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The development of visible sky area as an alternative daylight assessment method for high-rise buildings in high-density urban environments

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This research aims to develop a new daylight assessment method for high-rise residential buildings located in high-density urban environments. The new visible sky area (VSA) method was developed based on data gathered from an extensive survey of high-rise residential building plans and layouts in Hong Kong and followed by a large number of daylight simulation experiments. The results of simulations showed a very small daylight quantity arriving at windowpane of lower floor level of high-rise residential buildings due to high-obstruction from nearby buildings and also self-obstruction. The new method would guarantee the availability of sky area seen from windowpane in order to provide a good vertical daylight factor (VDF), which has been adopted as a performance-based daylight indicator in Hong Kong. A minimum VSA of 12% and 6% for habitable rooms and kitchens, respectively, is proposed for this situation.

Keywords: daylight assessment method; high-rise buildings; high-density environments; visible sky area; vertical daylight factor

Introduction

Hong Kong context

As a vertical city, residential buildings in Hong Kong are mostly high-rise with typically 40–60 storeys, with the complexity of building envelope, and situated in high-density urban environments. This condition might have occurred because of population growth and economic expansion in the 1970s that generated great demands for housing and the limitation of buildable land. Due to land shortage, the average number of stories for apartment towers has risen from 4 to 6 stories during the post-war period of the 1950s to over 60 stories in the 2000s. As the consequences of this built form, living spaces at the lower parts of high-rise residential buildings are often disadvantaged of daylight, natural ventilation, and views.

Most of residential building designs consist of an 8-unit plan, which is about 61% of 147 private residential buildings completed in 2000 (Lau et al. 2006). This 8-unit plan made of mainly six types of plan: (a) cruciform, (b) pinwheel, (c) hybrid, (d) diamond, (e) X-shaped, and (f) Y-shaped. In addition to those, two other types exist: (g) 6-unit plan and (h) 10-unit plan (Figure 1). Developers prefer the 8-unit to maximize profit from land. To attract buyers, bedrooms were placed outwards with the best views leaving kitchen and bathroom to be inward facing. To resolve ventilation problems, a gap called a "re-entrant" was allowed between the units. The *re-entrant* is an equivalent of a light well that resulted from the grouping of windows for kitchens, toilets, and other spaces of homes in an apartment building.

Building regulation for the provision of natural light

Prescribed window regulation

In Hong Kong, the provision of natural light has been controlled by the Building (Planning) Regulations B(P)Reg. 30, 31, and 32 (HKSAR 1997). Basically, this regulation controls the minimum window glazing area and the distance between buildings. It is stipulated that the minimum window glazing area is 10% of floor area. This window is referred as a prescribed window (see Figure 2).

According to these regulations (HKSAR 1997), no prescribed window shall be deemed facing into external air unless it faces into a street which is not less than 4.5 m wide; or it faces into space uncovered and unobstructed above the area defined by the rectangular horizontal plane (RHP). The RHP required that the minimum distance between building blocks is determined by a minimum inclined angle of 71.5° and 76° above the RHP for habitable rooms and kitchen, respectively. For window facing site boundary, these angles shall be 81° and 83° for habitable rooms and kitchens, respectively. It is also stipulated that the RHP should have a minimum width of not less than 2.3 m, with area not less than 21 m^2.

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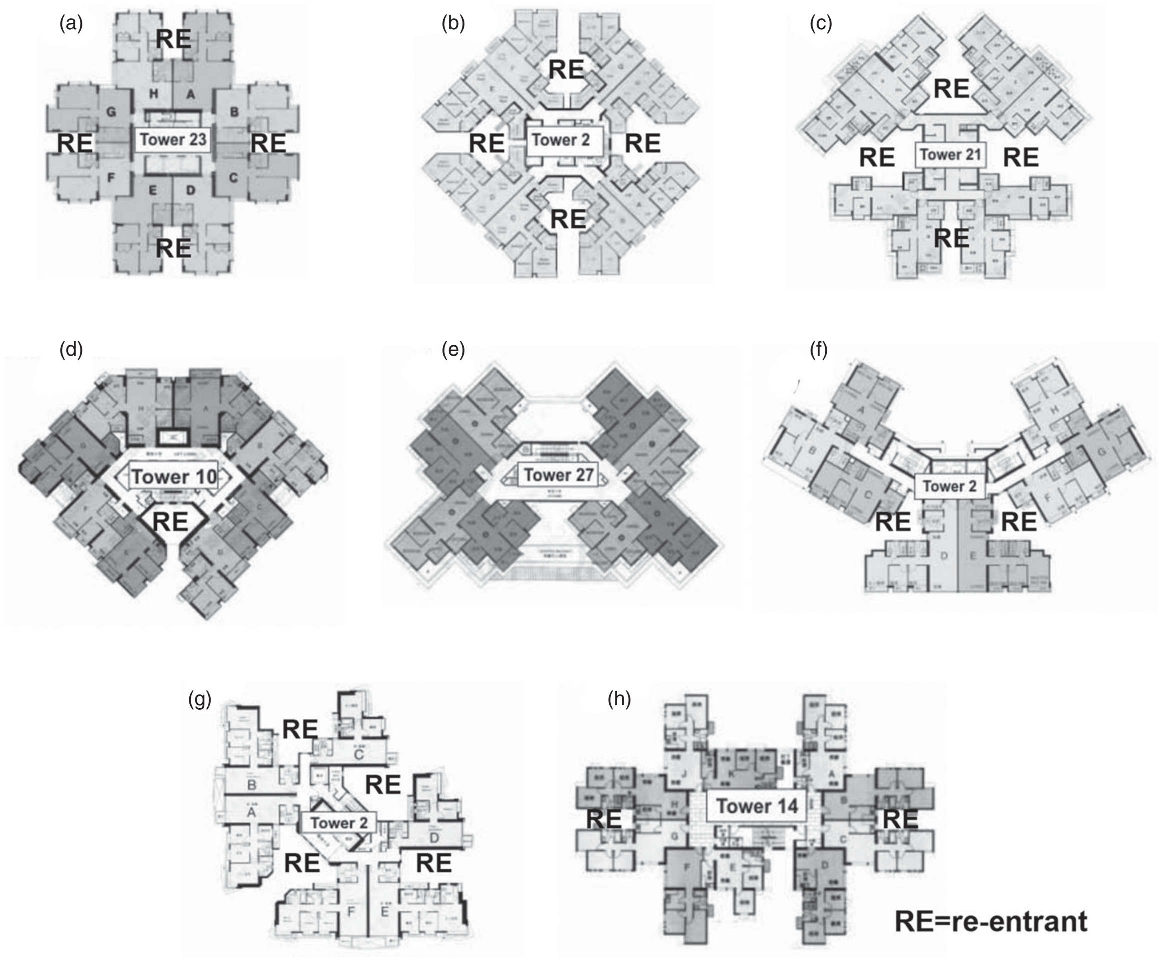


Figure 1. Typical floor plan of private housing in Hong Kong: (a) cruciform, (b) pinwheel, (c) hybrid, (d) diamond, (e) X-shaped, (f) Y-shaped, (g) 6-unit, and (h) 10-unit plan.

