stage urban design and development.

2. Methodology

This section is composed of three parts: location and climate conditions; urban layouts; daylighting simulations.

2.1 Location and climate conditions

This study was based on Harbin (Latitude: 45.8° N; Longitude: 126.8°E), a mega city in north-east China. Given the Chinese building regulation [28], the climate zone of Harbin is labelled as No. I 'Severe Cold'. In Harbin, therefore, the average temperature in January (coldest month) ranges from -31°C to -10°C, while the warmest month (July) has an average temperature below 25°C. The annual global horizontal solar irradiance is around 140~200 W/m^2. The annual and winter sunlight hours in Harbin are 3922 and 696 respectively. According to a study [29], solar access in winter has been recognized as the most important issue to achieve the passive design in Harbin's residential areas.

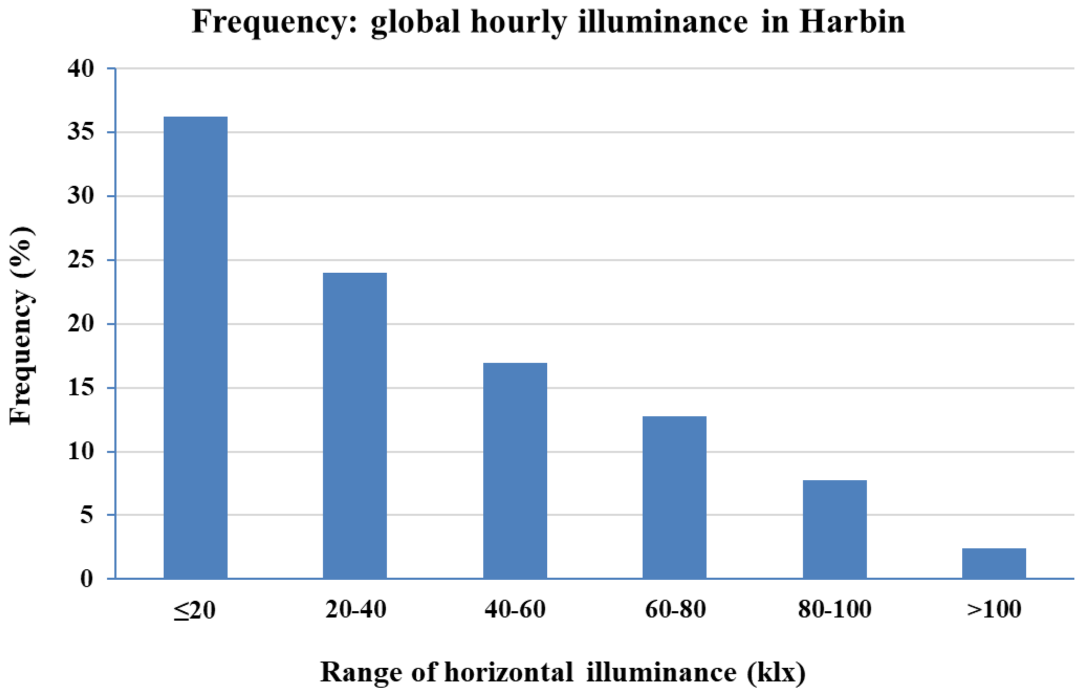

Figure 1. *Annual Daylight availability: frequency of hourly global horizontal illuminance in Harbin (time: 6am – 6pm). [25, 30]*

Another Chinese building regulation [25] has pointed out: the area around Harbin was labelled as No. V daylight climate zone (a zone with the lowest daylighting availability in China). The annual average global horizontal illuminance is < 25klx, which indicates a very low potential for utilizing daylighting compared with other cities in China [25]. The daylight availability (time: 6am – 6pm) in Harbin is given in Figure 1 and Table 1 (the hourly illuminances were derived from solar irradiations of the weather data of Harbin [25, 30]). The categories of hourly global horizontal illuminance (HGHI) in Figure 1 are the follows: HGHI ≤ 20klx; 20klx< HGHI ≤40klx; 40klx< HGHI ≤60klx; 60klx< HGHI ≤80klx; 80klx< HGHI ≤100klx; HGHI>100klx. Apparently, the frequency of HGHI ≤ 20klx can be found as around 36% of the working day (6am – 6pm) of the year. Table 1 presents the monthly average global horizontal illuminance at Harbin (6am – 6pm). April, May, June and July have the four highest average global illuminances while the minimum values are found in November, December, January and February. Thus, winter could be a particularly critical period for daylighting utilization.

2.2 Urban layouts in a residential area

Figure 2, 3 and 4 show three basic urban layouts (Model1, Model2 and Model3) studied in this article. The three urban models are selected based on the fact that they are currently typical urban forms applied in residential areas of Harbin city according to a design guidebook [31], and recommended by local planning authorities [32]. Based on both national and local planning regulations [4, 32], the building dimensions and the distances between buildings were defined in the models to produce three heavily dense residential areas. This aims to evaluate daylight availability in the 'worst' situation (the shortest distance and the biggest height if possible), which can be currently found in most developed urban areas of Harbin. Each layout includes several single high-rise buildings with a height of 72m (around 24 floors) and two fundamental plans: square and rectangular. The square building has a width (length) of 25m, whilst the width and length of the rectangular building are 15m and 60m respectively. In a square building, four apartments (area of each: 156m^2) are generally arranged on each floor; each floor of a rectangular building could have six apartments (area of each: 150 m^2). Model1 (Fig. 2) is a uniform 'dot' distribution with only square buildings. The distance between adjacent buildings (L1= L2) is 48m. A building with a rectangular plan is the major element in Model2 (Fig. 3), which has a 'linear' distribution (distance: L1= 13m and L2= 48m). The Model3 (Fig. 4), however, is constituted by both square and rectangular buildings: each building row has buildings with the same plan while a different building type is found at the adjacent row. Three distances in this layout are 13m (L1, between rectangular buildings), 48m (L2, between square buildings) and 48m (L3, between rectangular and square rows). With a high height-to-spacing value of 1.5, the three urban layouts can be regarded as heavily dense residential areas. Orientation of the buildings is indicated in each figure. The general level of obstruction in models can be considered as: Model1 < Model3 < Model2.

In this article, all facades of the square building were assessed due to a fact that each side is generally arranged with a separate apartment. However, only south and north façades were studied in the rectangular building. In order to get possible cross natural ventilation for indoor spaces, generally, each apartment unit in the rectangular building is set up across south and north façades. Also, the main indoor spaces are located on the two façades. As a result, south and north facing windows are mainly concerned by architects.

The daylight availability was studied at heights of 2.10m, 34.55m and 69.95m above the ground and along a vertical line placed in the centre of the façade. The three heights are as assumed to represent the positions of the centre external window on the ground, middle and top floors.

