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Optimization of façade design based on the impact of interior obstructions to daylighting

Yao Lu · Tina Wolf · Jian Kang

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Abstract Overcrowding in the perimeter zone is an inevitable issue in residential rooms with limited space. Obstructions, such as furniture and household items, may block the existing windows, and therefore affect interior daylight conditions. A façade design approach is needed that simultaneously takes into account daylighting and the volume of usable space for obstructions in the perimeter zone of such rooms. This study simulates daylight distributions in a typical small residential room with obstructions in front of windows. The simulation consists of two parts. First, the effects on horizontal illuminances caused by different positions and shapes of obstructions are examined under an overcast sky. Second, the maximum usable space volumes for obstructions of 51 optimized façade configurations are calculated in terms of four window-to-wall ratios ($WWRs$). The results of this study show that optimizing the forms of facade design can increase the usable interior space volume and meet the daylighting requirements of Chinese standards for small residential rooms. Additionally, by using the optimized façade forms, a façade with a WWR value of 50% provides the maximum usable space for obstructions. Based on the above results, this paper presents two matrices that can help architects in selecting the appropriate fenestration methods and confirming the size of usable space and allocation for residents.

Keywords Usable space · Perimeter zone · Façade design · Daylighting performance · Daylight simulation · Small residential room

F. Author · S. Author
Department of Technology and Design of Building Envelopes, Faculty of Architecture, Technische Universität München, Arcisstr. 21, 80333, Munich, Germany
Tel.: +49 17657863117
E-mail: l-yao@hotmail.com

T. Author
School of Architecture, The University of Sheffield, Western Bank, Sheffield S10 2TN, UK

Glossary

Obstruction	Fully used space in perimeter zones that obstructs daylighting
Cube	Hexahedron obstruction with an equal length and height of 600 mm
Vertical cuboid	Rectangular prism obstruction with a height longer than its length
Horizontal cuboid	Rectangular prism obstruction with a height shorter than its length
Wide solid wall	Opaque portion of the façade, whose width is longer than its height
Tall solid wall	Opaque portion of the façade, whose width is shorter than its height
w	Width of an obstruction (mm)
l	Length of an obstruction (mm)
h	Height of an obstruction (mm)
l_h	Distance from the horizontal middle line of the obstruction to the floor (mm)
l_v	Distance from the vertical middle line of the obstruction to the window edge (mm)
l_t	Total length of all obstructions in one model (mm)
D	Distance from the influenced point of the designated illuminance contours to the inner window projection line (mm)
$D_{800}, D_{500}, D_{300}, D_{200}$	Specific D in accordance with the target illuminance contours of 800 lux, 500 lux, 300 lux and 200 lux, respectively (mm)
w_{max}	Maximum acceptable width of the obstruction that can ensure the target illuminance level (mm)
V_{max}	Maximum volume of the obstruction in accordance with the maximum acceptable width (m^3)

1 Introduction

Personal living space in many metropolises is still restricted. For example, the average "saleable area" in Hong Kong was 15.6 m^2 in 1999 [Liu et al, 1999], and the average living space in Shanghai was 17.3 m^2 in 2012 [SHANGHAI, 2012]. The development of high density residential buildings leads to small dwelling units [Chan et al, 2002]. Unlike in large dwellings, residents of small units have to make efficient use of every centimeter of space so that complicated living functions are conducted in one crowded space [Rooney, 2003]. Numerous studies have been conducted on using the space more efficiently in small residential units, in terms of user behaviors, furniture layouts, and spatial configurations [Gifford, 2007; Mahtab-uz Zaman and Lau, 2002; Bordas-Astudillo et al, 2003]. Surveys in occupied rooms reveal that space use patterns are based on daylight distribution. The space in perimeter zones (i.e., window area) is often used for the activities, such as reading and cooking, that require high light levels [Ruck et al, 2000]. The Wong's study indicates that the use-territory for each user activity can be demarcated by the related furniture layouts and associated space [Wong, 2010]. Compared with the room size, furniture is relatively oversized [Rooney, 2001] in small residential rooms. Thus, the furniture or other household items usually occupy most of the perimeter zone for activities that require high light levels. Moreover, a piece of fully used furniture no longer functions as a single plane, but is a three dimensional solid that obstructs daylight (see Figure 1). In this way, the used space in perimeter zones appears as an opaque obstruction with a reflectance value, which, however, may negatively affect the interior daylighting conditions. Current studies of residential building façades typically investigate daylighting in empty rooms, which differs substantially from the post-occupancy situation. The inevitable overcrowding in small residential rooms necessitates the investigation of a novel façade design solution that simultaneously takes into account daylighting and space use in perimeter zones. The challenge lies in optimizing the proportion and distribution of opaque areas of a façade to assist residents in making full use of the space behind the opaque areas and ensuring that indoor daylight levels meet the requirements of Chinese daylight standards.

The approach to solving this problem is related to studies in the field of façade design, which includes the façade design of residential rooms, daylighting performance, daylight simulation and daylight use in occupied rooms. Since a façade functions as the interface for obtaining natural light and solar energy in a building as well as for the outward appearance [Hausladen et al, 2008], research

Fig. 1 Use of space in perimeter zones in a space-limited room

on façade design involves a wide range of issues, such as aesthetics, user preference, human behavior, lighting, indoor thermal comfort, natural ventilation and energy consumption [Cheung and Chung, 2008; Alkhresheh, 2012; Hochberg et al, 2010; Gagne and Andersen, 2012; Smith and Levermore, 2008; Lavafpour and Sharples, 2014; You et al, 2013]. In the past decade, as natural lighting has been shown to be environmentally benign and psychologically satisfying for living and working [Leslie, 2003; Du and Sharples, 2011], an enormous amount of research has been conducted on how windows influence overall interior daylighting [Bougdah and Sharples, 2009; Lartigue et al, 2013; Baker and Steemers, 2002]. The primary research approaches are based on a numerical analysis of daylight distribution in rooms in different ambient conditions [Ghisi and Tinker, 2005; Husin and Harith, 2012; Ünver et al, 2003; Li, 2010; Jin, 2002]. Many noteworthy results have been obtained. For instance, Markus has demonstrated that a long horizontal window can illuminate almost twice as much area in a room as three vertical windows [Markus, 1967]. Mohamed illustrates the contours of daylight penetration with side windows of different widths, which clearly reveals how the width of the window affects the depth and position of the daylight area in an empty room [Mohamed, 2008]. Su and Zhang analyze the lighting energy consumption of different window types with respect to the window-to-wall ratio [Su and Zhang, 2010]. Research methods have developed which range from the traditional on-site measurements or static calculations in real or scaled test rooms [Ruck et al, 2000] to computer-aided dynamic simulations using climate data [Reinhart and Wienold, 2011].