Performance-based VDF regulation

The existence of prescribed window regulation, however, presents some considerable problems in high-rise residential buildings. One of them is an inadequacy of daylight illuminance in building interior in some of high-rise buildings (Chung 2003; Lau et al. 2006; Ng 2001a, 2001b). In order to overcome this problem, the Buildings Department has commissioned a consultancy study to review the standards of the lighting and ventilation requirements in buildings. Based on the findings from the consultancy study, the Buildings Department issued an alternative performance-based approach for the provision of natural light and natural ventilation for habitable rooms and domestic kitchens for the purpose of Building (Planning) Regulations B(P)Reg. 30, 31, and 32 (Buildings Department 2005). This new approach has been issued in the Practice Notes for Authorized Persons (PNAP) 278 in 2003, which was later renumbered as PNAP APP-130 in 2005 (APP means application). PNAP APP-130 required a minimum vertical daylight factor (VDF) of 8% and 4% for habitable rooms and kitchen, respectively. VDF is the ratio of the illuminance that falls onto the vertical surface of a building to the unobstructed horizontal illuminance excluding direct sunlight. The VDF is measured or calculated at the centre of the tested windowpane.

In order to calculate the VDF values for the tested windows, PNAP APP-130 provides a simple method called the unobstructed vision area (UVA) method. UVA basically refers to the open area that the window can "see" when surrounded by high external obstruction. The correlation between the UVA and the VDF can be found in the PNAP APP-130 (Buildings Department 2005). Figure 3 illustrates the use of the UVA method to calculate the cone area in front of the window. Some of the principles of the UVA method are as follows (Buildings Department 2005):

(1) The UVA of a window is the unobstructed area bounded by a cone with horizontal angle measuring 100° up to both edges of the window glazing

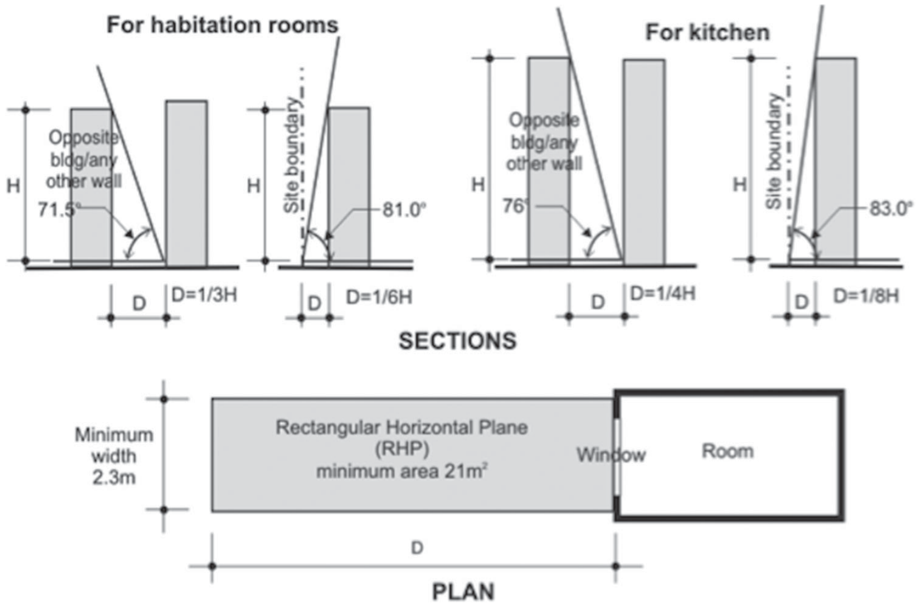


Figure 2. The minimum prescribed clearance for habitation rooms and kitchen windows facing opposite building and site boundary (above), and the minimum requirement of RHP (below).

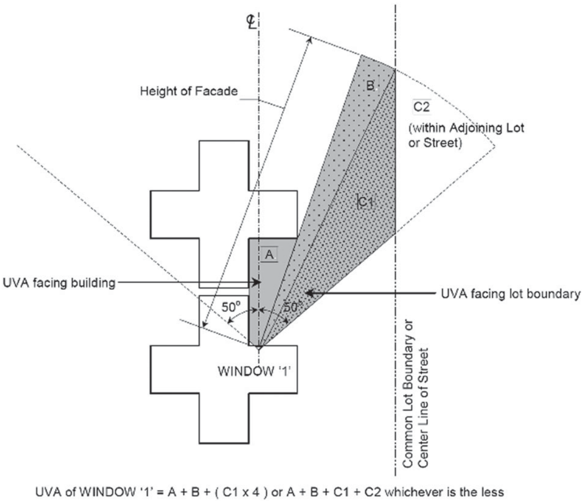


Figure 3. Measurement of UVA with the cone protruding beyond the site boundary. Source: Buildings Department (2005).

pane, symmetrically and perpendicular to the windowpane.

(2) The maximum length of the cone is equal to the height of façade in which the window is located.

According to Ng (2003b, 136),

> The UVA method considers an area in the shape of a cone that is 100° wide; beyond 100° the efficacy of light entering the window is reduced. The length of the cone is equal to the height above the window. When such a cone is overlaid onto the site plan, the surrounding buildings will obstruct part of the area. The resultant area is the Unobstructed Vision Area that the window "sees".

It is a simplified method to assess the VDF performance of residential buildings. The correlation between the UVA area and the VDF values for different building heights can be seen in the PNAP APP-130 (Buildings Department 2005). It is a tool that is convenient enough to be used especially in the site planning stage. Nonetheless, this tool has several limitations. Firstly, it cannot be used to assess the daylight performance of high-rise buildings that have different heights (Ng 2003a, 2003b), which limits its application in Hong Kong, where buildings' heights within housing estates are not always the same, which allows more daylight for residential buildings (Ng 2005). Secondly, this method cannot be used to assess the building with overhanging projections above the window (Lau and Baharuddin 2007). Thirdly, the correlation between the UVA and the VDF is not completely convincing (HK-BEAM Society 2004). Similarly, Baharuddin and Lau (2008) found a low coefficient determinant R^2 of 0.63 between the UVA and the VDF. In addition, the UVA method does not account the variation of building reflectance in the building design.

The orthographically projected area of obstruction above the horizon (g_a) method is another method to calculate the VDF at the windowpane of building units in high-density urban environments. This method is basically an inverse of the sky solid angle method proposed by Capeluto (2003), because it calculates the obstruction area instead of the sky area. The area of g_a can be used to predict VDF values. Different VDF values are expected using

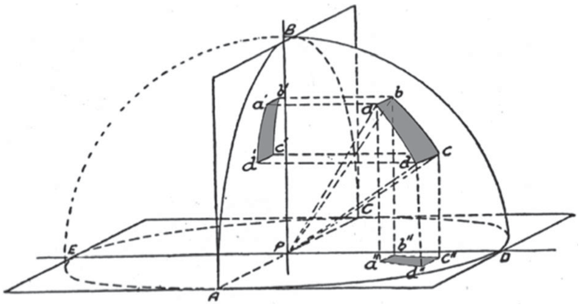


Figure 4. The projected patch of sky on vertical plane ($a'b'c'd'$) and horizontal plane ($a''b''c''d''$) (adapted from Waldram 1950).

the polynomial regression lines for nine combinations of building and ground surface reflectance values. The area of g_a can be calculated from the layout plan if their heights above the reference point are known (Cheung and Chung 2005). Despite the accuracy of this method to calculate the VDF on the outside of the windowpane, it has several limitations. First of all, Cheung and Chung (2005) study did not recommend the minimum g_a or sky area to ensure good daylighting in the Hong Kong context. In contrast, this study argues that it is important to define the minimum sky area to guarantee the availability of daylight in the lowest floor of high-rise and high-density residential buildings. In addition, the study does not provide any example of how to do the calculation of g_a area and therefore, it might be difficult to use by building designers or architects.