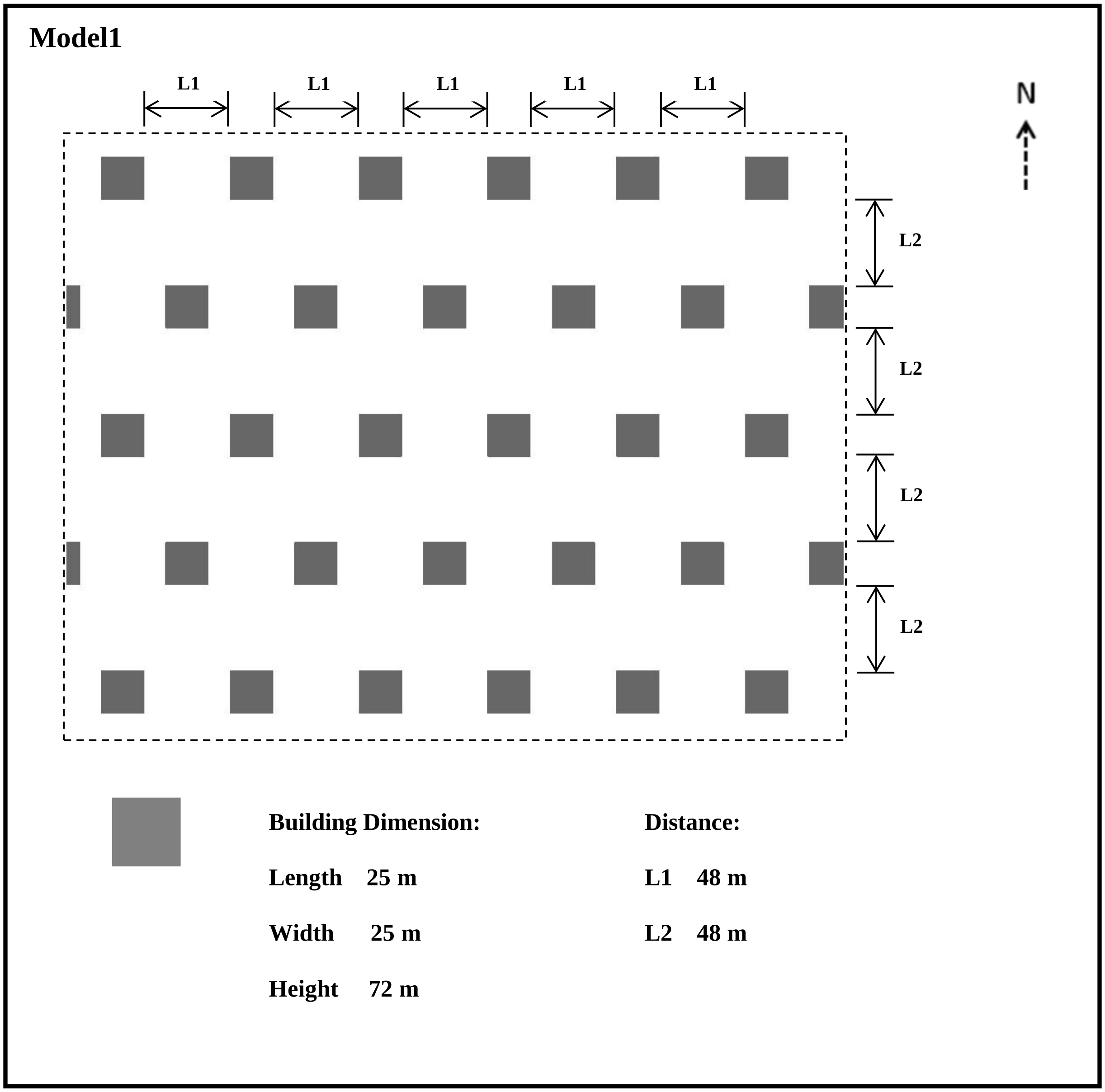

Figure 2. *Layout and dimension of the Model1.*

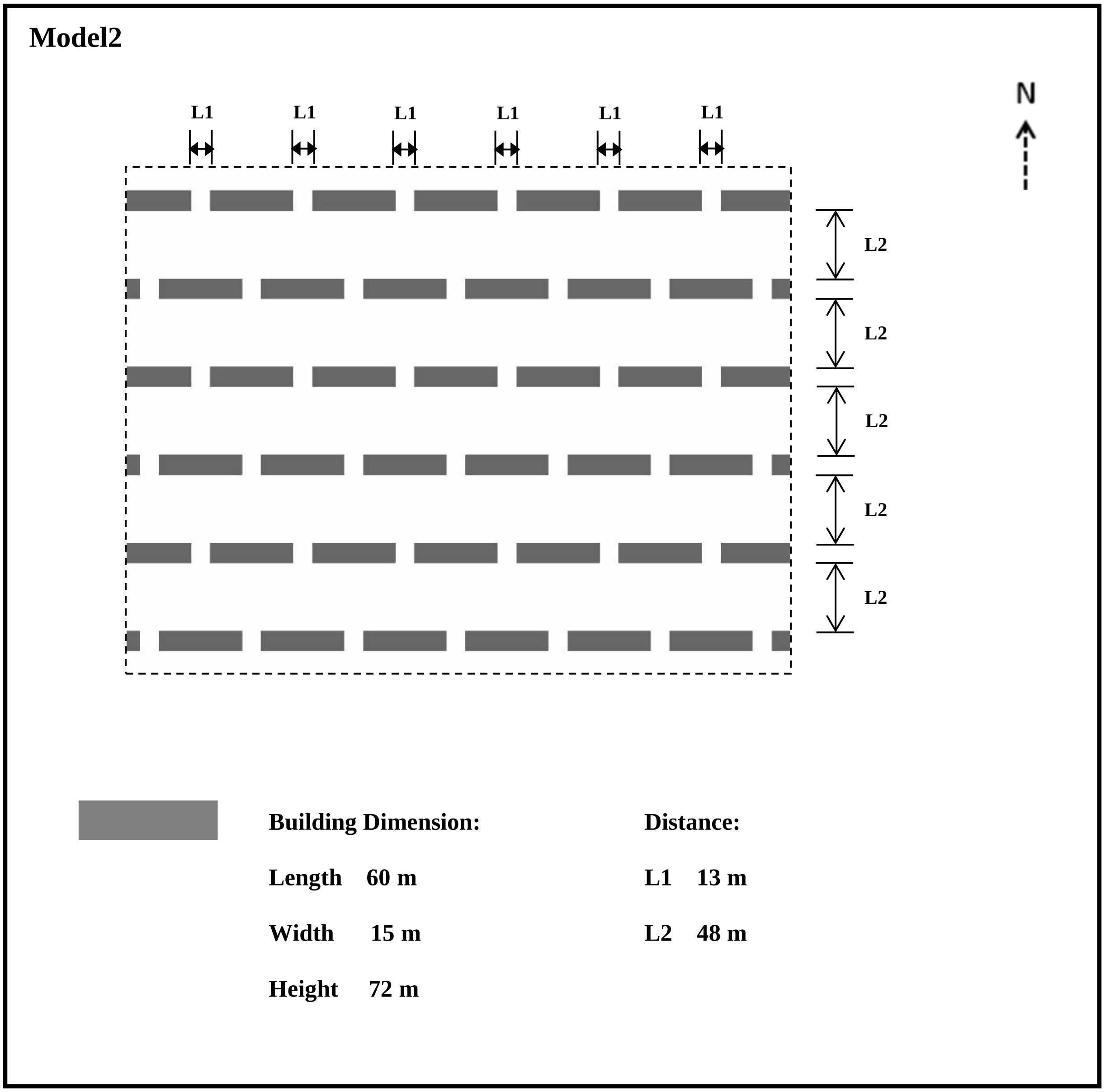

Figure 3. *Layout and dimension of the Model2.*

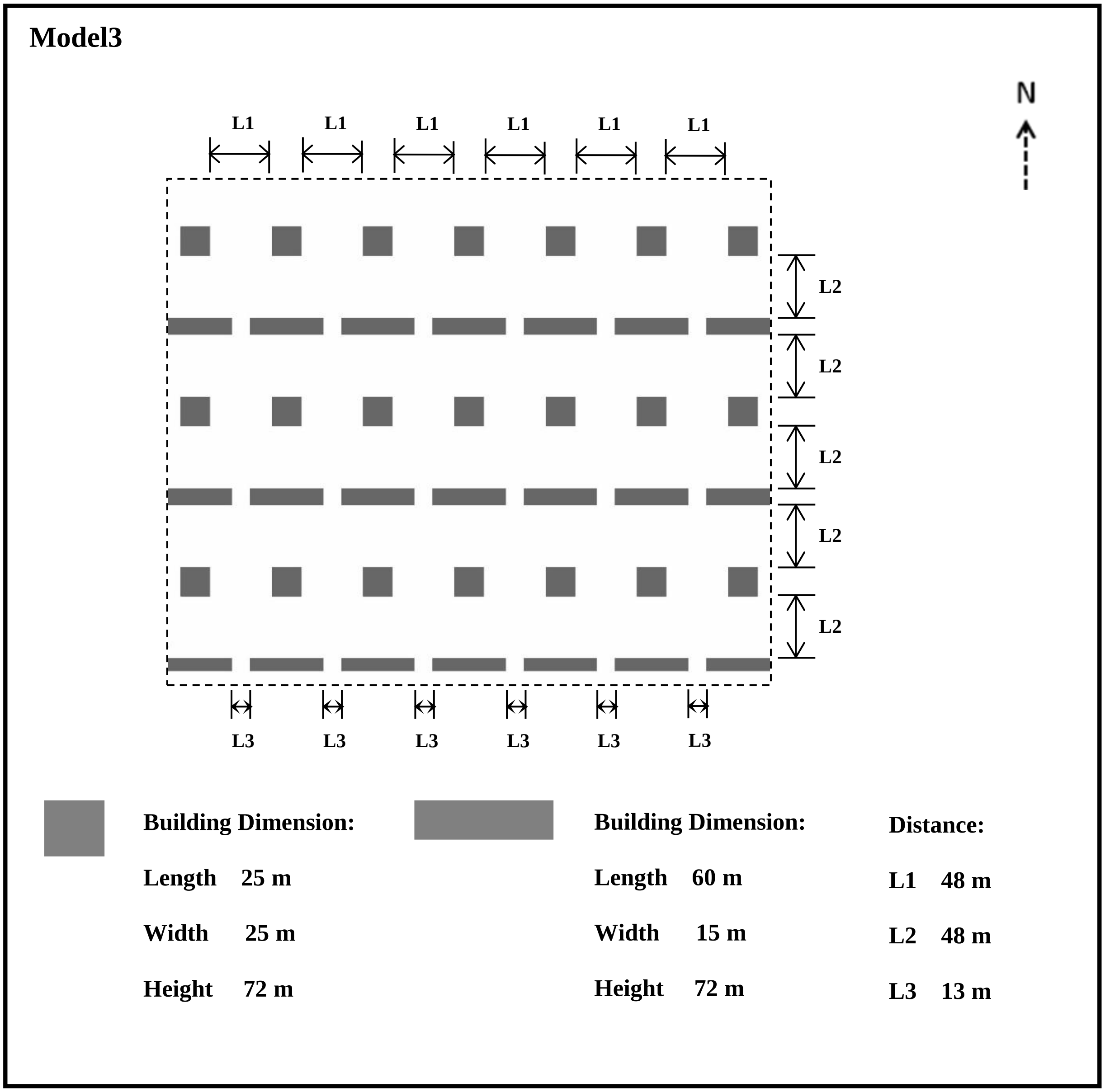

Figure 4. *Layout and dimension of the Model3.*

2.3 Dynamic daylighting simulations using CBDM

CBDM (climate-based daylight modelling), an innovative daylighting simulation technique, has been developed more than ten years to predict daylight levels in a dynamic approach [27]. According to the daylighting standard in UK [15], CBDM is described as 'the prediction of various radiant or luminous quantities (e.g. irradiance, illuminance, radiance and luminance) using sun and sky conditions that are derived from standard meteorological datasets'. The absolute illuminance predicted by CBDM are dependent on 'the locations (i.e. geographically-specific climate data is used), the building orientation (i.e. the illumination effect of the sun and non-overcast sky conditions are included), as well as the building's composition and configuration' [16]. In practice this method delivers the predictions of time-varying daylight illuminance in an annual profile, depending on sun and sky parameters derived from the weather data such as the global, direct and diffuse solar radiation [27]. Using CBDM a daylight analysis under the prevailing real weather conditions over an entire year will be achieved instead of a simple static overcast sky. Currently, several dynamic climate-based metrics supporting CBDM simulations have been well established to evaluate daylighting levels within indoor spaces of single buildings [33, 34].

Daysim/Radiance [35], a daylight simulation package based on CBDM, was adopted in this study for the calculation of vertical global daylight illuminance. Using the weather data for Harbin, an annual profile of vertical daylight illuminance was achieved by Daysim/Radiance simulations for 6am ~ 6pm and a calculation step of one hour. Each position therefore has 4745 illuminances calculated. In a reference book for Radiance simulation [17], five typical ambient parameters are needed to be considered for the accuracy of the daylighting calculations in an architectural space as follows: 'AD (ambient divisions) - indirect illuminance calculation; AS (ambient super-samples) – will be applied only to the ambient divisions which show a significant change; AB (ambient bounces) - the maximum number of diffuse bounces computed by the indirect calculation; AR (ambient resolutions) - determining the maximum density of ambient values used in interpolation; AA (ambient accuracy) - approximately equals the error from indirect illuminance interpolation'. The ambient settings for Daysim/Radiance simulations in this article were: AD (ambient divisions): 2048, AS (ambient super-samples): 256, AB (ambient bounces): 5, AR (ambient resolutions): 128, AA (ambient accuracy): 0.1. These settings were used to achieve a proper simulation accuracy through the convergence test mentioned in the reference [17]. The building surface and ground in each urban model were set with a reflectance of 0.4 and 0.2 respectively.

The statistical models to analyze simulated data of hourly global daylight illuminances are: monthly average hourly values at typical times, yearly average values and external useful daylight illuminance (EUDI). In terms of an important reference book of solar radiation and daylight models [36], the monthly average hourly method is generally used to display variations of solar irradiance and illuminance at different times. A typical application of this model can be found in one research article concerning mapping daylight illuminance [37]. For a specific time, in this study, this value was calculated by the equation: $\frac{\sum_{i=1}^{n} VI}{n}$, where i is the number of the day in a specific month; n is the total days of the month; VI is the illuminance at the time of the day. Three typical times of 9am, 12pm and 3pm were chosen to express the daylight availability in the morning, at noon and in the afternoon respectively (section 3.1). The yearly average vertical daylight illuminance was used to present an annual overview of daylight availability between 6am-6pm (section 3.2), which is the average of 4745 hourly illuminance values in a year. In order to display the frequency of daylight illuminance, furthermore, a new metric of external useful daylight illuminance (EUDI) was proposed in this study, which follows the fundamentals of an existing indoor dynamic daylight metric UDI [33]. Used for assessing daylight illuminance based on CBDM simulations, UDI is described as 'the annual occurrence of illuminances across the work plane that are within a range considered 'useful' by occupants' [38]. There are four illuminance (E) ranges in the UDI system [38]: 1) E≤100lx; 2) 100lx<E≤300lx; 3) 300lx<E≤ 3000lx; 4) E>3000lx. On basis of a survey of occupant preferences and behavior in daylit spaces, daylight illuminance between 100 and 300lx can be regarded as 'effective either as the sole source of illumination or in conjunction with artificial lighting'; daylight illuminance within the range 300lx to 3000lx is 'perceived either as desirable or at least tolerable' [33, 38]. The UDI achieved is defined as the annual occurrence of daylight illuminances in the range 100lx to 3000lx. This can be interpreted as: a 'good' daylight condition is the high occurrence of the UDI (100lx<E≤300lx); the UDI (300lx<E≤ 3000lx) means a significant part of the occurrence of useful daylight [38]. In addition, the UDI (E>3000lx) indicates the propensity for visual discomfort and/or excessive solar gain [38]. One study [18] mentioned a linear relationship of daylight illuminances between external centre window surface and indoor working plane: Mean Daylight Illuminance (at working plane) / Daylight Illuminance (at external window centre) = k, which has also been suggested in a previous study [14]. In order to clarify the relationship between indoor horizontal illuminance and external vertical illuminance for this article, a pre-study using simulations has been implemented as given in the Appendix. Based on three typical room models applied in the square and rectangular buildings in the urban layouts (Fig. 2-4) and Harbin weather data, k value has been found as 1/7 through the regression analysis (Appendix). Therefore, a new metric of

EUDI (external useful daylight illuminance) can be proposed, whose four ranges to categorize the external vertical daylight illuminance (E_v) at facade are derived using '7×UDI ranges' as follows: 1) $E_v \leq 0.7$klx; 2) 0.7klx$<E_v \leq$2.1klx; 3) 2.1klx$<E_v \leq$ 21klx; 4) $E_v>$21klx. The achieved EUDI is the annual occurrence of external vertical daylight illuminance within the range 0.7klx to 21klx. A higher EUDI (0.7klx to 21klx) indicates a 'good' outdoor vertical illuminance that would result in a proper indoor illuminance across the working plane. The EUDI (2.1klx to 21klx) will display an 'excellent' external daylighting conditions. If the EUDI (>21klx) has a higher value, the external façade surfaces will receive excessive solar gain & daylight illuminance. This can mean a higher risk to get visual discomfort and overheating problems in the indoor spaces. A shading design will be necessarily considered at the following stage of building design. The applications of EUDI in this study are discussed in section 3.3.