The above studies provide the theoretical support for a better daylighting façade design, but the result of the post-occupancy evaluation of daylight quality in hospitals demonstrates that the lighting performance predicted in pre-occupancy stages changes after use [Alzoubi et al, 2010]. One leading cause of this difference is the influence of human activities and the related furniture on daylighting in a post-occupied room [Parpairi et al, 2002]. Current studies on indoor light distribution, however, typically assume a room to be empty or to contain only one working table, both in simulations and on-site tests [Ruck et al, 2000; Kim and Kim, 2010]. These assumptions may lead to an overestimation of the window effect or an overly conservative use of bright space in perimeter zones, an effect that is probably more significant in an over-crowded residential room. Thus, in the study of daylighting in small residential rooms with side windows, it is essential to consider the perimeter zone a functional place with usable space, which may obstruct daylighting. This is the only way research results can closely approximate real performance. To the best of our knowledge, no quantitative analysis has been conducted on how the occupied space in perimeter zones changes the light distribution in a room, nor how much space can be used without jeopardizing the illumination of the areas farther away from windows.

This work, therefore, proposes a façade design solution for small residential rooms by investigating the daylight distributions and usable space volumes. To this end, the following three research questions will be addressed: 1) How does the used space in front of windows with different geometries and positions influence the daylight distribution? 2) What is the maximum volume of the potential usable space in the bright area of rooms with different façade fenestrations? 3) What is the optimized façade design that can provide the maximum useful space with respect to daylighting performance? The above research questions are examined by simulating room models with different forms of used space in front of windows to assess the daylight distributions on working planes. Based on the results, the façade configurations are then optimized. Through simulating the optimized designs with different window-to-wall ratios ($WWRs$), the maximum usable space volumes are calculated and compared. Finally, the primary findings are presented in two tables to assist those who are seeking window façade design solutions that deliver reliable performance to occupants.

2 Methods

2.1 Simulation tool and validation

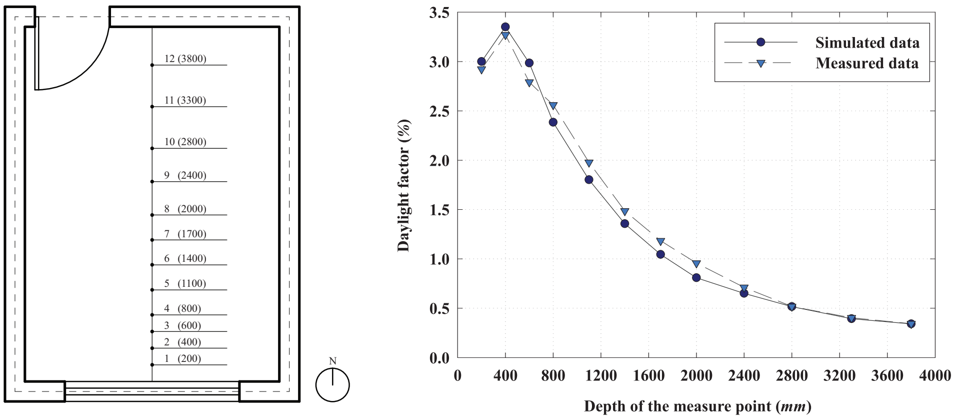
This study uses DIAlux 4.11.0.2 as the simulation tool. DIAlux is a light planning program developed by DIAL GmbH that can calculate and photo-realistically visualize the daylight performances following the standards (EN12464, ISO 8995). Many academic studies have used DIAlux as an analysis tool [Zhao and Mei, 2013; Ullah and Shin, 2014]. Although DIAL lighting laboratory has evaluated the reliability of the simulation results produced using DIAlux against the international standard CIE 171:2006 [DIALux, 2013], the accuracy of its results in a small-scale space with particular boundary conditions, as in this study, is still worth confirming. To this end, a validation experiment was conducted.

The experiment test-bed is a south-oriented room in a small apartment. The building is located in Xi'an, China (latitude 34.23° N and longitude 108.94° E), with no obstruction in front of the building. The room is 3300 $mm \times$ 4500 $mm \times$ 2700 mm. The window in the southern façade is 2100 $mm \times$ 1500 mm and has a single glazing with a pollution factor of 60%. The materials and the reflectance values of surfaces are shown in Table 1.

Table 1 Room surface materials and parameters

	Surfaces			Glazing
	Walls	Floor	Ceiling	Single glazing 3 mm
Material	Roughcast plastering white	Fine concrete	White plaster	Transmittance
Reflectance	72%	27%	71%	90%

To validate the reliability of the simulation, a comparative analysis was conducted of the horizontal daylight factors from measured data and from the DIAlux-simulation. The on-site test took place from January 4 to 6, 2013, from 8:00 to 17:30 under overcast skies. The average horizontal ambient illuminance at 12:00 was 13170 lux. Twelve measurement points on the working plane were set in the centerline of the room (Figure 2a). The working plane height was 850 mm. The light meter TES 1336A was used to take measurements every half hour. After the on-site test, the same simulation model was created in DIAlux. The horizontal daylight factor was calculated for an overcast sky from the same days in Xi'an. The average horizontal ambient illuminance at 12:00 was 11757 *lux*. Figure 2b presents the comparison between the measured results and the simulation results of the average daylight factors at the 12 measurement points. The relative deviation between the two ranges is from 0.035% to 15.505% throughout the test, but the average relative deviation was 5.846%. The result shows that the simulation has achieved an acceptable deviation in comparison to the actual measurements.



a. The on-site measurement points

b. The average daylight factors by measurement and simulation

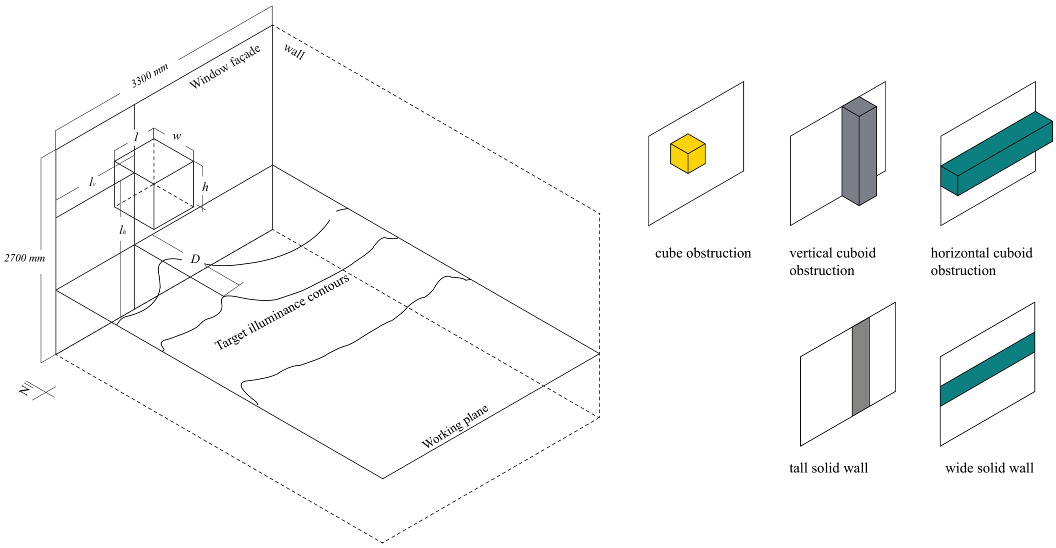
Fig. 2 The on-site measurement points and the average daylight factors by measurement and simulation

2.2 Simulation models

Based on the Chinese design codes, the daylighting of a southern oriented residential room must meet the recommended illuminance levels for different activities at midday of the winter solstice under an overcast sky. [GB50180, 2002; GB50352, 2005; GB50034, 2013], thus the weather data in this study is taken from 22 December at 12:00 in Xi'an, China. In the following studies, the sky model is an overcast sky, and the horizontal ambient illuminance is 11500 *lux*. The results under this condition should ensure that there is at least one hour of daylight on the day of the winter solstice, which should meet the light requirement of the inhabitants.