The new assessment tool called the visible sky area (VSA) method is an alternative method to calculate the VDF in early design stage. It was developed and proposed to overcome some of the limitations found in the other methods, which was based on the daylight performance of existing apartment buildings and Hong Kong sky condition.

VSA definition

VSA is defined as the ratio of projected area of sky (PAS) on the vertical plane that can be seen from the centre of the windowpane to the whole projected area of the unobstructed sky on the horizontal plane. The maximum area of projected sky on the vertical plane is half of circle area, that is, $\pi/2$ (1.571), while the maximum projection of unobstructed sky on the horizontal plane is equal to a circle area, that is, π (3.142). Therefore, the maximum value of VSA area is 50%. This VSA area is similar to the *Sky factor* proposed by Waldram (1950) (see Figure 4). In this figure, the *Sky factor* is defined as the area of projected sky on the vertical plane ($a'b'c'd'$) to the projected area of the unobstructed hemisphere on the horizontal plane in the form of circle *AECD*.

Figure 4 shows the projection of a sky patch as seen from a reference point at the window. The graph reveals that the area of sky visible from the reference point can be projected on the vertical or horizontal plane. However, the areas of these two projections are not equal because they are affected by the cosine effect. The cosine of the angle has a maximum value of 1 at angle of 0° and a minimum value of 0 at angle of 90°. Therefore, the sky patch that is located at the zenith will have a maximum area if projected on the horizontal plane, but a minimum area on the vertical plan. Inversely, the sky patch that is located at the horizon will have maximum area if projected on a vertical surface, but minimum area if projected on a horizontal surface.

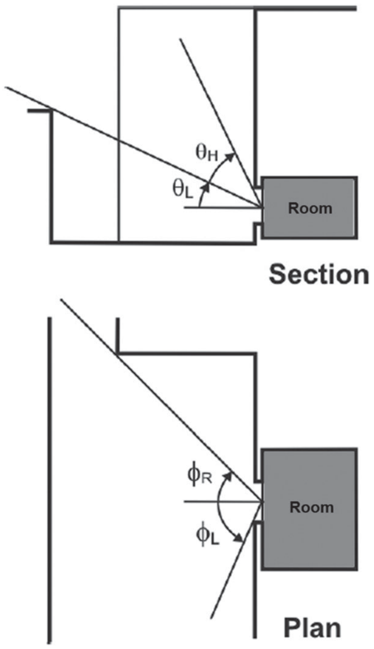


Figure 5. The area of sky visible is defined by the areas θ_L and θ_H in altitude, and ϕ_L and ϕ_R in azimuth (source: Tregenza 1989).

In order to get the VSA area from a point at the centre of the windowpane, the projected area of the sky patch (visible from the window) should be calculated. Several methods can be used for this purpose. Firstly, the calculation can be done using the integral equation with four defining angles (see Figure 5). This projected area of visible sky on the vertical surface can be calculated using the global illuminance equation (Tregenza 1989) as follows:

$$\mathrm{EW} = L_{\theta\phi} \int_{\theta_L}^{\theta_H} \int_{\phi_L}^{\phi_R} \cos^2\theta \cos\phi \, d\phi \, d\theta, \qquad (1)$$

where

EW = the illuminance on the window from the sky

$L_{\theta\phi}$ = the luminance of a point in the sky patches at altitude θ and azimuth ϕ

Based on Equation (1), by excluding the luminance $L_{\theta\phi}$, the PAS can be calculated as follows:

$$\mathrm{PAS} = \int_{\theta_L}^{\theta_H} \int_{\phi_L}^{\phi_R} \cos^2\theta \cos\phi \, d\phi \, d\theta. \qquad (2)$$

Table 1. Description of samples.

No.	Housing estates	Location	Date of occupation permit	Building heights	Layout	Plan type	Number of unit per floor
1	Taikoo Shing	HK Island	Dec 1979	23–30 F	Closed	Cruciform	8
2	Heng Fa Chuen	HK Island	Mar 1988	13–21 F	Semi-closed	Cruciform	8
3	The Orchards	HK Island	Jul 2003	38 F	Closed	6-unit plan	6
4	Bedford Gardens	HK Island	Apr 1981	18–19 F	Parallel	Cruciform	8
5	City Garden	HK Island	Apr 1983	26–27 F	Closed	Cruciform	8
6	The Belchers	HK Island	Dec 2001	44–48 F	Semi-closed	Cruciform	8
7	South Horizon	HK Island	Feb 1994	25–42 F	Semi-closed	Cruciform	8
8	Sorrento	Kowloon	Oct 2003	51–65 F	Closed	Pinwheel	8
9	Charming Garden	Kowloon	May 1998	20–23 F	Closed	10-unit plan	10
10	Park Avenue	Kowloon	Feb 2001	35–45 F	Semi-closed	Hybrid	8
11	New Harbour View	Kowloon	Aug 2003	44 F	Parallel	Cruciform	8
12	Nob Hill	Kowloon	May 2001	29 F	Semi-closed	Y-shaped	8
13	The Metro City 2	Kowloon	Apr 2000	42–43 F	Semi-closed	Cruciform	8
14	Riviera Gardens	NT & Islands	Dec 1989	34–41 F	Closed	Cruciform	8
15	Park Island 3	NT & Islands	Feb 2005	26 F	Parallel	Hybrid	8
16	Park Island 5	NT & Islands	Jun 2006	26 F	Closed	X-shaped	8
17	Tierra Verde	NT & Islands	Jun 1999	34–40 F	Closed	Pinwheel	8
18	Villa Esplanada	NT & Islands	Jan 1998	35–40 F	Semi-closed	Cruciform	8
19	Caribbean Coast	NT & Islands	Jul 2005	49–52 F	Open	Diamond	8

By integrating Equation (2), the PAS can be further calculated as follows:

$$\mathrm{PAS} = (\sin\phi_{\mathrm{R}} + \sin\phi_{\mathrm{L}}) \times \left(\frac{\theta_{\mathrm{H}} - \theta_{\mathrm{L}}}{2} + \frac{\sin 2\theta_{\mathrm{H}} - \sin 2\theta_{\mathrm{L}}}{4}\right). \quad (3)$$

The VSA then can be determined by the following formula:

$$\mathrm{VSA} = \frac{\mathrm{PAS}}{\pi} \times 100\%. \quad (4)$$

Methodology

This study involved two major methods, that is, field survey and computer simulation. Field survey has been carried out to collect plans, layouts, and façade properties of the 19 selected high-rise residential buildings in Hong Kong. Additional information was also gathered from the Internet at http://www.centadata.com. The results of the field survey were used to generate 3D CAD drawing for the simulation purposes. The computer simulation RADIANCE software was then used to simulate the VDF of selected building samples.