3. Results

This section presents variations of vertical daylight illuminance on external facades in terms of typical times, yearly average values and EUDI. The buildings in various urban models were named as follows: Model1-s (square building in Model1), Model2-r (rectangular building in Model2), Model3-s (square building in Model3), and Model3-r (rectangular building in Model3). Each building model is located in the middle of the urban layout.

3.1 Vertical daylight illuminance: typical times

This part shows the varying trend of monthly average hourly vertical illuminance at three floors of building facades in three urban models studied, including 9am, 12pm, and 3pm. In each figure, the daylight illuminances at the same positions without obstructions have also been given as a reference (the red line is for unobstructed model).

3.1.1 South façade

Fig. 5-7 gives the illuminances at three various floors of south facades. At top floors, generally, peaks of daylight illuminances occur in spring (March) and autumn (October), while valleys are found in July (summer) and January (winter); vertical daylight illuminances on the top floors are largely invariant to which urban model is used. For the three times, interestingly, daylight illuminances of July are approximately equal to those of January. In summer (from May to August), urban models with obstructions just achieve a slightly higher daylight illuminance than the unobstructed models (red line).

For middle floors, unsurprisingly, a more complicated variation of daylight illuminance is found. At 9am, 12pm and 3pm, the unobstructed condition brings in higher daylight illuminances than three urban models across the year (red line), especially from October to March (winter and autumn). July and January can still see the valley of varying curves, while daylight illuminances at 9am and 3pm in January are much lower than July in all models. A similar trend is found at 12pm in most urban models except for Model1-s. The peak positions in Model1-s are still the March and October, while the maxima of Model2-r, Model3-s and Model3-r are moving toward April and September. Middle floors of Model1-s and Model3-r generally receive higher incident illuminances than Model2-r and Model3-s from April to September. The period from October to March has a different variation in terms of urban layouts and times: at 9am Model3-r receives higher illuminances than Model3-s and Model2-r; at 12pm Model3-r and Model3-s have lower illuminance than Model2-r; at 3pm no significant differences can be found at middle floors of all urban models.

For ground floors, the unobstructed condition apparently leads to much higher illuminances at all times than three urban models, except for May and June. No big differences of illuminance can be however achieved in May and June. The illuminance differences between unobstructed and urban models tend to be lower when approaching the 12pm. At 9am and 3pm, in urban models, daylight illuminances start to increase from January and peak at April or May, and then decrease toward the end of the year. Model3-r and Model1-s generally have slightly higher daylight illuminances than Model3-s and Model2-r. At 12pm, a trend similar to middle floors is found throughout the 12 months in urban models.

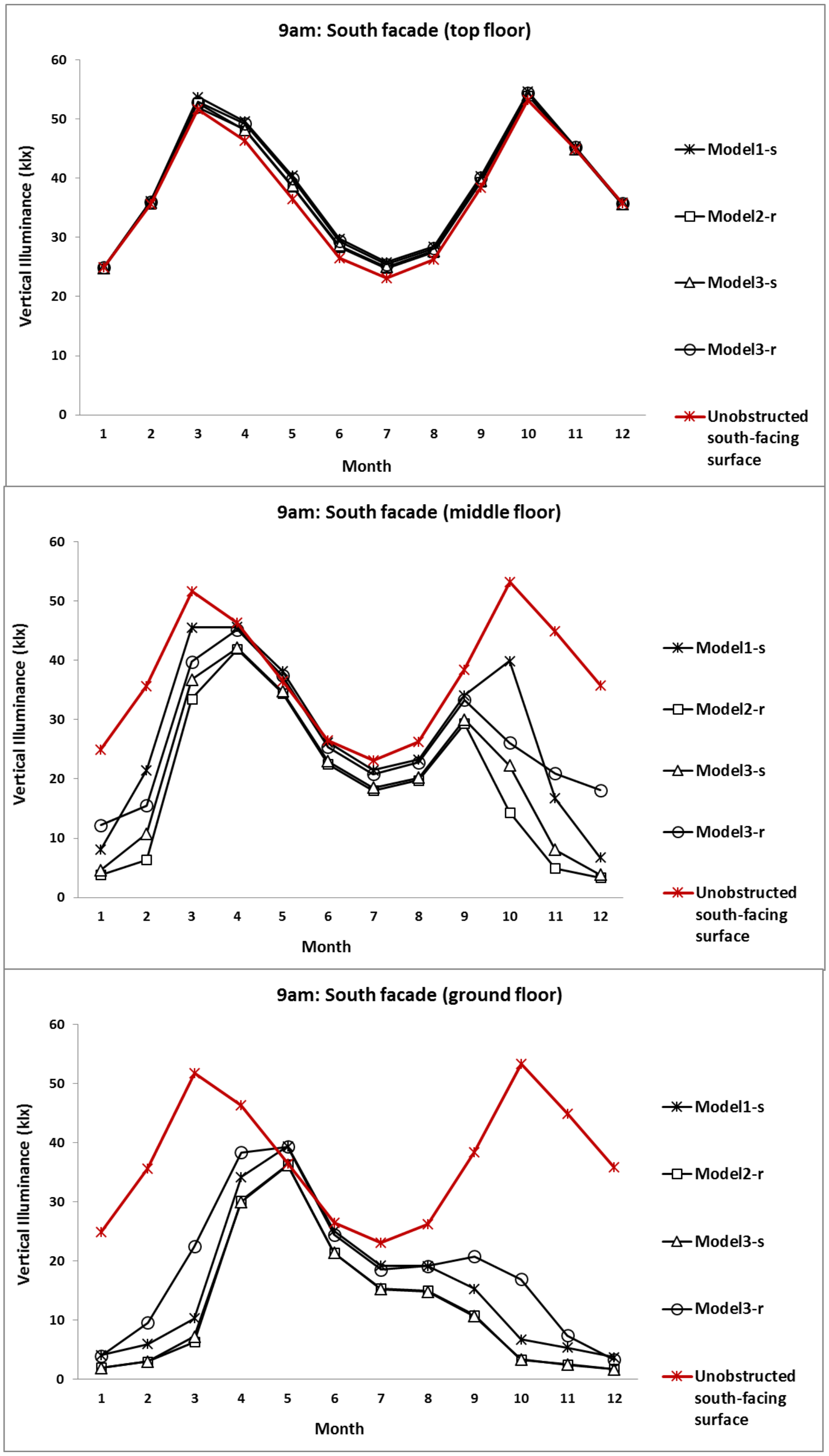

Figure 5. *Monthly average hourly vertical daylight illuminance at* ***south facades*** *of various urban models (****time: 9am****).*

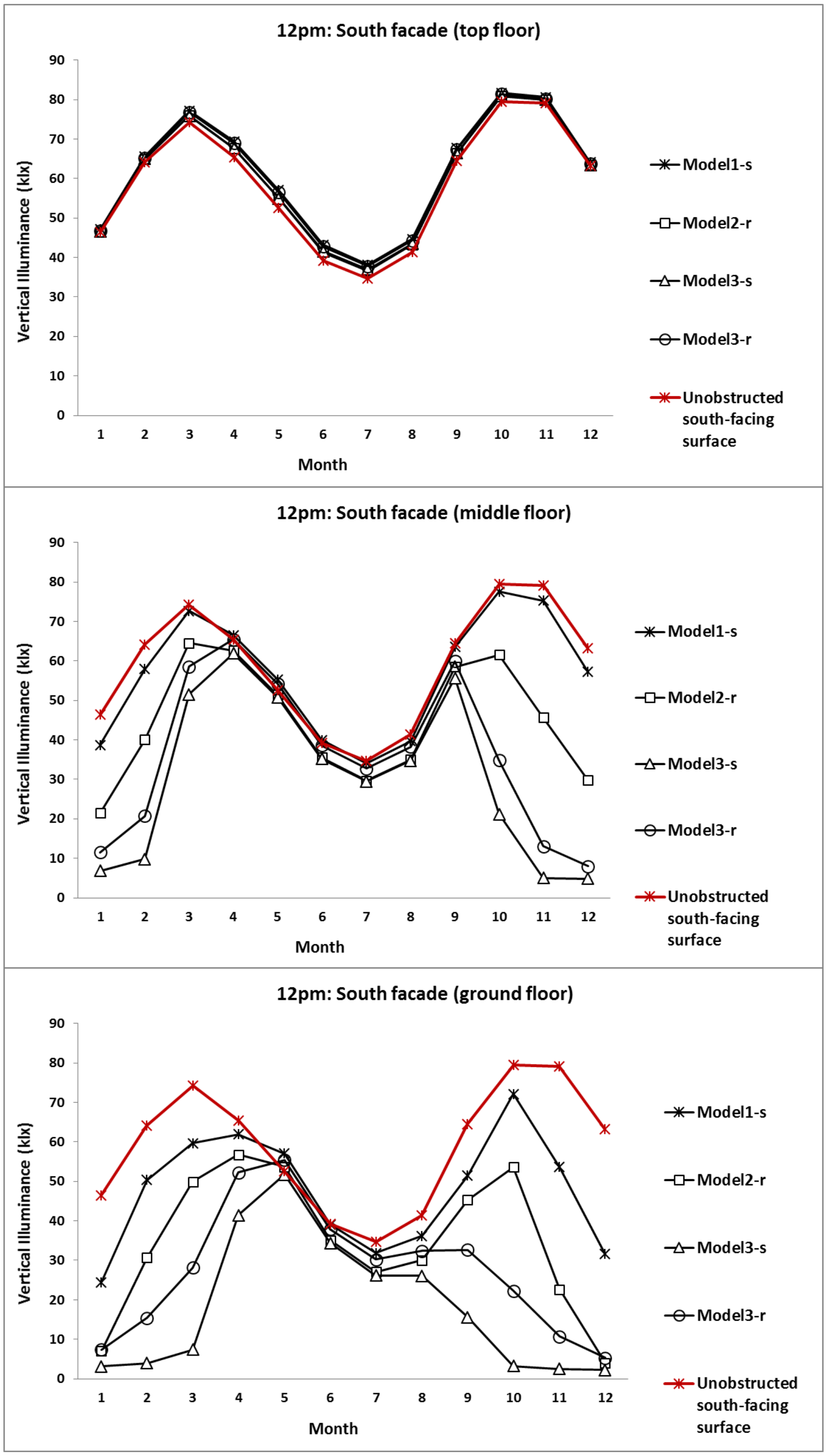

Figure 6. *Monthly average hourly vertical daylight illuminance at* ***south facades*** *of various urban models* ***(time: 12pm)****.*