The room model is designed in accordance with the validated room (Figure 3a). The surface and glazing materials are set at the values in Table 1. Two differences must be noted: first, the glass is assumed to be clean, so the pollution factor is 80%; second, to analyze different possibilities, the window is assumed to cover the entire southern façade. Four daily working planes are selected. Their heights are 0 *mm*, 400 *mm*, 850 *mm* and 1100 *mm*.

Since a fully used space in perimeter zones functions as an obstruction to light, in this study, "obstruction" is introduced as a research object to investigate both the space that can be occupied by household items and the opaque parts of a façade, e.g., solid walls, in façade design. In the simulation, different obstructions are placed in front of a façade with fenestration (i.e., window) only. The obstruction here represents a space that is fully used. Then the daylight distributions are evaluated in this condition. If the daylighting meets the requirement of Chinese standards, the surface of the obstruction that adheres to the window represents the potentially opaque part of the façade, which means that by using this façade fenestration, the residents can get a usable space volume as large as the examined obstruction volume. The obstruction is defined as a cube or cuboid with a reflectance of 40%. Three types of obstructions are investigated, namely cube, vertical cuboid and horizontal cuboid (Figure 3b). The cube is a hexahedron obstruction with a length and height of 600 mm. This type of obstruction represents household items with a box form. The vertical cuboid is a rectangular prism obstruction with a height longer than its length, while the horizontal cuboid is a rectangular prism obstruction with a height shorter than its length. The two latter types represent the basic forms of furniture. In façade design, the potentially opaque part of the façade that corresponds to the investigation results of a vertical cuboid is described as a tall solid wall, whose width is shorter than its height. The potentially opaque part of the façade corresponding to the investigation results of a horizontal cuboid is referred to as a wide solid wall, whose width is longer than its height(Figure 3b).



a. The parameters, variables and indicators in the simulation model

b. The types of obstructions and solid walls

Fig. 3 The model and obstruction types in the simulation

2.3 Simulation variables

Five variables are defined with regard to the dimensions and positions of the obstructions (Figure 3a), namely width (w) (unit mm), length (l) (unit mm), height (h) (unit mm), l_h (unit mm) and l_v (unit mm). The distance from the horizontal middle line of the obstruction to the floor is l_h, while the distance from the vertical middle line of the obstruction to the window edge is l_v. For a model with more than one vertical obstruction, the total length of all obstructions in one model is defined as l_t.

During the investigation of daylighting, the target illuminance levels are varied depending on the task and the detail level required by the inhabitants. Table 2 shows the recommended illuminance in residential buildings in China [GB50034, 2013]. Based on the table, for a single obstruction effect analysis, the evaluation illuminance levels are 300 lux, 500 lux and 800 lux. For combined obstructions effect analysis, 200 lux and 300 lux are selected as the designated illuminance levels.

Table 2 Recommended illuminance for different types of work for residential buildings

Typical Locations	Activities	Recommended illuminance (lux)		
		Ideal	Average	Minimum
Living room, Bedroom	Movement of people	50	30	20
	Writing, reading	300	200	150
	Work requiring perception of detail	500	300	200
Kitchen, dining room	Cooking	50	30	20

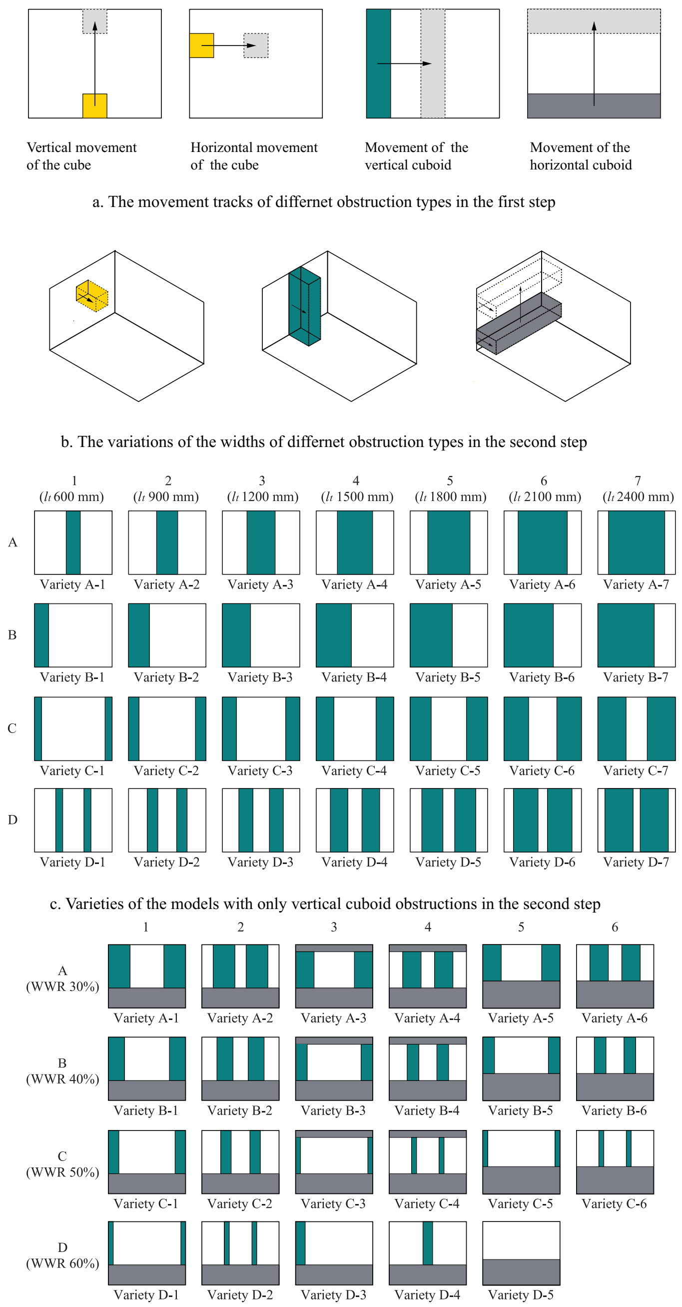
2.4 Evaluation indicators

Because of the obstructions, the illuminance contours in front of the obstructions change dramatically and sometimes a valley point appears. As a result of this research, the façade design should ensure that the illuminance in the area in front of a used space meets the recommended illuminance level on the day of the winter solstice for at least one hour at midday, according to the Chinese daylight design codes for residential buildings [GB50180, 2002; GB50352, 2005; GB50034, 2013]. Therefore, in this study, evaluation indicator D is introduced to evaluate whether the daylighting meets the Chinese standards if the space in front of the opaque part of the façade is occupied and to what extent the space can be used. D is defined as the distance from the influenced point of the designated illuminance contours to the inner window projection line, unit m (see Figure 3a). If the designated illuminance contour does not exist in the area in front of the obstruction, the D value is 0, meaning that the used space has an enormous effect on the recommended illuminance level and the corresponding façade fenestration fails to reach the daylighting level. If the same illuminance contour appears several times, the D is assigned the farthest distance. The specific D is defined as D_{800}, D_{500}, D_{300} and D_{200}, in accordance with the target illuminance contours. The maximum acceptable width of the obstruction that can meet the target illuminance level is named w_{max} (unit mm). By multiplying the w_{max} value with the height and length of the obstruction, the corresponding maximum volume of the obstruction is achieved and called V_{max} (unit m^3).