Samples for the study

The location and description of the 19 selected samples are illustrated in Table 1. The samples were selected from three territories in Hong Kong SAR, namely Hong Kong Island, Kowloon, and New Territories & Islands. They represent different dates of occupations, building heights, layout and plan types, and number of units per floor.

Method of analyses

Data generated from computer simulation were analysed using SPSS statistical package. A number of statistical analyses methods were employed in this study. They were as follows:

1. Regression analyses. Regression analysis is a statistical tool used for investigating the relationship between variables. This tool has been used to determine the relationship between the VSA and the VSC values for all cases at the layout level.
2. Scatter-plot analyses. In order to see the pattern of the relationship between two variables, scatter-plot analysis has been used to draw the values of VSA against the values of VDF. This is an effective way to analyse the impact of building plans and layout, and ground and building reflectance on the VDF performance.
3. The mean bias error (MBE) and root mean square error (RMSE) analysis.
4. Best-fit analyses. This method was employed to select the best model for VSA method.

Results and discussion

VSA distribution of the selected housing estates

A number of VSA values were calculated and analysed. These VSA areas were calculated and analysed at two different levels, namely at the building plan stage (without obstruction) and the layout level (with obstruction). Figure 6 shows the distribution of VSA values at building plan (left) and building layout (right) levels. In the building plan level, the largest frequency of VSA data falls in

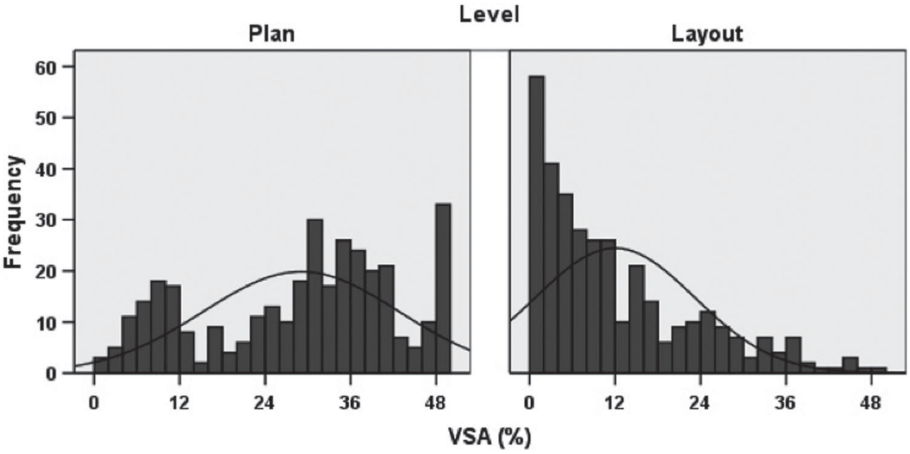


Figure 6. Distribution of VSA areas of all cases at building plan (left) and layout (right) levels.

the range of 12–50% (80% of data), while at the building layout level, they are mostly in the range of 0–12% (63% of data). This confirmed that most VSA values at the building plan level are sufficient, while at the building layout level, this figure was dominated by poor VSA values. Specifically, a VSA below 12% reflects the situation in a high-density environment. In a high-density situation, the windows at the lower floor level have a very little, if any, access to the sky due to the obstructions.

The correlation between VSA and VSC

Vertical Sky Component (VSC) is widely used as an indicator to predict daylight in building environments, as it has been well accepted by researchers and practitioners. Following the same principle, a new VSA method is proposed as a daylight predictor for high-density situations. This method would be used to calculate the VDF, which has been accepted as performance-based regulation for daylight in Hong Kong. The VSA method has been developed based on the overcast sky condition as the worst-case scenario for daylight calculation (Mardaljevic 1998).

In order to investigate the relationship between VSA and VSC, a regression analysis was carried out. Regression analysis shows that VSA and VSC have a strong linear relationship. This is indicated by the coefficient correlation R of 0.993 and coefficient determinant R^2 of 0.986. Based on this analysis, it is believed that VSA would be as good as VSC to indicate good daylight performance. Both VSA and VSC are expressed in percentage value. The relationship between VSA and VSC can be established using the mathematical formula as follows:

$$\text{VSC} = 0.605 + 0.761\,\text{VSA}. \qquad (5)$$

Definition of sky area for the VSA method

Based on the sample calculation provided in Littlefair (2001), the minimum VSC for Hong Kong can be determined. The amount of horizontal diffuse illuminance that exceeds 70% of the day is 18 klx (Rahim et al. 2008). Based on this horizontal diffuse illuminance, the minimum VSC for Hong Kong can be calculated according to Littlefair (2001). The minimum VSC would be 100% × 1.7/18 = 9.44%. In order to get this minimum VSC, the required VSA could be calculated using the linear regression as shown in Equation (5). By substituting the VSC with 9.44%, the required VSA can be calculated as follows: VSA = (9.44 − 0.605)/0.761 = 12%. This means that a minimum 12% of VSA is required to provide a minimum 9.44% of VSC for good daylighting in Hong Kong. In the following analyses, the VSA 12% will be used as a standard to determine the performance of the windows. For habitable rooms (bedrooms and living rooms), a VSA of 12% or more will be considered as a good performance, while less than 12% will be considered as a poor one.

Determination of the VSA area

As mention in the previous section, the VSA area can be determined after having the projected area of sky (PAS) calculated. The biggest PAS of sky patches is coming from the sky directly in front of the vertical plane (small horizontal and vertical angles) and the smallest one is coming from the sky patches that have large horizontal and vertical angles. This is actually due to the cosine effect. The maximum PAS of sky patches on the vertical plane is $\pi/2$ or 1.571, which is equal to 50% of VSA.

The VSA calculation will be based on the unobstructed sky from the area of 60° to the left and 60° to the right in horizontal angles, and 0° to 70° of vertical angles. This area of sky provides 1.34 of PAS with corresponding VSA 42.56%. The reasons for selecting this sky area are as follows:

(1) The sky area outside this area will have a very small contribution on the illuminance falling in the

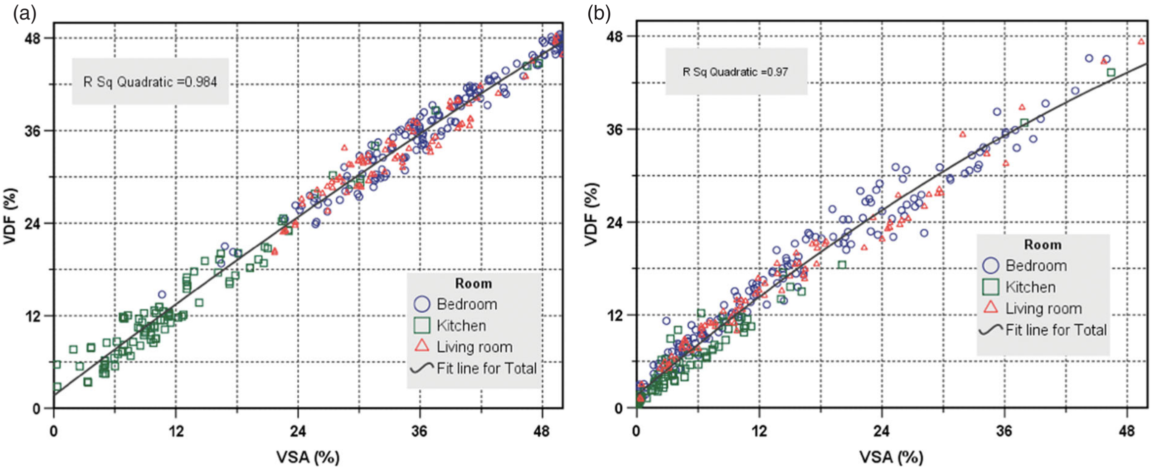


Figure 7. The impact VSA area on the VDF values at the plan level (a) and the layout level (b).

vertical facade and inside the building. Therefore, excluding this area in the VSA calculation will not significantly affect the VDF value.