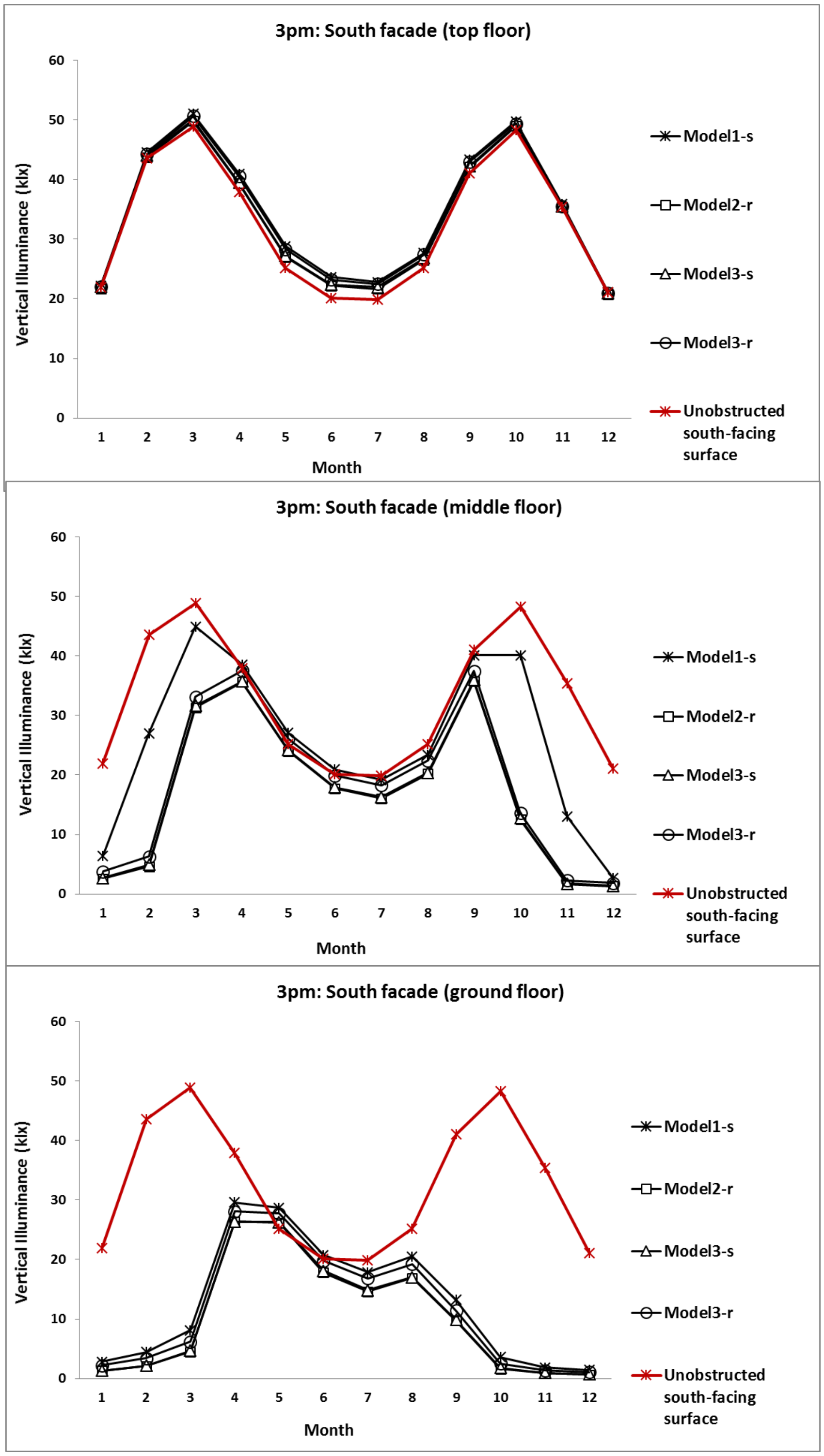

Figure 7. *Monthly average hourly vertical daylight illuminance at* ***south facades*** *of various urban models (****time: 3pm****).*

3.1.2 North façade

The variations of monthly average hourly daylight illuminance at three floors of north facades are displayed in Fig. 8 (9am), Fig.9 (12pm) and Fig.10 (3pm). For models without obstructions (red line), top floors see the lower illuminances at three times than those of three urban models. The same trend can be found at 12pm and the middle floor. At 9am and 3pm, unobstructed models achieve relatively lower illuminances at middle floors in spring and autumn than the urban models, whereas summer and winter have no clear differences. For ground floors of unobstructed models, summer will bring in higher illuminances than urban models at 9am and 3pm. No significant differences of illuminance between these models can be found at 12pm.

For urban models with obstructions, the general varying trend at 9am and 3pm can be summarized as follows: 1) the illuminances start to increase from January and peak in June or July (summer), and then decrease toward December; 2) no big divergence of illuminances between urban models occurs at top and middle floors; 3) for ground floors the maximum and minimum illuminances are found in Model1-s and Model2-r respectively; 4) façade positions only affect the absolute illuminances, but not the general varying trend in terms of various periods. At 12pm, however, a relatively even distribution of illuminance is found in the warm period from April to September. The winter period from December to January has lower illuminances. The model configurations can affect the illuminances at 12pm, especially for top and middle floors. In general, Model3-s has the highest illuminance, whereas the lowest value occurs in Model3-r. Model2-r and Model1-s will see a medium value in between. It seems that the obstruction could benefit the daylight availability at north facade.

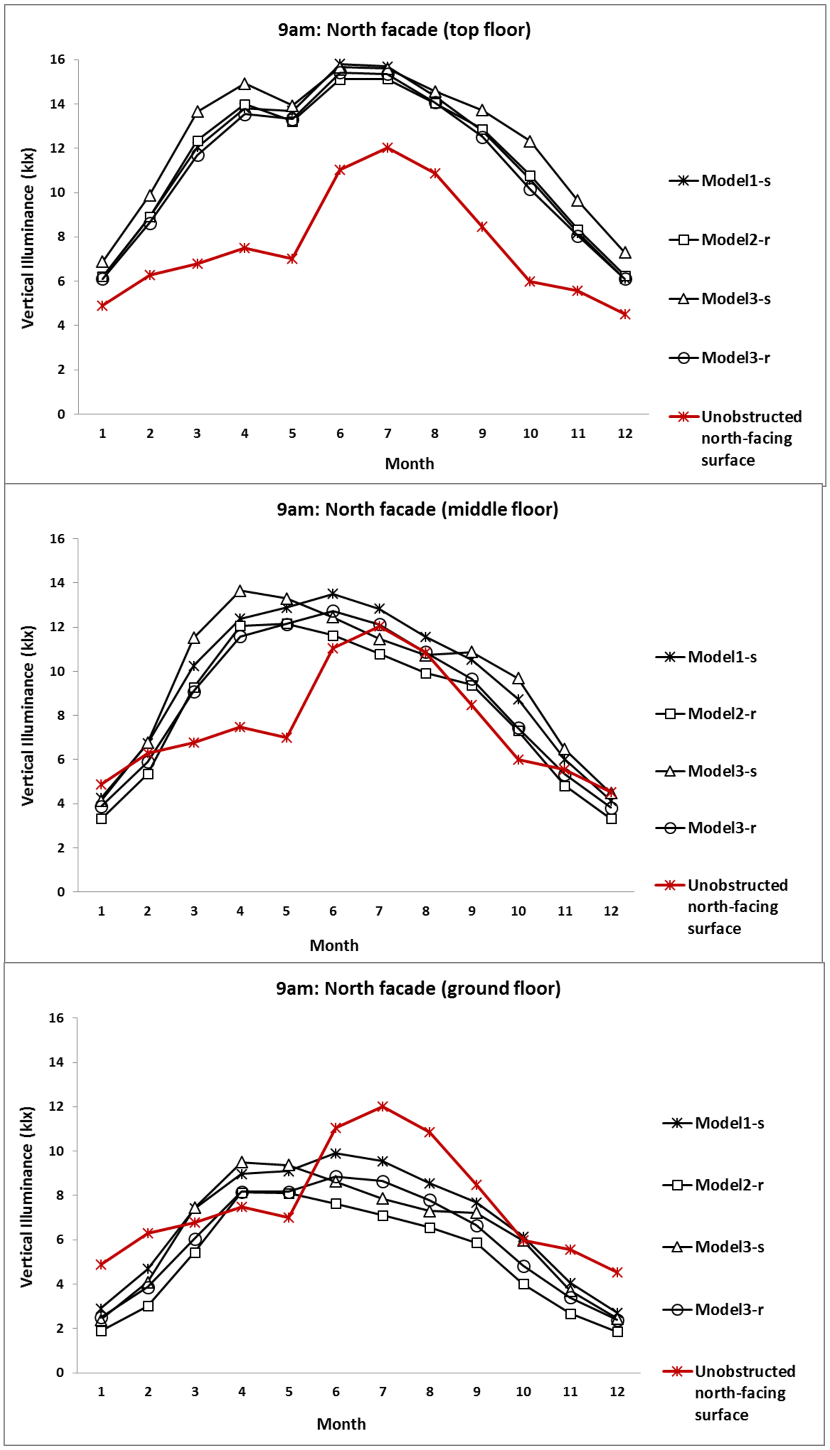

Figure 8. *Monthly average hourly vertical daylight illuminance at* ***north facades*** *of various building models (**time: 9am**).*