2.5 Simulation process

The simulation process consists of three steps:

- Step 1: Investigate the effect of obstruction position. The obstructions are moved along a vertical or horizontal track in front of the window (Figure 4a). The distance between each position point is 300 mm. The vertical track is along the vertical middle line of the window. The horizontal track is a horizontal line at a height of 1800 mm, but only from one window edge to the middle of the window; thus, the l_v values are from 300 mm to 1650 mm. The w value for the cube is 600 mm. The w, h and l values for the horizontal cuboid are 600 mm, 600 mm and 3300 mm, respectively. The w, h and l values for the vertical cuboid are 600 mm, 2700 mm and 600 mm, respectively.
- Step 2: Investigate the effect of obstruction width. Each of the obstructions is placed at the middle of the window ($l_v = 1650$ mm), and the w varies from 0 mm to 1000 mm with an interval of 100 mm. The differences in the simulation for each obstruction type are as follows:
  1. Cube: The l_h value for the cube is 1800 mm (Figure 4b).
  2. Horizontal cuboid: The h and l values are 600 mm and 3300 mm, respectively. The l_h values range from 600 mm to 2100 mm with an interval of 300 mm (Figure 4b).
  3. Vertical cuboid: The study for the vertical cuboid is divided into two parts: (1) The effect of widths are analyzed by changing the w values. The h and l values are 2700 mm and 600 mm, respectively; (Figure 4b)(2) based on the outcomes of the first part, the maximum width



a. The movement tracks of differnet obstruction types in the first step

b. The variations of the widths of differnet obstruction types in the second step

c. Varieties of the models with only vertical cuboid obstructions in the second step

d. Varieties of the model with both vertical and horizontal obstructions in the third step

Fig. 4 The simulation steps

of the obstructions are reported with regard to different total lengths and arrangements. Twenty-eight varieties of simulation models are proposed (Figure 4c). These varieties are different in two respects. The first respect is the total length or l_t. The chosen l_t values range from 600 mm to 2400 mm with an interval of 300 mm. The second is the obstruction distribution method. Four methods are used to arrange the obstructions. They are described as follows: one single obstruction placed next to the left edge of the window; one single obstruction placed at the middle of the window; two obstructions placed next to the two edges of the window; two obstructions placed with equal distances between the two window edges and each other. The h values for the vertical cuboid obstructions in all the varieties are 2700 mm.

– Step 3: Calculate the maximum usable space. Twenty-three varieties of optimized models with vertical and horizontal cuboid obstructions are designed based on the results of the previous two steps (Figure 4d). For each model, the V_{max} values of vertical and horizontal cuboid obstructions are calculated for both 200 lux and 300 lux illuminance contours on the 850 mm high working plane. The dimensions and distribution methods of the obstructions are as follows:
  1. Horizontal cuboid obstructions: Three types of horizontal cuboids are selected for different varieties. Two types consist of only one horizontal cuboid with an h value of 850 mm and 1150 mm. The third type consists of two horizontal cuboid obstructions: one located on the floor with an h value of 850 mm and one under the roof with an h value of 300 mm. The h value of the horizontal cuboid used in the last variety is 1080 mm because of the WWR limitation.The l values for the horizontal cuboid obstructions in all the varieties are 3300 mm.
  2. Vertical cuboid obstructions: The distribution method of two obstructions placed with equal distances between the two window edges and each other is used in all but three model varieties. In two of these exceptional varieties, a single vertical cuboid is used, because when l_t is less than 250 mm, using one vertical cuboid is more practical than two in a real project. The l_t values of the vertical cuboid are different with regard to four WWR values, which range from 30% to 60%.

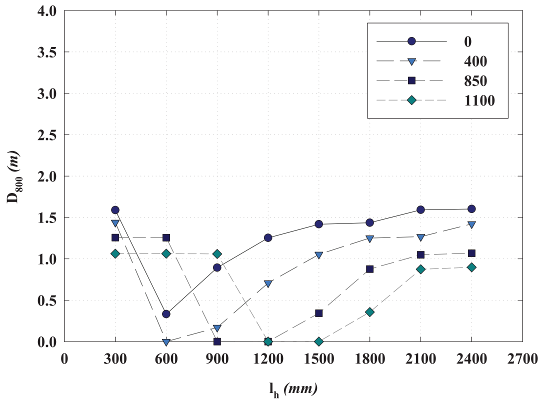
3 The effect of the single obstruction position

In this section, a single cube or cuboid obstruction is moved along the vertical and horizontal tracks in front of the window. The D values are calculated for 300 lux, 500 lux and 800 lux illuminance contours on four working plane heights, which are 0 mm, 400 mm, 850 mm and 1100 mm.

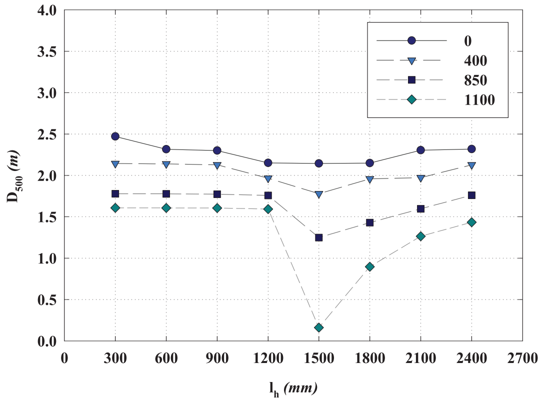
3.1 Cube position

The variations in D values at eight position heights are displayed in Figure 5. For 800 lux illuminance contours, the D_{800} values decline sharply when the obstruction is located above yet close to the working plane, in particular, when the difference between the l_h value and the working plane height ranges from 50 mm to 600 mm. For the 500 lux illuminance contours, the worst D_{500} values on all working planes appear in l_h at 1500 mm, while the D_{300} values decrease marginally with the increase of l_h. The average difference with the highest D_{300} value is 247 mm.