(2) This limit of sky area will be beneficial to the calculation of sky area using the manual calculation and spreadsheet method because it will be more efficient to calculate this area rather than to calculate the whole sky area.

The Impact of VSA on the VDF values

In order to present the impact of VSA on the VDF performance, statistical analyses using scatter-plot graphs with trend line analyses have been carried out. The analyses were based on two scenarios, that is, plan level (without obstructions) and layout level (with obstructions).

Figure 7(a) shows the impact of VSA on the VDF values at the plan level. As can be seen from the graph, most of kitchens have VSA between 0% and 20%, while most of bedrooms and living rooms have VSA ranging from 20% to 50%. The consequences of these conditions are that most kitchens have VDF values less than 14%, while all living rooms and most of bedrooms have VDF values more than 20%. In this condition, without external obstructions, most of the bedrooms and all living rooms have a very good VDF performance, while most of the kitchens have unsatisfactory VDF performances. The reason for kitchens having such a poor performance is that kitchens are mostly self-obstructed by other structures or walls, as they are mostly located in the *re-entrant* area.

Different situations should be expected when the external obstructions are included in the simulations. The results can be seen in Figure 7(b), which shows the impact of VSA on the VDF values. When compared to the plan level, the VSA and VDF performances at the layout level were much worse than at the plan level. Indeed, most kitchens have a VSA below 12%, the VSA of bedrooms is distributed quite evenly from 0% to 45% and most living rooms have VSA values between 0% and 30%. As a result, the VDF of most rooms becomes worse in reality, as most of the values are below 12%. In this condition, external obstructions created by surrounding buildings reduce the VSA substantially and therefore reduce the VDF performance significantly.

The impact of reflectance on the VDF values

To analyse the effect of building reflectance (ρ_b) for different ground reflectance values (ρ_g) on the VDF performance, statistical analyses using a scatter-plot graph of VSA versus VDF were carried out (Figure 8). Figure 8(a) shows the impact of three values of building reflectance for ground reflectance 0.2. As seen in this figure, at VSA 12%, the improvements of building reflectance (ρ_b) from 0.2 to 0.4 and from 0.2 to 0.6 would improve the VDF by about 17% and 45%, respectively. At ground reflectance (ρ_g) 0.3, at the same VSA of 12%, the improvement of building reflectance (ρ_b) from 0.2 to 0.4 and 0.2 to 0.6 would improve the VDF values by about 23% and 53%, respectively (Figure 8(b)). At the ground reflectance (ρ_g) 0.4 (see Figure 8(c)), at the same VSA of 12%, the improvement of building reflectance (ρ_b) from 0.2 to 0.4 and 0.2 to 0.6 would improve the VDF values by about 18% and 45%, respectively. These figures confirmed that at the same ground reflectance and VSA, the improvement of building reflectance values would significantly improve the VDF value.

Development of new VSA method

Regression analysis

The regression analyses of the nine combinations of ground reflectance (ρ_g) and building reflectance (ρ_b) were carried out using the curve fit of regression analysis from SPSS

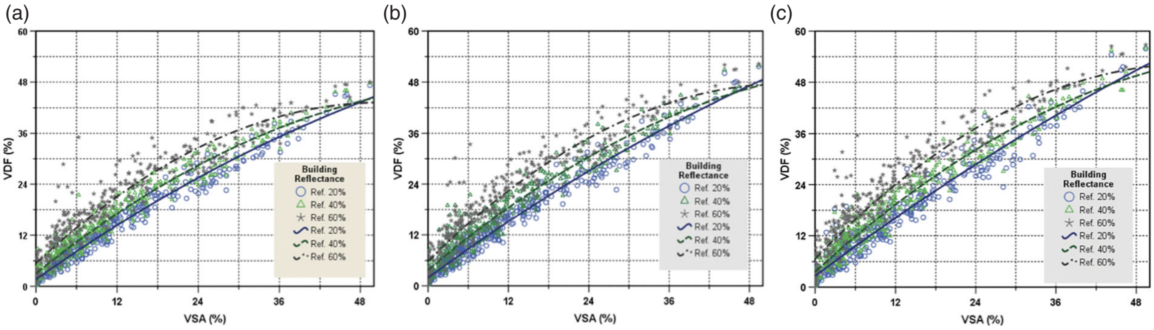


Figure 8. The effect of different building reflectance values on the VDF categorized on different ground reflectance values (ρ_g): (a) 0.2, (b) 0.3, and (c) 0.4.

version 15.0 software. The regression involved 3078 data of the VDF and VSA gathered from computer simulation. For each combination of ground reflectance (ρ_g) and building reflectance (ρ_b), one equation was selected as the best fit according to their significance of the regression equation, the R^2, and the significance of coefficient. If both models had the same "significance" value, then the selection was based on the R^2 and the significance of each coefficient of regression model. The regression, which had higher R^2, was chosen as the best fit. The best-fit selection for nine models is summarized in Table 2.

Selection of models for the VSA method

In order to select which models to be used in the VSA method, a validation study that involves all the nine regression models above was carried out. The results of validation study are illustrated in Table 3.

Table 2. Summary of quadratic regression equations.

Ground reflectance	Building reflectance	The best fit of equations	R^2	Model no.
$\rho_g = 0.2$	$\rho_b = 0.2$	$\text{VDF} = 1.644 + 1.121\ \text{VSA} - 0.005\ \text{VSA}^2$	0.970	Model 1
	$\rho_b = 0.4$	$\text{VDF} = 3.040 + 1.276\ \text{VSA} - 0.009\ \text{VSA}^2$	0.952	Model 2
	$\rho_b = 0.6$	$\text{VDF} = 5.378 + 1.483\ \text{VSA} - 0.015\ \text{VSA}^2$	0.898	Model 3
$\rho_g = 0.3$	$\rho_b = 0.2$	$\text{VDF} = 1.923 + 1.155\ \text{VSA} - 0.004\ \text{VSA}^2$	0.970	Model 4
	$\rho_b = 0.4$	$\text{VDF} = 3.770 + 1.332\ \text{VSA} - 0.009\ \text{VSA}^2$	0.939	Model 5
	$\rho_b = 0.6$	$\text{VDF} = 5.826 + 1.559\ \text{VSA} - 0.015\ \text{VSA}^2$	0.908	Model 6
$\rho_g = 0.4$	$\rho_b = 0.2$	$\text{VDF} = 2.634 + 1.173\ \text{VSA} - 0.004\ \text{VSA}^2$	0.948	Model 7
	$\rho_b = 0.4$	$\text{VDF} = 3.619 + 1.426\ \text{VSA} - 0.010\ \text{VSA}^2$	0.948	Model 8
	$\rho_b = 0.6$	$\text{VDF} = 6.642 + 1.621\ \text{VSA} - 0.014\ \text{VSA}^2$	0.905	Model 9

Table 3. The MBE % and RMSE % of VSA models against RADIANCE results.