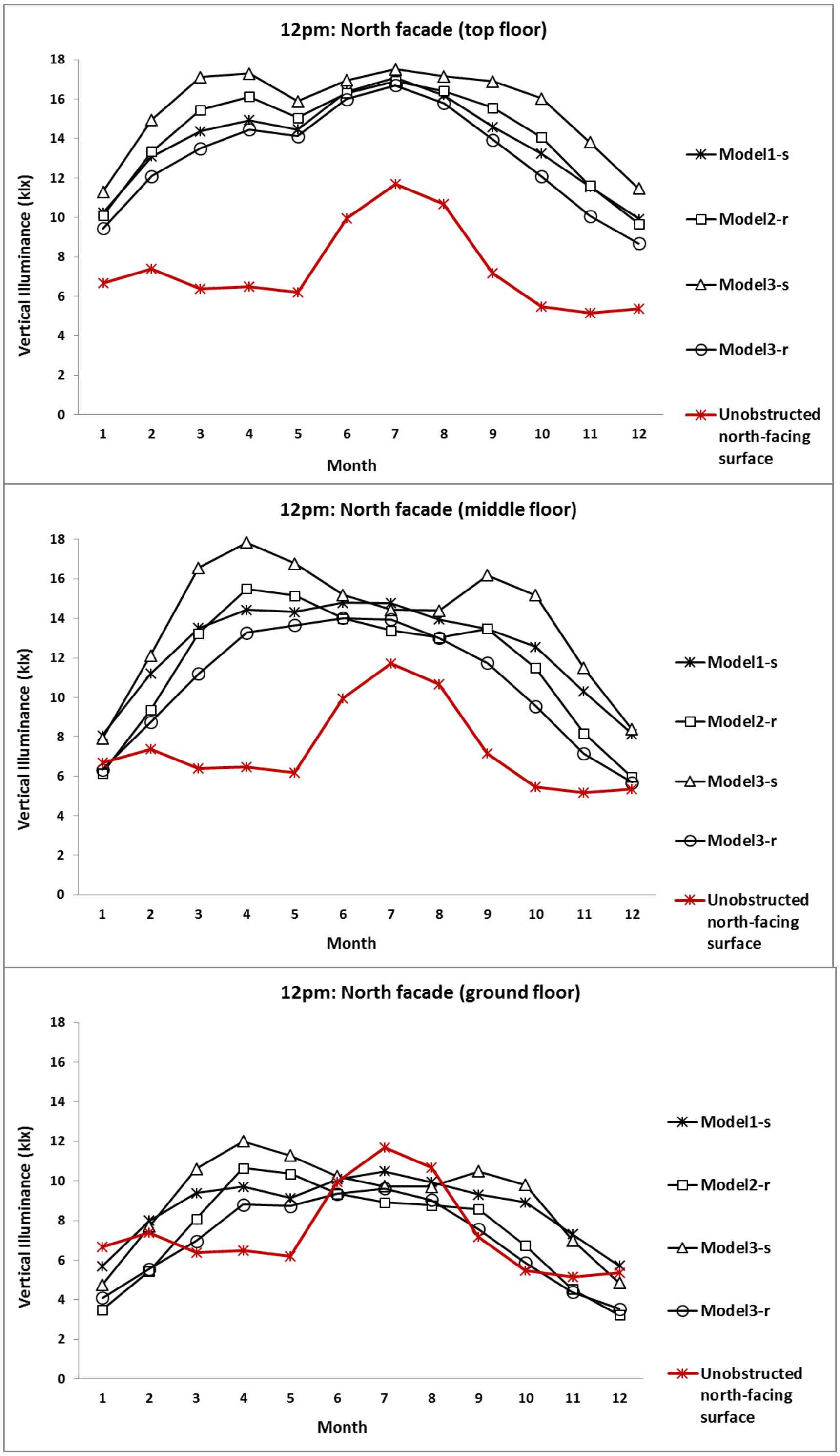

Figure 9. *Monthly average hourly vertical daylight illuminance at* ***north facades*** *of various building models (****time: 12pm****).*

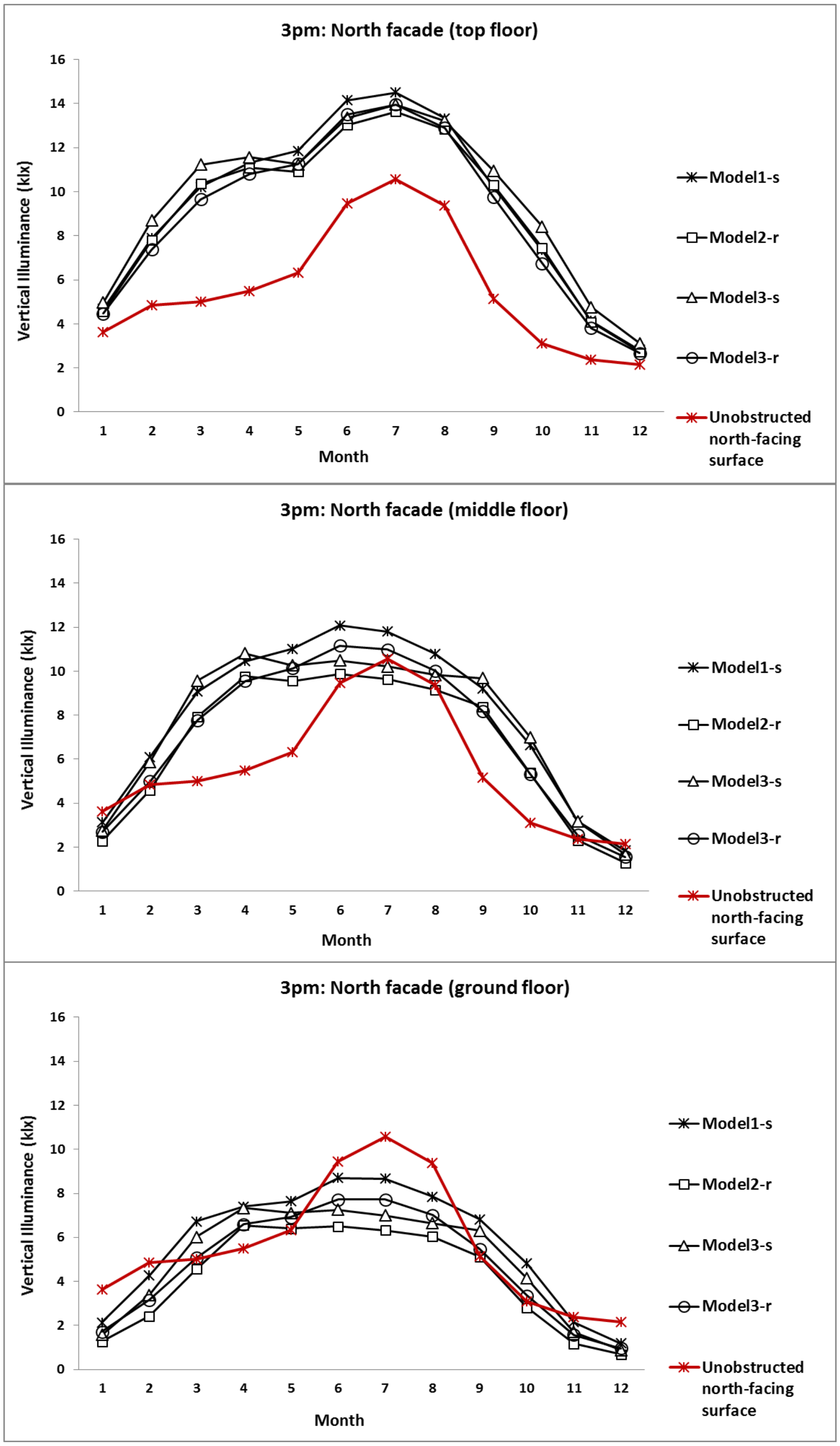

Figure 10. *Monthly average hourly vertical daylight illuminance at **north facades** of various building models (**time: 3pm**).*

3.1.3 East and West façades

Fig. 11 and 12 give the varying trend of daylight illuminance of three floors on east and west facades respectively. As mentioned in section 2.2, only the east and west facades of square building in Model1 and Model3 (Model1-s & Model3-s) have been assessed.

For models without obstructions (red line), variations of illuminance at 9am of east façade are similar to the values at 3pm of west façade. Both varying trends are close to those of the top floors in Model1-s and Model3-s. Another similar result can be found between illuminance variations at 3pm of east façade and 9am of west façade, both of which are almost identical to those of the ground floors in Model1-s and Model3-s. At 12pm and on the two facades, generally, unobstructed models have lower illuminances than the top floors of Model1-s and Model3-s; while the period from April to June sees illuminances of all urban models are larger than unobstructed models.

For three urban models, the winter (December and January) sees the minimum illuminance on all floors. For east facades, the illuminance at 9am peaks in May on all floors of square buildings, while another peak in October is found only on middle and top floors. The illuminances in May are higher than the values in October. July can see the peak illuminances at 12pm for east facade. At 3pm and on east façade, the warm period (from April to September) sees a relatively even variation on all floors; whilst January and December are the periods having the lowest illuminance. For west facades, the varying trend of illuminance at 9am can be found very similar to that of east facades at 3pm, which might be explained by a clear sky dominated weather in the morning and the symmetric sunpath. At 12pm, the daylight illuminances of all floors at west facades peak in May. At 3pm, however, the top and middle floors have two illuminance peaks of April and September. The largest daylight illuminance is found in April for west facade. The ground floors at 3pm receive the maximum daylight illuminance in May. For all floors, in addition, Model1-s will achieve relatively higher illuminances at 9am (west façade) and 3pm (east façade) than Model3-s.

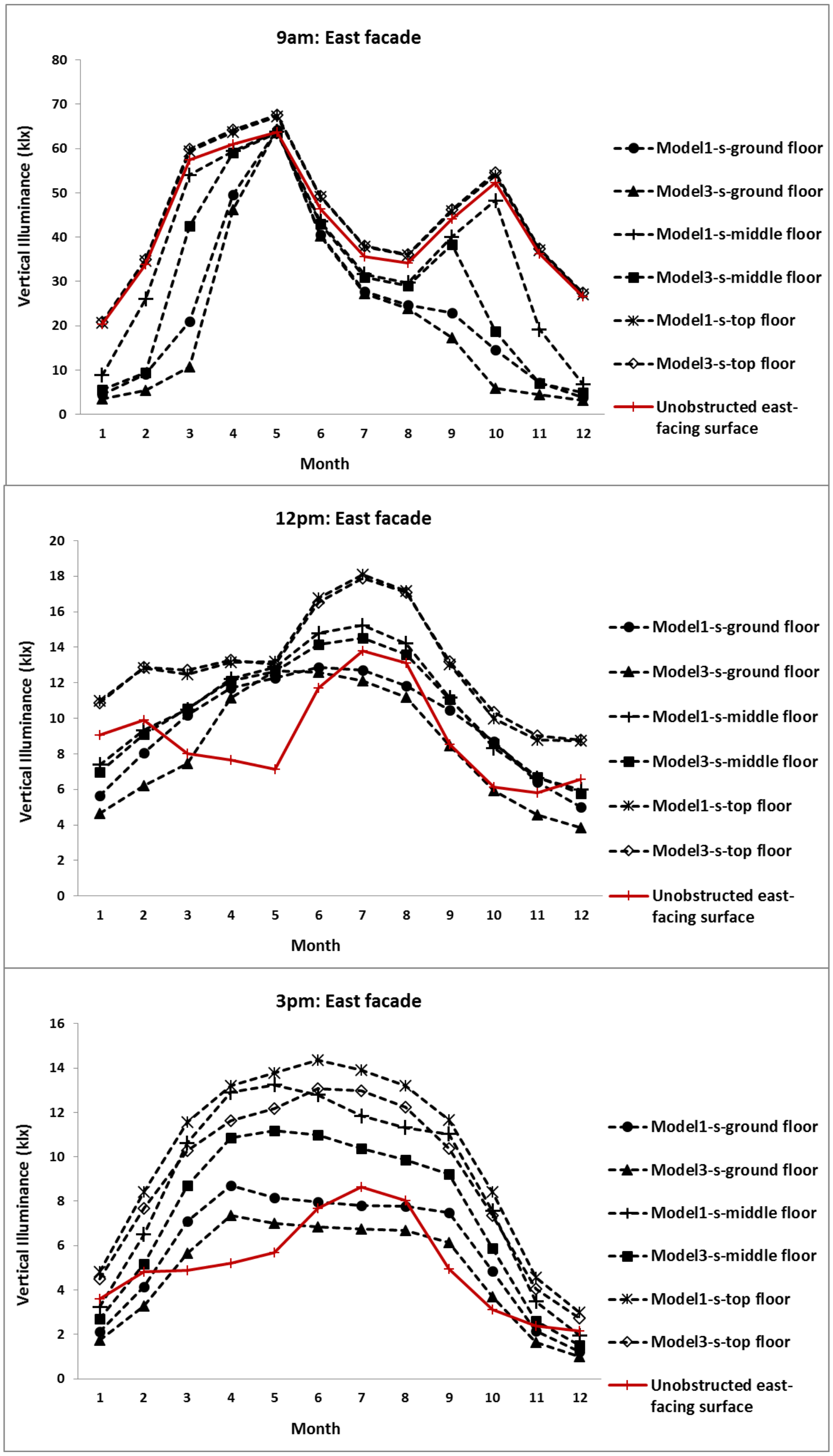

Figure 11. *Monthly average hourly vertical daylight illuminance at* ***east facades*** *of various building models (****time: 9am, 12pm, 3pm****).*