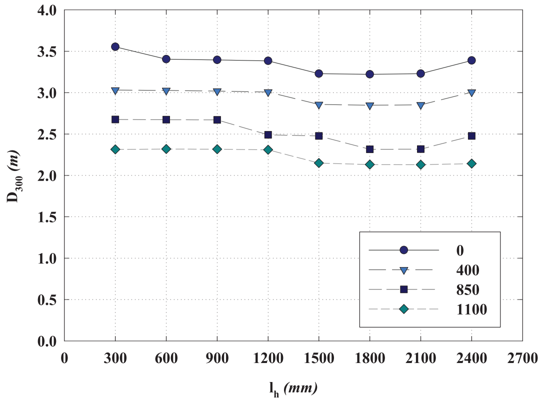
Based on the results above, when l_h reaches 1800 mm, the obstruction effects all three illuminance contours, but none of the D values is equal to 0. Therefore, 1800 mm is selected as the l_h value in the investigation of the effect of horizontal positioning so that all changes can be observed. Figure 6 shows the results. The best-performing D_{800} and D_{500} are achieved when the l_v values are greater than 1200 mm, while the l_v values for the best-performing D_{300} can be as low as 900 mm. For all the illuminance levels, the results show relatively flat curves around the best-performing



a. 800 *lux*



b. 500 *lux*



c. 300 *lux*

Fig. 5 *D* values of the cube at different position heights for different illuminance contours

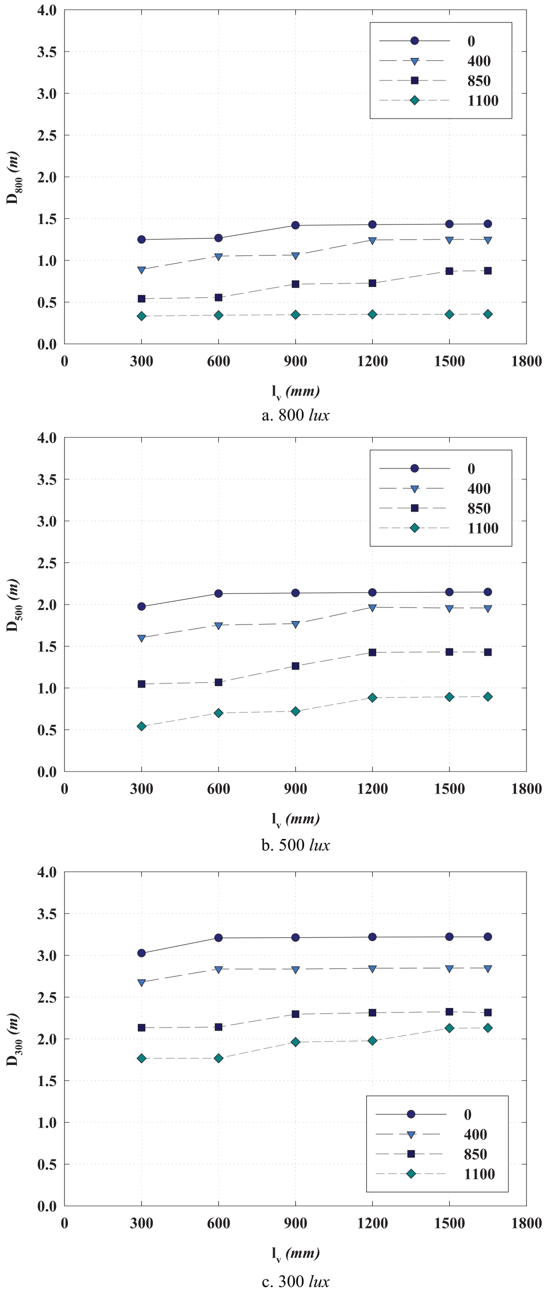


Fig. 6 *D* values of the cube at different horizontal positions for different illuminance contours

values, and the average differences between the lowest and the highest D values range from 226 mm to 316 mm.

Based on these two groups of experiments, the impact of the vertical position change of a small obstruction for lower illuminance contours is found to be minimal. For medium light requirements, placing an obstruction at a height of 1500 mm should be avoided. The suggested placement of the obstruction is at least 600 mm higher than the working plane for higher light requirements. In particular, for the working planes with heights of 0 mm, 400 mm, 850 mm and 1100 mm, the suggested placement heights of the obstruction are 600 mm, 1000 mm, 1450 mm and 1700 mm, respectively. The change in horizontal position of a small-sized obstruction has an imperceptible effect on daylighting.

3.2 Vertical cuboid position

Due to the larger volume of the vertical cuboid in comparison with the cube, this paper only presents the D_{300} values on all working planes. See Figure 7 for the results. As is evident, curves of D_{300} on a lower working plane increase slightly with an increase in l_v. For 0 mm, 400 mm and 850 mm high working planes, the average differences between the lowest and highest D_{300} values are 107 mm, 88 mm and 156 mm, respectively. Note that, for the 1100 mm high working plane, the D_{300} values are 0 when the l_v values are equal to or smaller than 600 mm, thus a vertical cuboid should be placed at least 900 mm away from the window edge under this condition.

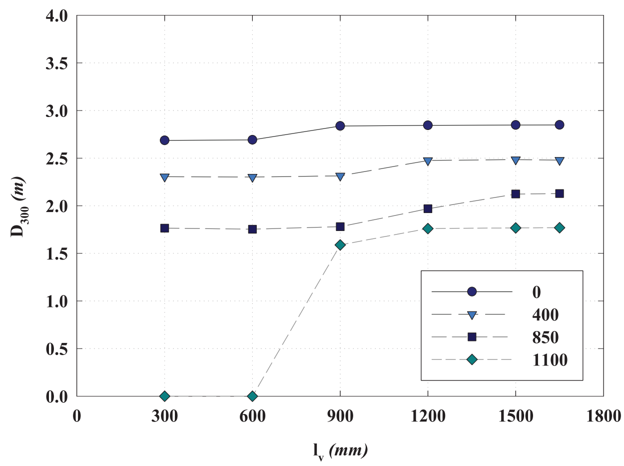
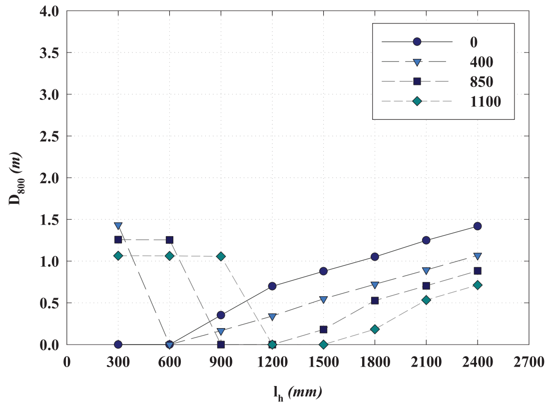


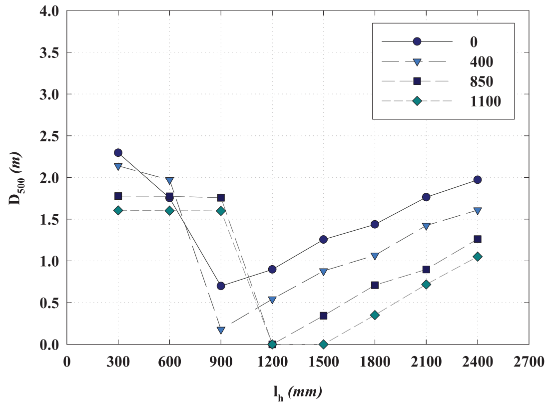
Fig. 7 D of the vertical cuboid at different horizontal positions for the 300 lux illuminance contour