Ground reflectance	Building reflectance	VSA models	MBE (VDF %)	RMSE (VDF %)	R	R^2
$\rho_g = 0.2$	$\rho_b = 0.2$	Model 1	0.35	1.20	0.961	0.924
	$\rho_b = 0.4$	Model 2	1.38	2.02	0.949	0.900
	$\rho_b = 0.6$	Model 3	2.94	3.59	0.930	0.864
$\rho_g = 0.3$	$\rho_b = 0.2$	Model 4	0.27	1.38	0.958	0.918
	$\rho_b = 0.4$	Model 5	1.67	2.42	0.944	0.890
	$\rho_b = 0.6$	Model 6	3.02	3.87	0.921	0.849
$\rho_g = 0.4$	$\rho_b = 0.2$	Model 7	0.57	1.71	0.953	0.908
	$\rho_b = 0.4$	Model 8	1.21	2.36	0.938	0.880
	$\rho_b = 0.6$	Model 9	2.72	3.89	0.907	0.822

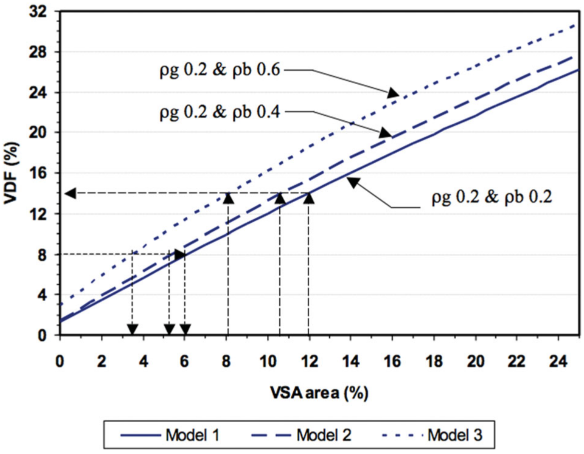


Figure 9. VSA graph for three combinations of ground and building reflectance values: (a) ρ_g 0.2 and ρ_b 0.2; (b) ρ_g 0.2 and ρ_b 0.4; and (c) ρ_g 0.2 and ρ_b 0.6.

After going through the validation process, it is found that among all simple regression models, Model 1 has the best performance; it has the smallest RMSE, but the largest R and R^2 (Table 3). This model gives the smallest VDF prediction; therefore, the results gathered from this model will be more stringent than other models. With RMSE 1.20 and R^2 0.924 (Table 3), it is believed that this model will satisfactorily produce good results for predicting daylight performance at the site plan stage. For reference, the UVA model developed by Ng (2003a) has R^2 of only about 0.68–0.80. In order to calibrate this model, the coefficient of constant of a regression equation should be subtracted by the value of MBE, that is, 0.35. As a result, the modified regression equation will be written as follows:

$$\mathrm{VDF} = 1.294 + 1.121\,\mathrm{VSA} - 0.005\,\mathrm{VSA}^2. \qquad (6)$$

For the purposes of providing an alternative way to increase the VDF without enlarging the VSA, two equations, that is, Model 2 (Equation 7) and Model 3 (Equation 8), were also included in this VSA method. Similar to Model 1, to reduce the bias caused by the prediction equations, both models should be subtracted by their respective MBE values. Therefore, the modified models will be written as follows:

$$\mathrm{VDF} = 1.380 + 1.276\,\mathrm{VSA} - 0.009\,\mathrm{VSA}^2. \qquad (7)$$

$$\mathrm{VDF} = 2.940 + 1.483\,\mathrm{VSA} - 0.015\,\mathrm{VSA}^2. \qquad (8)$$

Figure 9 shows the graphical representation of all models for the VSA method. As shown in this figure, Model 2 and Model 3 would produce more VDF value than Model 1. For the same VDF value of 12%, Model 2 and Model 3 only require about 10.6% and 8.2% VSA values, respectively. Similarly, for the minimum 8% VDF requirements, Model 2 and Model 3 require less VSA than Model 1; they only require about 5.3% and 3.5% VSA, respectively. For kitchens, a 6% VSA is proposed. This VSA could produce about 8% VDF. The VDF values that resulted from this method are much better than that required by the PNAP APP-130.

Example of VSA calculation

The example of calculation is presented in Figures 10 and 11. Figure 10 shows the manual calculation of VSA at Point 10, where the heights of external obstructions are varied. In order to calculate the VSA of this point, a site plan with known building heights is required. In this site plan, several segments are defined in the ranges of 60° left and 60° right. Each segment is defined by horizontal and vertical angles. The horizontal angles (ϕ_L and ϕ_R) were measured by a protractor, while the vertical angles θ_L were calculated based on H (height) and D (distance) of the obstruction building, and θ_H was calculated based *on h* (height*)* and *d* (distance) of the projection above. As seen in Figure 10, there were nine segments that could be defined from Point 10.

After all segments within 60° left and 60° right were drawn, then the next step was to calculate the VSA area using the spreadsheet programme such as Microsoft (MS) Excel as shown in Figure 11. Figure 11(a) shows the example of spreadsheet calculation, which shows the VSA calculation at P10 for window without projection above. As seen in this figure, segments #7–9 have no contribution to the VSA value, while segment #5 has the largest one, which was 6.12%. The contributions of other segments on the VSA range from 0.02% to 0.05%. The total VSA area seen at this point is 6.28%, which was corresponding to the VDF of 8%. The VDF at this point has already satisfied the Hong Kong regulation. However, this figure would not produce good daylight performance, which required a minimum VSA of 12% as mention earlier.

The VSA of window with projection above can be seen in Figure 11(b). The existence of projection above the window (i.e. balcony) reduced the VSA value significantly, from 6.28% to 4.74%. This VSA only corresponds to the VDF of 6.5%, which is less than the minimum performance-based VDF regulation (8%). In this calculation, only segment #5 has contributed to the VSA of the window.

The guidelines for VSA calculation for window without projection above can be carried out in the spreadsheet program MS Excel using the following procedures:

1. Put the segments number according to the number of segments in the site plan in the cell A2–A10.
2. Put the horizontal angles (ϕ_L and ϕ_R) of each segment in cell B2–B10 and C2–C10, for the right angle and left angle, respectively.
3. In the cells D2–D10, fill in with “N/A” (means no projection).