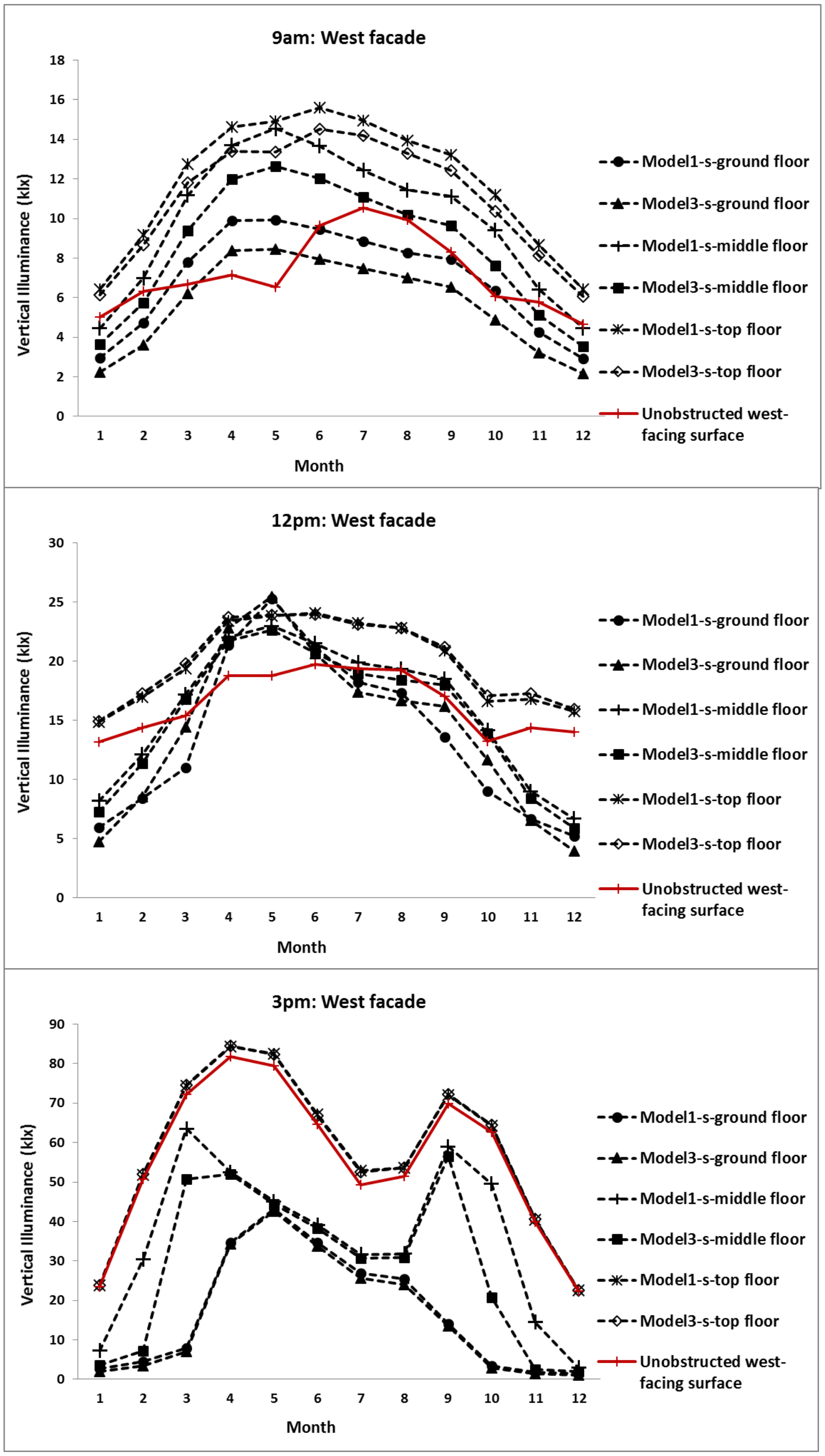

Figure 12. *Monthly average hourly vertical daylight illuminance at* ***west facades*** *of various building models (****time: 9am, 12pm, 3pm****).*

3.2 Vertical daylight illuminance: yearly average values

This section displays the yearly average vertical daylight illuminance on various facades of three urban models and unobstructed models (daily time: 6am - 6pm).

3.2.1 Model1

Fig. 13 includes comparisons of illuminance between Model1 and the unobstructed model. Generally, top floors on four facades of Model1 have higher illuminances than the unobstructed model. The largest difference of illuminance occurs at the top floor of north façade: an increase of illuminance by 55% for Model1. On south, east and west facades, the illuminances of unobstructed model are larger than the values achieved at both middle and ground floors of Model1. However, the middle floor on north façade sees slightly higher illuminances than the unobstructed north-facing surface. For Model1, daylight illuminances on south facade are much higher than other facades. The overall yearly illuminance at north façade is just 31% of the value on south façade, while the ratios for east and west facades are 58% and 66% respectively. In Model1, west façade receives relatively bigger daylight illuminance than east façade (overall 14% higher), especially at the top floor. Apparently, the daylight illuminance of Model1 is significantly sensitive to the orientation.

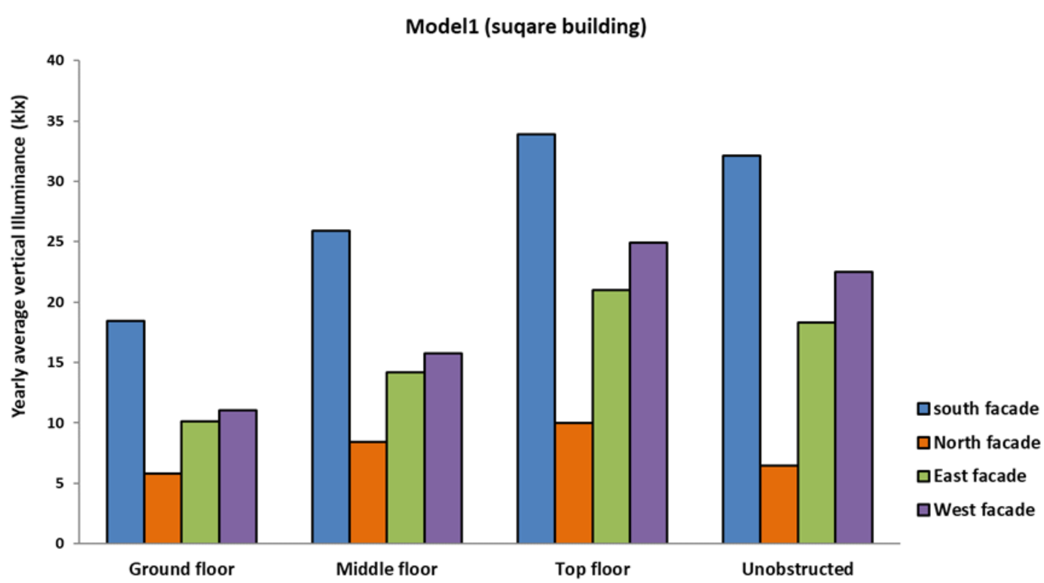

Figure 13. *Yearly average vertical daylight illuminance at various facades of Model1 (**daily time: 6am -6pm**).*

3.2.2 Model2

As shown in Fig. 14, the comparison between Model2 and unobstructed model follow the similar trends as the Model1 discussed above (section 3.2.1). Compared with the unobstructed model, the illuminance of north façade in Model2 has an increase by 54% or 16% at top or middle floor. The ground floor however receives a decrease by 27%. For south façade, Model2 sees a slightly higher illuminance at top floor than unobstructed model, but 41% and 61% reductions of illuminance at middle and ground floors. For Model2, illuminances of middle and ground floors at south façade are 57% and 38% of the values of top floor, while the ratios on north façade are 75% (middle floor) and 47% (ground floor).

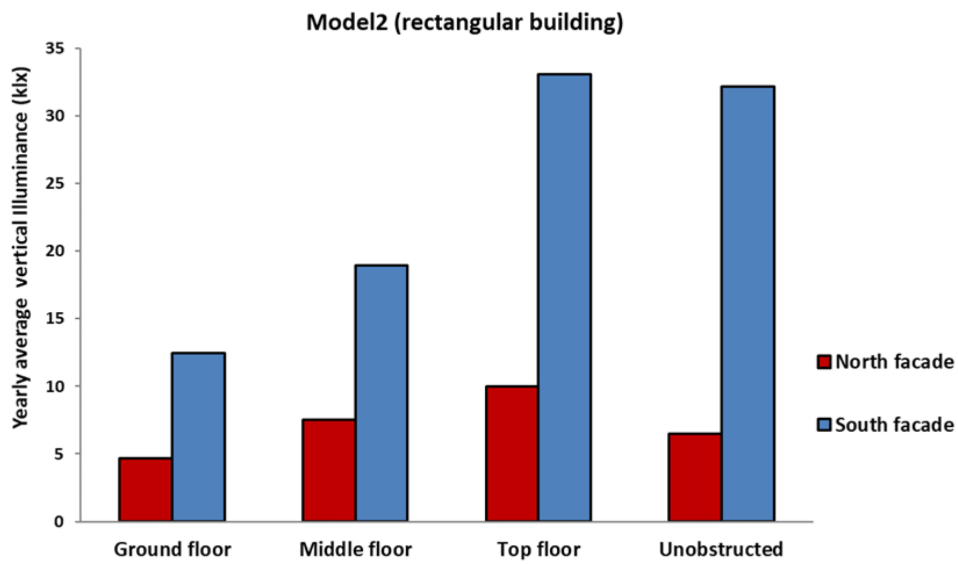

Figure 14. *Yearly average vertical daylight illuminance at various facades of Model2 (**daily time: 6am -6pm**).*

3.2.3 Model3

In Fig. 15, it seems that the differences from the unobstructed model for the square and rectangular buildings in Model3 are closed to the same buildings in Model1 & 2. For the square building in Model3, south façade receives lower illuminances than Model1, especially for middle and ground floors (decreased by 27% and 43% respectively); while no big difference at north façade can be found between the two models. However, east and west façades of square building in Model3 have slightly lower illuminances than the two facades of Model1. For the rectangular building, Model3 sees the higher illuminances than Model2, at ground floor of the north façade (an increase by 12%), and the middle and ground floors of south façade (an increase by 25% and 51% respectively).