3.3 Horizontal cuboid position

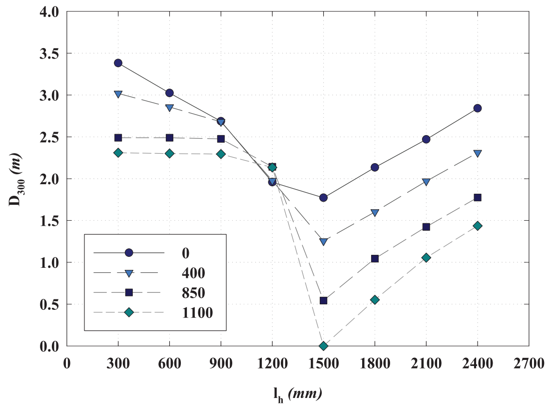
Figure 8a presents the D_{800} values of the horizontal cuboid at different position heights on all working planes. The lowest D_{800} values for all working planes appear when the difference between the l_h and the working plane height ranges from 50 to 600 mm. Figure 8b shows that the lowest D_{500} value on 0 and 400 mm high working planes appears when l_h is 900 mm, while the lowest values on 850 mm and 1100 mm high working planes are reached when the values of l_h range from 1200 mm to 1500 mm. Compared with D_{800}, the worst D_{500} values appear in a much narrower l_h range, and the affected positions are higher. The results shown in Figure 8c indicate that the D_{300} values



a. 800 *lux*



b. 500 *lux*



c. 300 *lux*

Fig. 8 *D* values of the horizontal cuboid at different position heights for different illuminance contours rapidly sink to the lowest point on all working planes, when l_h reaches 1500 mm. In the highest position, the D values are close to the largest D values; however, the average difference between the D_{300} at the highest position and the greatest D_{300} value is 755 mm, which is considerable.

Overall, the impact of the horizontal position change is less significant than the impact of the vertical position change. Based on these results, the suggested positioning of a single tall solid wall is at least 900 mm away from the façade edge, if the required working plane is higher or equal to 1100 mm. With regard to a wide solid wall, its placement at the height of 1500 mm has the most adverse effect for a lower illuminance requirement. For higher illuminance requirements, the adverse effect heights vary depending on the working plane height. In general, the suggested placement of a wide solid wall is at least 600 mm higher than the working plane. In particular, for the working planes with heights of 0 mm, 400 mm, 850 mm and 1100 mm, the suggested placement heights of the wide solid wall are 600 mm, 1000 mm, 1450 mm and 1700 mm, respectively.

4 The effect of obstruction width

In this section, D values of the three obstruction types with different widths are calculated. Based on these results, this paper presents the maximum widths of all obstruction types and the maximum volumes of combined vertical cuboid obstructions with regard to different WWR values.

4.1 Cube width

The D values on all working planes are shown in Figure 9. For the 1100 mm working plane, the curves of D_{800} and D_{500} values appear to have relatively significant declines with the increase of w. The differences between the minimum and maximum D values on the same working plane range from 0 mm to 711 mm. However, for other working planes the differences are smaller: The smallest value is 3 mm, while the greatest value is 369 mm, and the average differences range from 110 mm to 225 mm. Therefore, the width has a larger effect on daylighting on the 1100 mm high working plane than on other working planes when the obstruction height is 1800 mm. If 500 mm is set as the acceptable difference level for the 1100 mm high working plane, the suggested w_{max} values are 500 mm for the 800 lux illuminance contour, 400 mm for the 500 lux illuminance contour, and 800 mm for the 300 lux illuminance contour; for other working planes, the width of the obstruction can reach 1000 mm.

4.2 Vertical cuboid width

Figure 10a shows that the D_{800} values decline sharply to 0 in a very narrow w range of 100 to 300 mm on all the working planes. For the 500 lux illuminance contour, Figure 10b shows that, on all working planes, the D_{500} value remains the same or decreases slightly before a certain w value and then the D_{500} value declines sharply to the 0 point. As shown in Figure 10c, when the illuminance contour is as low as 300 lux, there is no 0 point for D_{300} on 0 mm and 400 mm high working planes. However, the same trend also appears for the D_{300} values on a higher working plane. As is evident from Figure 10d, the differences between all the D_{300} values and the minimum D_{300} value range from 0 mm to 533 mm before the abrupt declines, which means that the daylighting is scarcely influenced by the width before this point. This phenomenon reveals that the w that leads to the 0 value of D is indicative of the maximum width of the obstruction, or w_{max}.

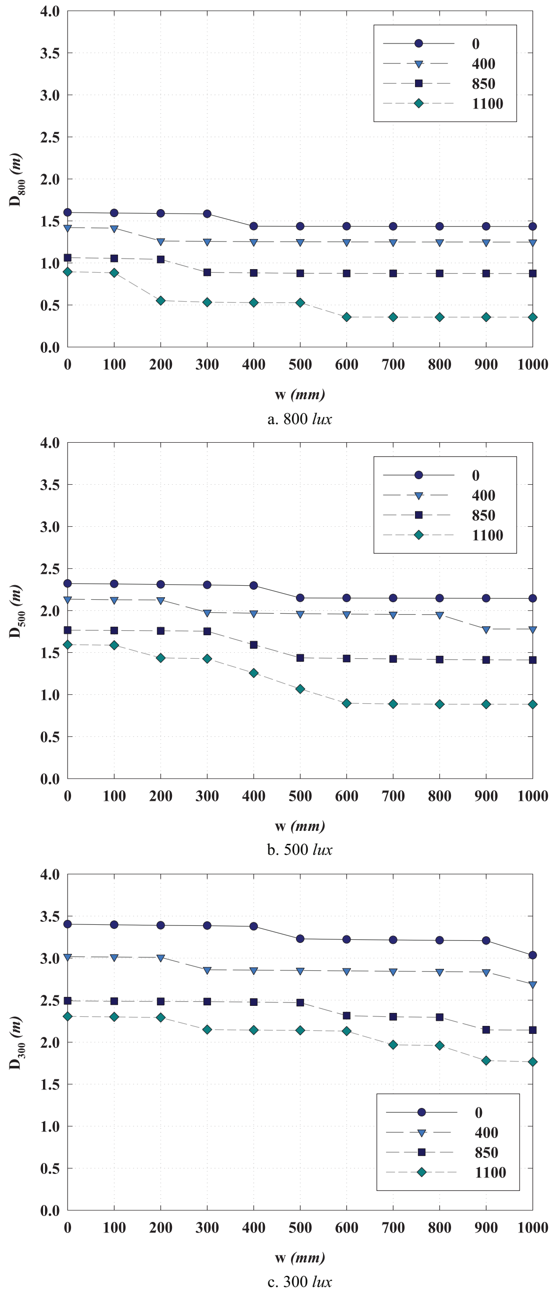


Fig. 9 D values of the cube with different widths for different illuminance contours