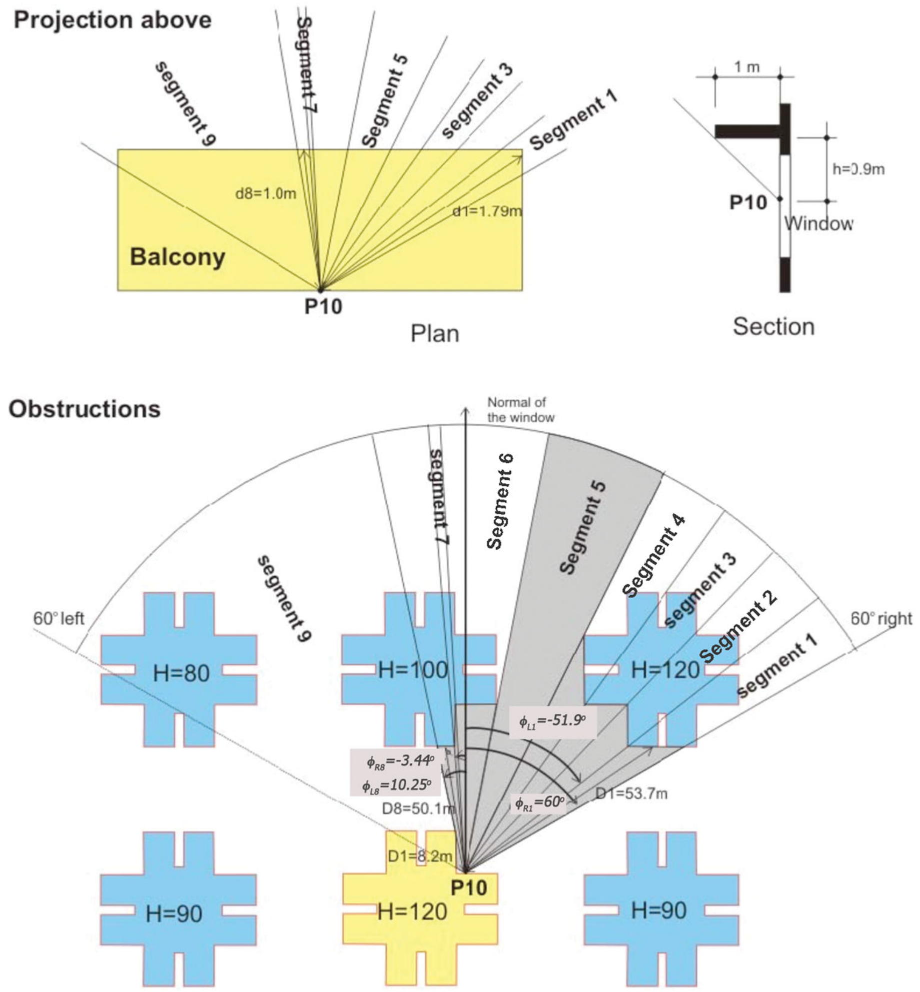


Figure 10. The example of PAS and VSA calculation at Point 10.

(4) In the cells E2–E10, fill in with “N/A” (means no projection).

(5) Fill in the height (H) of obstruction of each segment in the cell F2–F10; if no obstruction, put zero.

(6) Fill in the distance of obstruction (D) of each segment in the cell G2–G10; if no obstruction; put any positive number.

(7) In the cell H2, fill in number 70 (maximum vertical angle counted in this VSA method).

(8) In the cell I2, write the formula: “ = IF((ATAN(F2/G2)*180/PI()) > = H2,H2, ATAN(F2/G2)*180/PI())” and then copy cell I2 to cells I3 until I10.

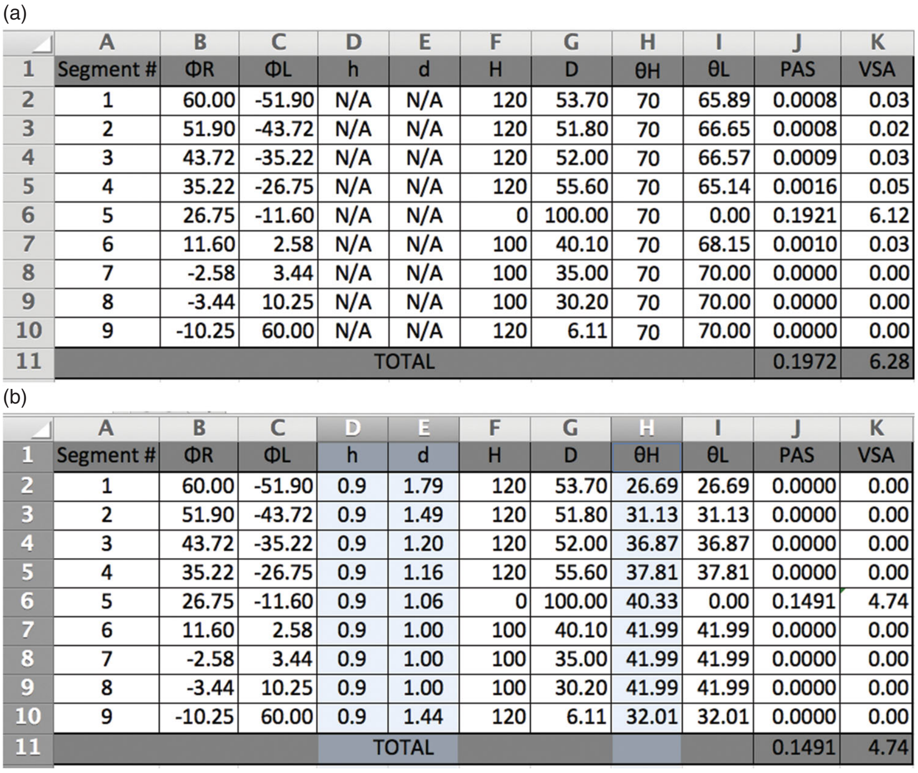
(9) In the cell J2, write the formula “ = (SIN(B2*PI()/180) + SIN(C2*PI()/180))*((((H2/180*PI())(I2/180*PI()))/2) + ((SIN(2*H2*PI()/180)-SIN(2*I2*PI()/180))/4))” and then copy cell J2 to cells J3 until J10.

(10) In the cell K2, write the formula “ = J2/3.14*100”, then copy cell K2 to cells K3 until K10.

(11) In the cell J11, write the formula “ = SUM(J2:J10)”.

(12) In the cell K11, write the formula “ = SUM(K2:K10)”.

The calculation of VSA for windows with projection above can be carried with similar procedures to those mentioned in the above guidelines. However, procedure numbers (3), (4), and (7) should be amended. The procedure numbers (3) and (4) should be filled in with their respective height (h) and distance (d) of the projection above. In addition to those cells, the cell H2 in procedure number (7) should be filled in with the formula “ = IF((ATAN(D2/E2)*180/PI()) > = 70, 70,ATAN(D2/E2)*180/PI())”.