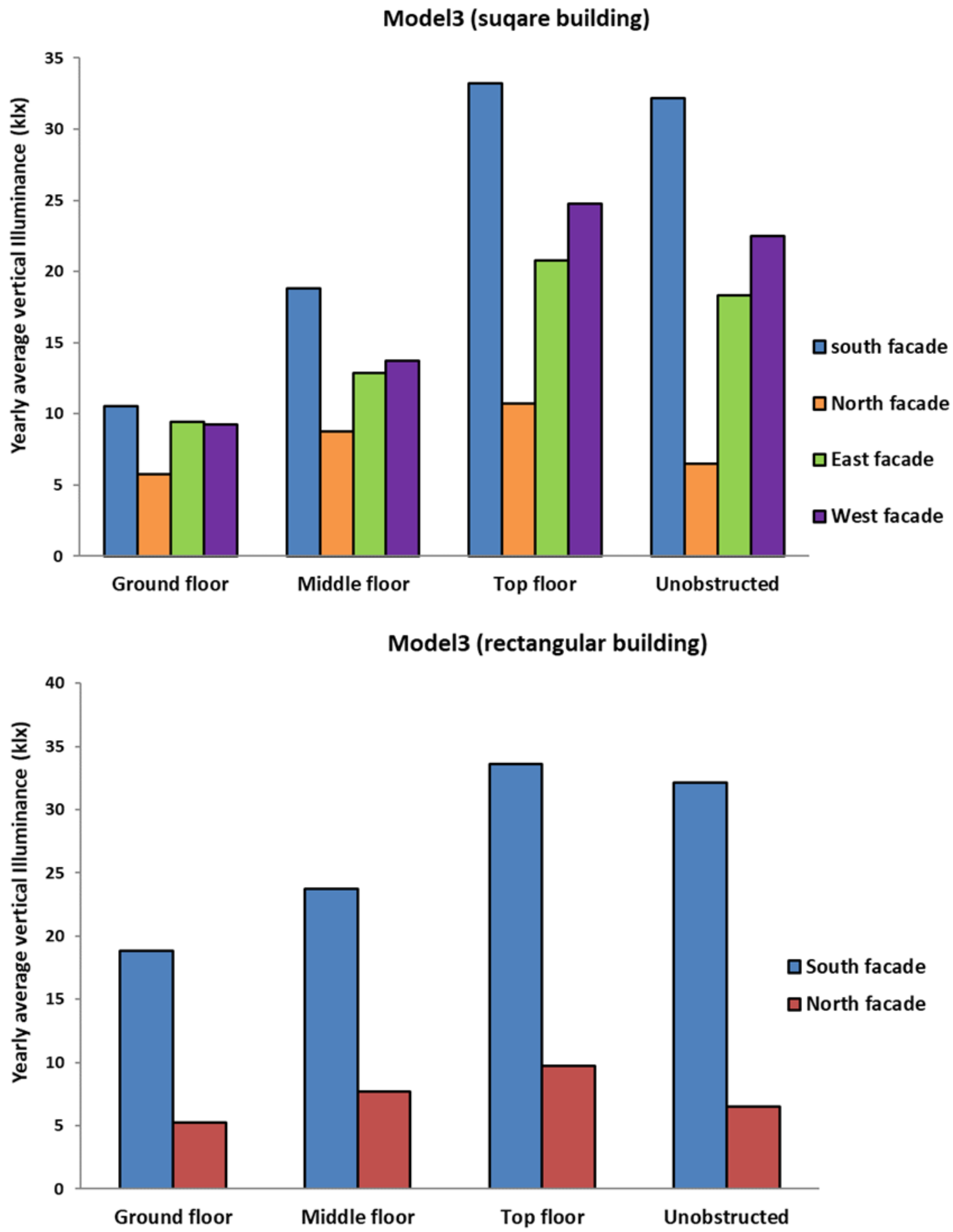

Figure 15. *Yearly average vertical daylight illuminance at various facades of Model3 (**daily time: 6am -6pm**).*

3.3 Vertical daylight illuminance: EUDI

3.3.1 Model1

The external useful daylight illuminance (EUDI) on various facades in Model1 has been given in Table 2. It has been clearly found that most of positions can achieve the EUDI (>2.1klx) of around 80%. The lowest values of EUDI occur in the range of 0.7~2.1klx. Most positions on all facades have the EUDI (2.1klx~21klx) of around 50% or more, except for the ground and middle floors of south facade. The values of EUDI (2.1klx~21klx) at the middle and ground floors are still 38.2% and 27.5% respectively. This apparently demonstrates a higher possibility to properly utilize daylighting in buildings of Model1. However, the higher EUDI (>21klx) values occur at all floors of south façade and the top floor of east and west façade (≥30%), which might indicate a higher risk of getting glare and overheating problems in the interior spaces.

3.3.2 Model2

For Model2 (Table 3), the EUDI (0.7klx~21klx) > 50% can be found at all floors on north façade and the ground and middle floors on south façade. The top floor on south façade can just achieve the EUDI (0.7klx~21klx) of around 29%. However, the middle and top floors at south façade see the EUDI (>21klx) >30%. North façade nearly has no EUDI value in the range (>21klx). Thus, it seems that the Model2 has little possibility to get glare and overheating problems for the spaces with windows at north façade.

3.3.3 Model3

For the square building (Table 4), the EUDI (0.7klx~21klx) values on four facades are larger than 50%, except for the ground floor on south facade. A EUDI (>21klx) >30% can be found at middle and ground floors of south façade and top floors of east and west facades. A higher possibility of getting glare or overheating would thus occur at these positions. Additionally, in Table 5, the rectangular building has the EUDI (>2.1klx) > 70% at all floors of both north and south facades. South façade sees the EUDI (>2.1klx) ≥30% at all floors, whilst there is nearly no EUDI (>2.1klx) found on north façade. This could support that there is a very low possibility to get thermal and visual discomfort problems in the north facing rooms.

In comparison to Model1, the square building in Model3 can achieve the higher EUDI (2.1klx~21klx) and the lower EUDI (>21klx) on south façade, while no significant differences between the values are found on other facades. This could indicate the higher possibility to get proper daylighting conditions. On the contrary, the rectangular building in Model3 would receive a higher EUDI (>21klx) on south façade when compared with Model2. Model3 would probably deliver a higher risk to get glare or overheating for the south façade of rectangular building.

4. Discussion

Based on simulated illuminances using a dynamic approach, this study shows that the daylighting potential in buildings receives the combined effect of climate condition, urban layouts and various façade positions. Fig. 16 (1-6) gives various obstructions in three urban models using the hemispheric views (viewing from the middle façade). Obstruction levels can be found as: 4) > 3) > 6) > 1 (south/north); 5) > 2) (east/west).

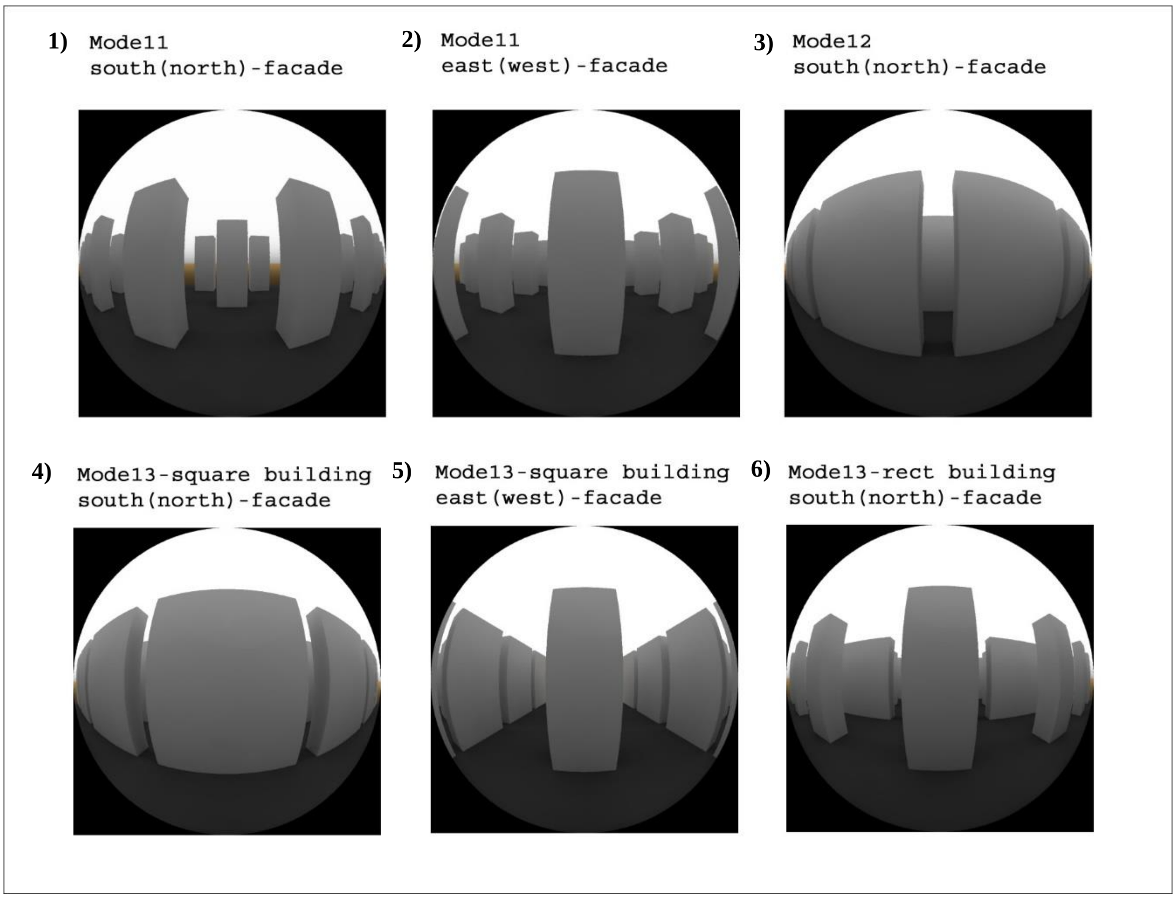

Figure 16. *Hemispherical views of obstructions at middle facades of the buildings in three urban models.*

South façade (see Fig. 16 (1, 3, 4, 6)): In addition to the daylighting condition including direct sunlight and diffuse skylight (relating to times and dates), as demonstrated in Fig.1 &Table 1, illuminances on south facing surfaces are fundamentally determined by obstructions (horizontal and vertical) in urban models. At top floors only low-level obstructions can be found for each model, confirming a fact that urban layouts do not substantially impact the daylighting from sun and sky. On the other hand, such obstructions can slightly contribute to daylighting illuminances via the reflected light from adjacent buildings. Thus, variations of illuminance in urban models are generally closed to the unobstructed condition, whereas their absolute values will be slightly higher. At middle floors, sensitivities to the obstruction of daylight illuminance tend to significantly increase. In cold and cool seasons (from September to April), sunlight and skylight with lower altitudes would be easily blocked by the medium-level obstruction. The models with lower obstruction would normally receive more direct sunlight and skylight (e.g. Model1-s). However, for the models having a larger obstruction, the reflected light could be the dominant component of daylight illuminances. This would explain why a heavily obstructed model (e.g. Model2-r) has a higher daylight illuminance than other models with less obstructions (e.g. Model3-r) at noon in winter. With the sunlight arriving at a very low altitude and from the side (i.e. 9am in winter), the larger obstruction could increase the reflected light (illuminances of Model3-r > illuminances of Model1-s). On the other hand, no clear differences can be found between models with higher obstructions at 3pm in winter (Model2-r, Model3-s, and Model3-r). This could be supported by the fact that only skylight was available in this period. In the warm period (from May to August), the higher-altitude sunlight would reduce the impact of obstructions on illuminances. The differences between models therefore tend to be lower. At ground floors, it is very difficult to receive large amounts of direct sunlight and skylight due to the high-level obstruction. The reflected light from adjacent buildings and the ground would be the main source. With the availability of reflected sunlight (at 9am and 12pm), the obstructions performance well on delivering light. For the condition of skylight (at 3pm), nevertheless, the diffused skylight would not bring in big differences of illuminance.