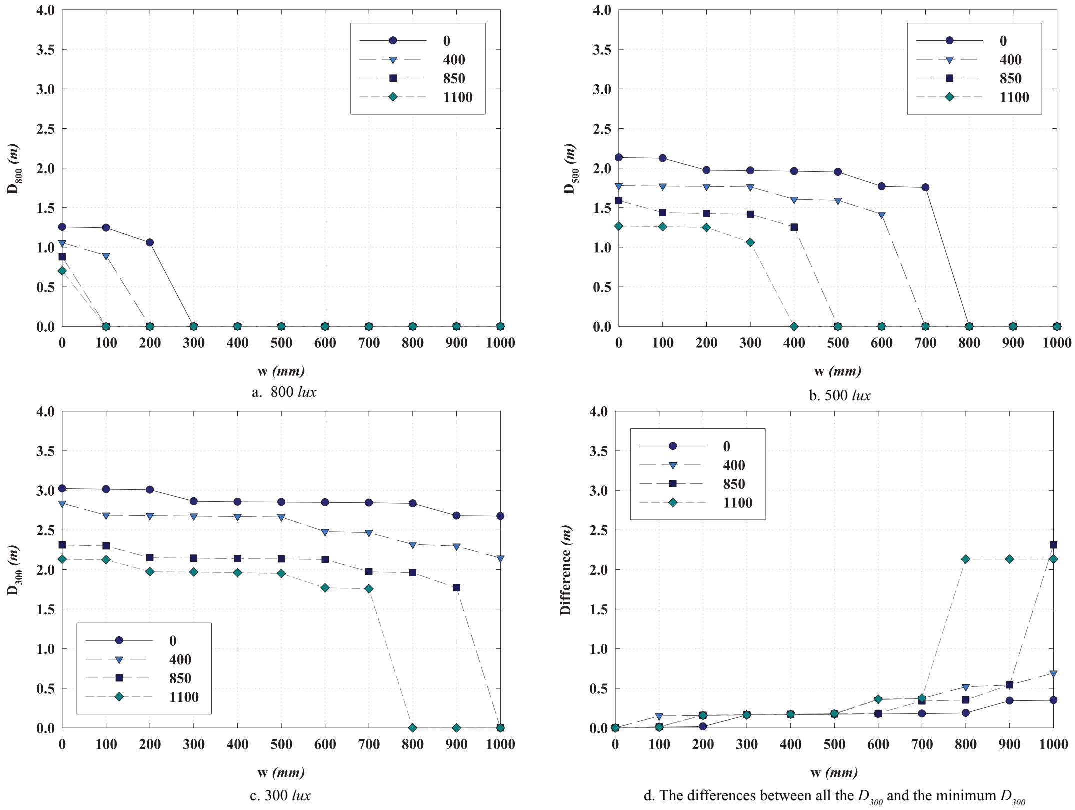
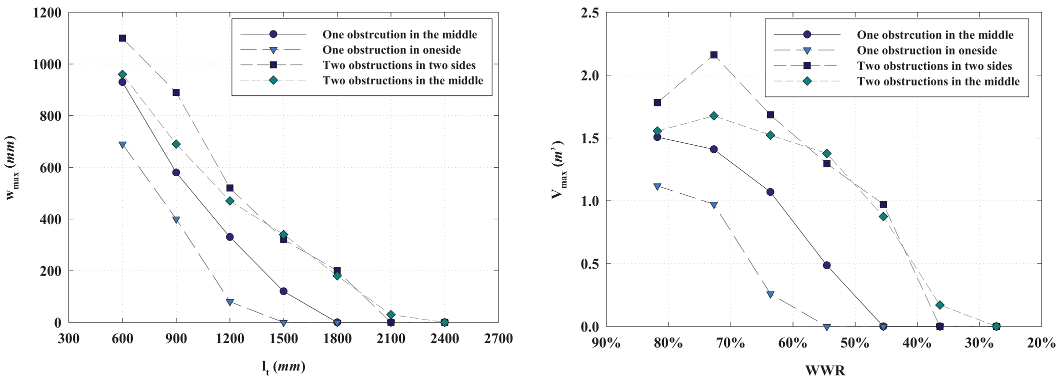


Fig. 10 D values of the vertical cuboid with different widths for different illuminance contours and the differences between all the D_{300} values and the minimum D_{300}

4.3 Maximum volume of the vertical cuboid

In line with the result in Section 4.2, twenty-eight simulation models are presented in Figure 4c. The simulations are conducted to identify the w_{max} of different vertical cuboid obstructions.

The w_{max} values of each variety for the 300 lux illuminance contour on the 850 mm high working plane are presented in Figure 11a. The maximum volumes V_{max} of the obstructions are calculated, as shown in Figure 11b, in which WWR is used in the x-axis. Figure 11a shows that when the l_t remains the same, the w_{max} curves of the models with two obstructions are above the curves of the models with one obstruction. For the models with a single obstruction, those with an obstruction at the middle of the window always achieve greater w_{max} values compared with the ones with an obstruction at the window edge. This result is consistent with the result for the maximum volume in Figure 11b. For the models with two separate obstructions, the obstructions located next to window edges perform better than the other distribution methods when the l_t values are smaller than 1500 mm, whereas with the increase of l_t, their performances tend to become similar. Note that, in Figure 11a, the greatest w_{max} for all curves appears when l_t is 600 mm, while in Figure 11b, the peak value of V_{max} appears when WWR is 72.72%, where l_t is 900 mm. Therefore, V_{max} is indicative of a more accurate value in usable space calculations. However, in practice, a WWR value greater than 60% is not recommended due to the energy performance of a façade [GB50034, 2013]; thus the calculation of V_{max} for combined constructions is necessary. The results are presented in Section 5.



a. The w_{max} of each variety

b. The V_{max} of each variety

Fig. 11 The w_{max}, V_{max} of each simulation variety for the 300 lux illuminance contour on the 850 mm high working plane