(a)

	A	B	C	D	E	F	G	H	I	J	K
1	Segment #	ΦR	ΦL	h	d	H	D	θH	θL	PAS	VSA
2	1	60.00	-51.90	N/A	N/A	120	53.70	70	65.89	0.0008	0.03
3	2	51.90	-43.72	N/A	N/A	120	51.80	70	66.65	0.0008	0.02
4	3	43.72	-35.22	N/A	N/A	120	52.00	70	66.57	0.0009	0.03
5	4	35.22	-26.75	N/A	N/A	120	55.60	70	65.14	0.0016	0.05
6	5	26.75	-11.60	N/A	N/A	0	100.00	70	0.00	0.1921	6.12
7	6	11.60	2.58	N/A	N/A	100	40.10	70	68.15	0.0010	0.03
8	7	-2.58	3.44	N/A	N/A	100	35.00	70	70.00	0.0000	0.00
9	8	-3.44	10.25	N/A	N/A	100	30.20	70	70.00	0.0000	0.00
10	9	-10.25	60.00	N/A	N/A	120	6.11	70	70.00	0.0000	0.00
11					TOTAL					0.1972	6.28

(b)

	A	B	C	D	E	F	G	H	I	J	K
1	Segment #	ΦR	ΦL	h	d	H	D	θH	θL	PAS	VSA
2	1	60.00	-51.90	0.9	1.79	120	53.70	26.69	26.69	0.0000	0.00
3	2	51.90	-43.72	0.9	1.49	120	51.80	31.13	31.13	0.0000	0.00
4	3	43.72	-35.22	0.9	1.20	120	52.00	36.87	36.87	0.0000	0.00
5	4	35.22	-26.75	0.9	1.16	120	55.60	37.81	37.81	0.0000	0.00
6	5	26.75	-11.60	0.9	1.06	0	100.00	40.33	0.00	0.1491	4.74
7	6	11.60	2.58	0.9	1.00	100	40.10	41.99	41.99	0.0000	0.00
8	7	-2.58	3.44	0.9	1.00	100	35.00	41.99	41.99	0.0000	0.00
9	8	-3.44	10.25	0.9	1.00	100	30.20	41.99	41.99	0.0000	0.00
10	9	-10.25	60.00	0.9	1.44	120	6.11	32.01	32.01	0.0000	0.00
11					TOTAL					0.1491	4.74

Figure 11. VSA calculation for window: (a) without, and (b) with projection above using spreadsheet MS Excel.

Conclusion

Based on the VSC requirement for good daylighting, the VSA area for Hong Kong situation has been determined. Using the diffuse horizontal illuminance of 18 klx for 70% of time, the VSA of 12% is required. This VSA area would produce about 14% VDF, which is far better than that required by the building regulation that is, 8%. However, the simulation of 19 residential building samples showed that it was very hard to achieve 12% of VSA in the existing building. Most of the selected existing buildings (63%) have very small VSA values (less than 12%), resulting in very low VDF performance.

A minimum VSA of 12% and 6% for habitable rooms and kitchens, respectively, is proposed for Hong Kong situation. The new method would guarantee the availability of sky area seen from the window in order to provide a good VDF on windowpane and thus daylight illuminance in interiors at lower floor level.

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References

Baharuddin, and S. S. Y. Lau. 2008. "The Improvement of Daylight Illuminance for Healthy High-rise Residential Buildings in Heavily Obstructed Environments", Proceeding of 5th Warwick Healthy Housing Conference, Coventry, UK, Faculty of Law, Warwick University.

Buildings Department. 2005. *Lighting and Ventilation Requirements – Performance-based Approach, PNAP APP-130*. Buildings Department, HKSARo. Accessed June 30, 2013. http://www.bd.gov.hk/english/documents/pnap/signed/APP130se.pdf

Capeluto, I. G. 2003. "The Influence of Urban Environment on the Availability of Daylighting in Office Buildings in Israel." *Building and Environment* 38 (5): 745–752.

Cheung, H. D., and T. M. Chung. 2005. "Calculation of the Vertical Daylight Factor on Window Facades in a Dense Urban Environment." *Architectural Science Review* 48 (1): 81–92.

Chung, T. M. 2003. "Daylighting in Hong Kong: Potential and Problems." *Lighting Research & Technology* 35 (1): 39–41.

HK-BEAM Society. 2004. *HK-BEAM 4/04 'New Buildings': An Environmental Assessment for New Buildings Version 4/04*. Hong Kong: HK-BEAM Societyo. Accessed June 30, 2013. http://www.beamsociety.org.hk/files/_404%20New%20Buildings%20(Full%20Version).pdf

HKSAR. 1997. *CAP 123F Building (Planning) Regulations – Regulation No. 30 Lighting and Ventilation of Rooms Used or Intended to be Used for Habitation or as Office or Kitchen*. Hong Kong: The Government of Hong Kong SAR, Chinao. Accessed June 29, 2013. http://www.legislation.gov.hk/eng/home.htm

Lau, S. S. Y., and Baharuddin. 2007. *Computer Simulation Study on Natural Lighting Performance of Proposed Hotel Development at North Point*. Hong Kong: Hong Kong, Department of Architecture, HKU.

Lau, S. S. Y., Baharuddin, W. Y. W. Lee, D. K. C. Leung, A. M. Ye, A. Amato, K. W. Chau, and S. K. Wong. 2006. "Reconsidering Daylighting Design Parameters for Tall Buildings in a Densely Built City." *Architectural Science Review* 49 (3): 285–294.

Littlefair, P. J. 2001. "Daylight, Sunlight and Solar Gain in the Urban Environment." *Solar Energy* 70 (3): 177–185.

Mardaljevic, J. 1998. "Daylight Simulation." In *Rendering with Radiance: the Art and Science of Lighting Visualization*, edited by G. W. Larson, and R. A. Shakespeare 341–390. San Francisco, CA: Morgan Kaufmann.

Ng, E. 2001a. "A Simplified Daylighting Design Tool for High-density Urban Residential Buildings." *Lighting Research & Technology* 33 (4): 259–272.

Ng, E. 2001b. "A Study on the Accuracy of Daylighting Simulation of Heavily Obstructed Buildings in Hong Kong." Proceedings of 7th International IBPSA Conference, Rio de Jenairo, Brazil. www.ibpsa.org/proceedings/bs01/BS01_1215_1222.pdf

Ng, E. 2003a. "Applying Computational Results to the Development of a Design Method for Daylighting Design and Regulation in High-density Cities." Proceedings of 8th International IBPSA Conference, Eindhoven, Netherlands.

Ng, E. 2003b. "Studies on Daylight Design and Regulation of High-density Residential Housing in Hong Kong." *Lighting Research & Technology* 35 (2): 127–139.

Ng, E. 2005. "A Study of the Relationship Between Daylight Performance and Height Difference of Buildings in High Density Cities Using Computational Simulation." Proceedings of 9th International IBPSA Conference, Montreal, Canada.

Rahim, R., S. Lau, Baharuddin, and R. Mulyadi. 2008. "A Preliminary Study on Daylight Availability in Hong Kong." Proceedings of 9th Senvar + 2nd ISESEE 2008, Shah Alam, Selangor, Malaysia, Universiti Teknologi MARA.

Tregenza, P. R. 1989. "Modification of the Split-flux Formulae for Mean Daylight Factor and Internal Reflected Component with Large External Obstructions." *Lighting Research & Technology* 21 (3): 125–128.

Waldram, P. J. 1950. *A Measuring Diagram for Daylight Illumination*. London: B.T. Batsford.