North façade (see Fig. 16 (1, 3, 4, 6)): Different from south facades, north façades are principally lit by the diffused skylight. Also, it is clear that obstructions can significantly increase the daylight levels through the reflection, especially at top and middle floors. These could support that illuminances of urban models are generally higher than the unobstructed surface. The north sky in winter gives rise to very lower daylight illuminances. In summer (from June to August), however, north façade could receive more light reflected from the opposite south facing surfaces. At 12pm, the higher obstruction would deliver more reflected light to north façade. As a result, Model3-s can achieves higher illuminances than others. At 9am and 3pm, the differences of illuminance between various urban models become lower since opposite buildings and the ground could receive less incident daylight.

East/west façade (see Fig. 16 (2, 5)): First, surfaces facing west can receive higher daylight illuminance (yearly average) than surfaces facing east according to climate conditions. For positions having direct sunlight and skylight (top and middle floors), thus, west façade sees higher daylight illuminances than east façade. Second, Model1-s has a lower obstruction than Model3-s, indicating that the two facades of Model1-s would receive a slightly higher illuminance. This can be particularly found at times when no direct sunlight was available, e.g. 9am for west façade, and 3pm for east façade. At 12pm, normally, there would be no clear differences of illuminance found in the two models since the sunlight can just arrive from the side.

The discussions above focus on the variations of daylight illuminance. More importantly, excessive level of daylight can give rise to problems such as overheating and glare in buildings. As shown in section 3.3, the values of EUDI (>21klx) can be used to justify the potential of shading application on the ground of overheating protection and keeping occupants' visual comfort.

5. Implications for Design and Planning

Some design strategies/guidelines that can be drawn from this study are presented as follows.

First, urban layouts do substantially impact the overall daylighting potential across south façade in buildings, especially at middle and low façade positions; interestingly, the overall daylighting potential of north, east and west facades in buildings will have no significant links to the urban layouts. According to the overall daylight availability, the square building in Model1 and the rectangular building in Model3 will have the larger potential for daylight utilization; while the relatively lower potential can be found in the square building in Model3 and the rectangular building in Model2.

Second, it can be found all façade positions (along centre line) in the three urban models will have a proper daylighting potential due to the fact that with over 80% working time the daylight illuminance is above 0.7klx. South and north facades have the largest and lowest daylighting potential respectively, while the medium potential is found on east and west facades. Compared with east façade, however, west façade would get a relatively higher potential for daylighting use. It could be necessary to pay more attention to the shading design in these buildings in order to avoid overheating and glare, in particular at south, east and west facades.

Third, seasonal factors could also be considered in the design process and the utilization of daylighting in these urban models. At high and middle positions of south facades, spring and autumn have much larger daylighting potential in comparison to other seasons. These periods will however require particularly careful consideration of shading applications. The low south façade can receive a relatively larger daylighting availability in spring, but has a comparatively low potential for daylighting utilization in other periods. At north façades, the largest and lowest potential for daylighting is found in summer and winter respectively; while there is no need to consider the shading application across the year due to the fact that nearly no higher illuminances (>21klx) can be found in all models. For east and west facades in the square building of Model1-s or Model3-s, the warm period could generally deliver a larger daylighting potential than winter.

According to the analysis using the frequency (EUDI), the urban layout of Model3 (Fig. 4) could be the optimal choice for a residential area in cities located at north-east China, especially when taking into account a proper balance of daylighting potential and indoor human comfort (e.g. visual and thermal environment).

Even though this study was limited to the fundamental urban layouts and specific location and climates, we believe that these design strategies could be applied to the area dominated by similar climate conditions, e.g. north Asia.

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Tables

Table 1. Monthly average global horizontal illuminance at Harbin (Latitude: 47.75N, Longitude: 126.63E), time: 6am – 6pm.

Average Global Horizontal Illuminance (klx)											
Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
11.95	21.51	38.15	53.45	65.82	56.83	45.49	39.46	38.99	29.80	18.11	12.08

Table 2. The external useful daylight illuminance (EUDI) at various façade positions in Model1 (g: ground floor; m: middle floor; t: top floor).

Model1 - EUDI (%)												
Illuminance Range	**South facade**			**North facade**			**East facade**			**West facade**		
	g	**m**	**t**	**g**	**m**	**t**	**g**	**m**	**t**	**g**	**m**	**t**
≤0.7klx	16.6	16.1	15.7	16.8	16.1	15.8	16.7	16.1	15.7	16.7	16.0	15.6
0.7-2.1klx	7.2	2.5	1.0	8.5	3.9	1.2	6.7	2.7	1.1	7.7	3.5	1.0
2.1-21klx	45.5	38.2	27.5	74.7	79.7	81.4	65.4	63.4	53.3	60.8	59.1	49.4
>21klx	30.7	43.1	55.9	0.0	0.3	1.6	11.1	17.8	29.8	14.8	21.4	33.9

Table 3. The external useful daylight illuminance (EUDI) at various façade positions in Model2 (g: ground floor; m: middle floor; t: top floor).

Model2 - EUDI (%)						
Illuminance Range	**South facade**			**North facade**		
	g	**m**	**t**	**g**	**m**	**t**
≤0.7klx	18.4	16.6	15.7	18.8	16.7	15.8
0.7-2.1klx	14.7	6.0	1.0	13.0	5.5	1.5
2.1-21klx	47.1	45.6	28.1	68.2	77.6	81.5
>21klx	19.8	31.8	55.2	0.0	0.2	1.2

Table 4. The external useful daylight illuminance (EUDI) at various façade positions in the square buildings of Model3 (g: ground floor; m: middle floor; t: top floor).

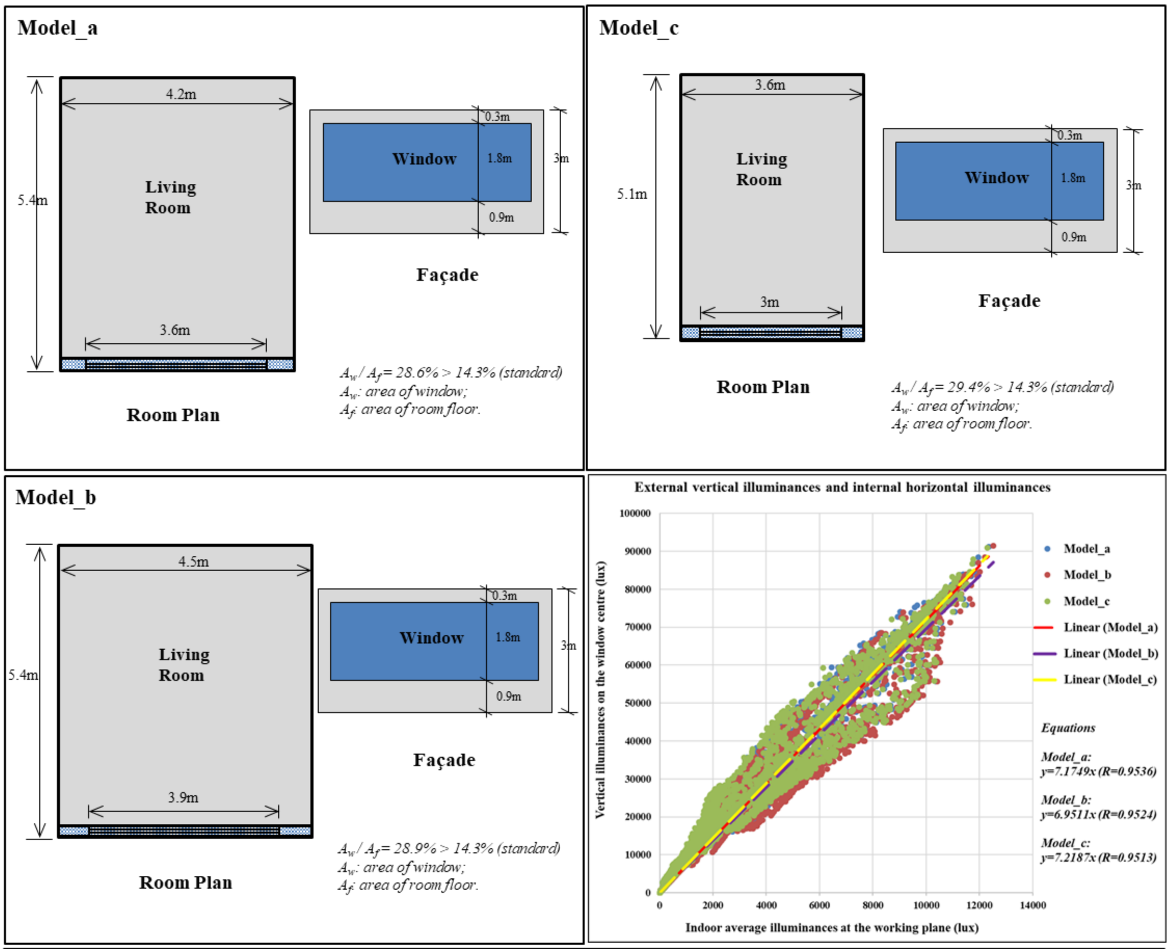
Model3 - square building - EUDI (%)												
Illuminance Range	**South facade**			**North facade**			**East facade**			**West facade**		
	g	**m**	**t**	**g**	**m**	**t**	**g**	**m**	**t**	**g**	**m**	**t**
≤0.7klx	18.1	16.4	15.7	17.7	16.5	15.8	16.8	16.2	15.7	17.4	16.2	15.6
0.7-2.1klx	14.7	5.4	1.0	9.7	4.6	1.2	7.9	3.6	1.2	11.0	4.8	1.1
2.1-21klx	50.5	47.6	28.0	72.6	78.7	81.7	64.3	63.9	53.3	59.9	60.4	49.3
>21klx	16.7	30.6	55.3	0.0	0.2	1.3	11.0	16.4	29.8	11.6	18.7	34.0

Table 5. The external useful daylight illuminance (EUDI) at various façade positions in the rectangular buildings of Model3 (g: ground floor; m: middle floor; t: top floor).

Model3 – rectangular building - EUDI (%)						
Illuminance Range	**South facade**			**North facade**		
	g	**m**	**t**	**g**	**m**	**t**
≤0.7klx	16.8	16.1	15.7	17.1	16.2	15.8
0.7-2.1klx	8.2	3.6	1.1	8.2	4.6	1.3
2.1-21klx	45.2	40.1	27.6	74.6	79.0	81.3
>21klx	29.8	40.1	55.7	0.0	0.2	1.6

Appendix:

Three typical room models were simulated using Daysim under Harbin's climate conditions to achieve the relationship between external vertical illuminance at centre window and average indoor illuminance at the working plane. (The layouts and façade configurations were defined based on the references [25, 28, 29, 31, 32].)



Note:

1. *Reflectances of room surfaces: 0.6 (Wall), 0.8 (Ceiling), 0.3 (Floor); Transmittance: 0.64 (Double-glazing Window). [25, 28].*
2. *The layouts and configurations of room and façade were typically applied in the high-rise residential buildings in Harbin city, which were defined based on the regulations and references: [25, 28, 29, 31, 32].*
3. *Simulation package: Daysim/Radiance.*

Results: the relationship of indoor average illuminances at the working plane (IAI) and external vertical illuminance at window centre (EVI)
Model_a: EVI=7.1749IAI; Model_b: EVI=6.9511IAI; Model_c: EVI=7.2187IAI;

Conclusion: indoor average illuminances at the working plane / external vertical illuminance at window centre = 1/7.