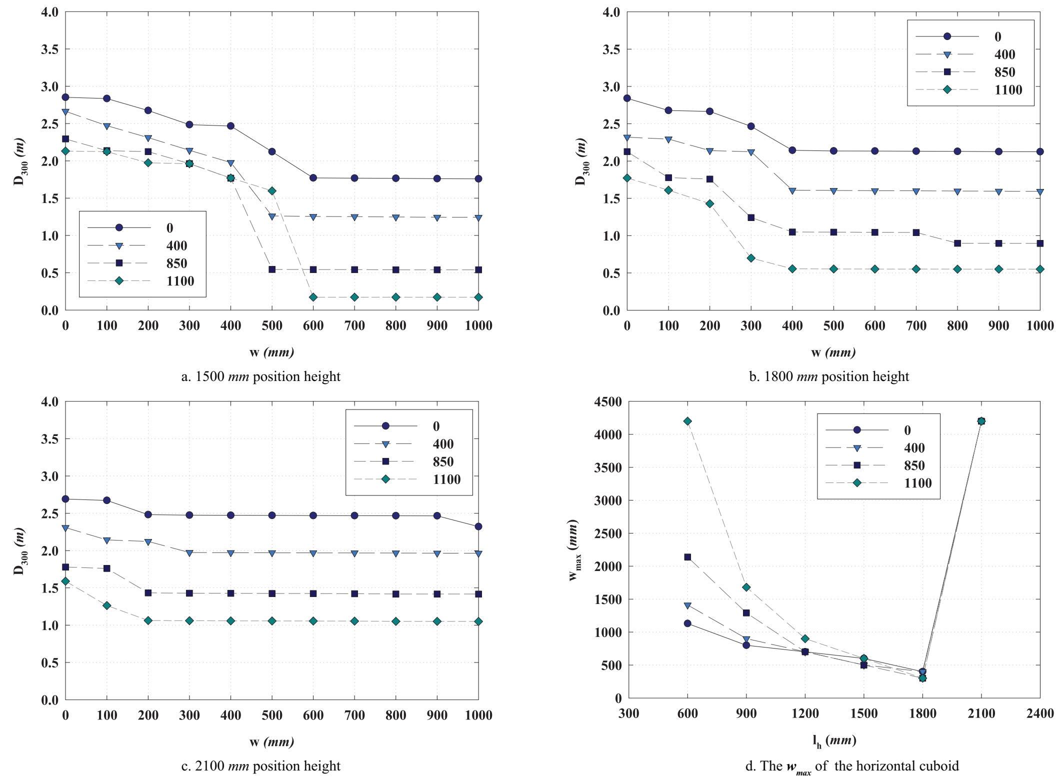
4.4 Horizontal cuboid width

The ideal locations for the horizontal cuboid are the area under the working plane and the area immediately under the ceiling. For other positions, six groups of models are simulated with different l_h values, ranging from 600 mm to 2100 mm. Figures 12a, b and c show the D_{300} values in three representative positions (1500 mm, 1800 mm and 2100 mm), which are higher than all working planes. In contrast to the curve trends in Section 4.2, only the curves of the obstructions in lower positions have abrupt declines, while at higher positions the curves gradually decrease with the rise of w. The gradual decline also appears for the D values on a higher working plane in low position heights. Therefore, accurate w_{max} values are difficult to determine in this situation. Figure 12d shows only the w values of the points at which the worst D_{300} values begin to appear. The results above indicate that the horizontal cuboid in the place where l_h ranges from 1200 mm to 1800 mm provides limited usable space and has serious implications for daylighting performance.

5 The maximum volume of combined obstructions

Taking into account all factors, the simulations in this section offer examples of how to select better-performing façade configurations to provide more usable space in perimeter zones without jeopardizing daylighting. Twenty-three varieties of simulation models were designed (Figure 4d), and for each model the V_{max} values of vertical and horizontal cuboids were calculated for both 200 lux and 300 lux illuminance contours on the 850 mm high working plane. The results are presented in Tables 3 and 4.

The results show that when the WWR values are equal, the model that has one vertical cuboid with an h value of 850 mm and two horizontal cuboid obstructions placed next to the window edges provides a larger usable space volume than the other models with different combinations. For both 200 lux and 300 lux illuminance contours, the greatest V_{max} value appears when the WWR is 50%, which is neither the lowest nor the highest WWR value. The second best V_{max} value for the 200 lux illuminance contour appears when the WWR is 40%, while for the 300 lux illuminance contour, the best value still appears when WWR is 50%, but with a different obstruction positioning (two vertical cuboid obstructions placed with equal distances between the window edges and each other). For the 300 lux illuminance contour, when the WWR is 30%, the available space volumes are significantly smaller than those under all other conditions, while for



a. 1500 *mm* position height

b. 1800 *mm* position height

c. 2100 *mm* position height

d. The w_{max} of the horizontal cuboid

Fig. 12 D values of the horizontal cuboid with different widths at different position heights for the 300 lux illuminance contour and the w_{max} of the horizontal cuboid for the 300 lux illuminance contour on the 850 mm high working plane

Table 3 V_{max} of the models with combined obstructions for the 300 lux illuminance contour (m^3)

	1		2		3		4		5		6	
	V-cuboid[1]	H-cuboid	V-cuboid	H-cuboid	V-cuboid	H-cuboid	V-cuboid	H-cuboid	V-cuboid	H-cuboid	V-cuboid	H-cuboid
A 30%	0.549	a[2]	0.480	a	0.195	a	0.391	a	0.244	3.112	0.195	1.746
B 40%	0.762	a	0.635	a	0.729	a	0.713	a	0.744	3.909	0.713	1.898
C 50%	1.271	a	1.122	a	0.746	a	0.574	a	0.495	4.364	0.653	2.315
D 60%	0.903	a	0.858	a	0.797	a	0.858	a		5.560		

[1] "V-cuboid" means the vertical cuboid, and "H-cuboid" means the horizontal cuboid.
[2] "a" means the w value of the obstruction can be as high as the room depth.

the 200 lux illuminance this difference is less significant. Except the best and worst performance points, the values in between are quite close, which means that the architects have a wider range of options in façade design if providing a large usable space at perimeter zones is not the only goal of their design. By referring to these two tables and the corresponding twenty-three varieties of façade fenestrations in Figure 4d, architects can determine the most suitable window configuration based on their design requirements for daylight level and usable space volume. The same method can also be used to find the V_{max} on other working planes or for other illuminance contours.

Table 4 V_{max} of the models with combined obstructions for the 200 lux illuminance contour (m^3)

	1		2		3		4		5		6	
	V-cuboid[1]	H-cuboid	V-cuboid	H-cuboid	V-cuboid	H-cuboid	V-cuboid	H-cuboid	V-cuboid	H-cuboid	V-cuboid	H-cuboid
A 30%	1.544	a[2]	0.892	a	0.977	a	0.830	a	0.635	4.326	0.391	3.036
B 40%	1.779	a	1.499	a	1.303	a	1.101	a	1.318	5.199	1.148	2.808
C 50%	2.096	a	1.568	a	1.049	a	0.812	a	0.772	5.806	0.944	3.036
D 60%	1.328	a	1.093	a	1.207	a	1.176	a		7.306		

[1] "V-cuboid" means the vertical cuboid, and "H-cuboid" means the horizontal cuboid.
[2] "a" means the w value of the obstruction can be as high as the room depth.

6 Conclusions

This paper investigates the effects of obstructions in front of a window on daylighting under an overcast sky. Based on the results, the maximum volumes of the usable space for 51 varieties of façade configurations are presented in two tables. These tables can help architects to determine the usable space volume for a façade with a similar fenestration geometry. The primary findings of this study can be summarized as follows:

First, the impact of a small-sized obstruction for lower daylight requirements is insignificant. In façade design, the suggested placement of wide solid walls is at least 600 mm higher than the required working plane so that the daylight level on the working plane can reach 800 lux, and 500 lux daylight can penetrate 350 mm or more deeper into the room. In addition, placing the wide solid walls at a height of 1500 mm, which has the most adverse effect on a lower illuminance requirement, should be avoided. The suggested placement of a tall solid wall is at least 900 mm away from the window edge for a higher working plane to make sure the daylight level in front of the wall reaches 300 lux.

Second, the results of the maximum usable space volume show that façades with two separate tall solid walls produce up to 1.43 m^3 more usable space than those with a single tall solid wall. Therefore, an even distribution of several tall solid walls and windows is recommended over a single large piece of tall solid wall and a window. For a façade with tall solid walls only, the maximum volume of usable space appears when WWR is 72.72%, which does not, however, meet energy standards; thus, an optimized façade design that incorporates all aspects of the built environment is essential.

Third, in terms of the optimized design of a façade with tall solid walls, wide solid walls and a fenestration in the middle, neither the greatest WWR value nor the smallest WWR value leads to the maximum volume of usable space. The optimal WWR found for usable space and daylight demand is 50%, which provides up to 2.10 m^3 of usable space volume. If the daylight requirement is lower, the WWR value of 40% provides the second largest maximum volume of usable space so that windows can be designed with considerable architectural freedom. However, a WWR value equal to or lower than 30% is not recommended for small residential rooms.

The conclusions of this study are drawn mainly based on evaluating the daylight level in a south oriented room with obstructions against Chinese standards. It would also be important to examine the impacts on the indoor thermal and visual, e.g., overheating and glare, of increasing WWR for a larger usable space, and the daylighting in rooms with obstructions in other orientations. Moreover, the effects of improved daylight condition on human behavior for lighting energy reduction would also be interesting to explore.

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