A SIMPLE METHOD TO DETERMINE THE DAYLIGHT FACTOR FROM THE VERTICAL DAYLIGHT FACTOR IN DIFFERENT STREET CANYON GEOMETRY

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ABSTRACT
This paper investigates the main characteristics of daylight on any window in a street canyon. The sky component and the light reflected from the surroundings are described to determine the vertical daylight factor (VDF). Several street canyon types are characterized taking into account their different height/width and any level of the window is analysed. A simple calculation method uses trigonometric equations based on the sky and the geometry of the canyon. The results were previously evaluated considering different daylight procedures obtained by other studies. This study reveals that the reflectance within an urban canyon plays an important role in the amount of daylight onto any window with more relevance in a deep canyon and low sky view. The graphical presentation that result from this investigation can rapidly assist building and urban designers in an early stage design where assumptions and the lay out of the main design take place.

KEYWORDS
vertical daylight factor, urban canyon, configuration factor, diffuse light, isotropic overcast sky

INTRODUCTION
A variety or architectural solutions were in the past and even now based on rules of thumb and not necessarily on simulations. An example of these rules is that the depth of a room should not be longer than 2.5 times the window header height (Reinhart 2005). Whatever the technique is, geometric or not, the amount of daylight on the window is crucial to provide sufficient natural light into a room, so it could be called daylit. When a building is located in a rural area, it might have an ample view of the sky. In these circumstances, the amount of available daylight is only dependent on the sky illuminance and on the geometry of the building. Alternatively, in the city, the building faces other buildings, which are an obstacle to the sky view. This definitely changes the perception of daylight when compared to the previous

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situation. Reflected components can be a great source of interior lighting, however, nearby buildings partially obstruct the sky view and consequently reduce received diffuse light.

The interior natural illuminance is often treated in terms of the daylight factor (DF) with an estimation based on an overcast sky and therefore excluding direct sunlight. This is generally considered to provide the worst daylight conditions which, from this point onwards, can only be improved. It has been a useful criterion provided by design manuals for architectural evaluation (Brown and DeKay 2001), (Szokolay 2008), (P. Tregenza and Wilson 2011), (Lechner 2015). DF can be estimated if the characteristics of the room, the window and angle of visible sky are known, considering externally diffuse and reflected light. However, in a street canyon, the reflected light coming from below the skyline and formed by the opposite buildings is not taken into account to estimate the average daylight factor. Only the angle of the visible sky is taken into account regardless of the height of the opposite building (Capeluto 2003), (Simm and Coley 2011), and (P. Tregenza and Wilson 2011). DF can also be estimated through the vertical daylight factor (VDF) on the outer surface of the window (P. Tregenza and Wilson 2011). VDF has been used as a way to determine the provision of natural lighting in buildings as per Li et al. (Li et al. 2009), considering Hong Kong as being a densly populated city. The minimum VDF required is 8% for habitable rooms and 4% for kitchens. The predicted VDF by RADIANCE simulation demonstrates that an upper obstruction of the window at 60º and a lower obstruction at 10º reduces the daylight level by up to 85% (Strømann-Andersen and Sattrup 2011). Obviously, the natural light available indoors strongly depends on the amount of daylight reaching the outer surface of the window (Li et al. 2010). Littlefair (Littlefair 2001) stated that under a standard CIE Overcast Sky, the maximum value of the VDF is almost 40% for a completely unobstructed vertical wall. When partially obstructed, as in a street canyon, estimating its value can be time consuming, and it does not encourage building designers to use an evaluated tool when beginning the design process. This is the main purpose of this study, to present building and urban designers with tools to help the early design process and thereby making it less time consuming. Several graphical presentations can assist building and urban designers in an early stage design before any computer simulation is introduced. These graphical outputs are the result of a proposed methodology that is being compared with other manual methods and therefore being validated.

Tregenza(P. R. Tregenza 1995) presented a method for estimating the mean illuminance on the working plane using solar normal illuminance and horizontal illuminance. It calculates direct illuminance on a window from sunlight and also from skylight as well as street reflected light and inter-reflection light between facades. This uses the configuration factor which is a geometric relationship that defines the obstructions seen from each facade. It is intended for manual calculation or for implementation in a simple computer spreadsheet. The methodology of the present study can be used in the same way as the graphical presentation for a quick estimation of the DF. The description of the method and the worked example refer to an urban canyon with buildings of the same height on both sides of the street. Wa-Gichia (Wa-Gichia 1998) presented a study that demonstrates that the opposite facade can increase the daylight on a window in clear sky conditions. When the sunlight falls directly on the opposite building, the reflected light will reach a window of the shadowed building which would not happen on an open field situation. Similar results were obtained by Tsangrassoulis et al. (Tsangrassoulis et al. 1999) when investigating the reflectivity of south-oriented facades. Unfortunately, during an overcast sky, the opposite buildings diminish the view of the sky and therefore the light that falls onto the window is reduced, as demonstrated in the present study.

As Li (Li 2010) stated, overcast skies are considered to provide the worst daylighting conditions when the sky diffuse component is dominant. To determine daylight, the traditional approach considers the effect of external obstruction using a mean angle of vertical obstruction with an average fraction of the sky luminance. Strømann-Andersen and Sattrup (Strømann-Andersen and Sattrup 2011) have found that the geometry of urban canyons has a significant impact on the energy consumption of a building. Ünver et al. (Ünver et al. 2003) have found that at a high obstruction angle, at the bottom of a deep canyon, the amount of indoor daylight relies on the transparency ratio of the façade in receiving light.

This paper presents a calculation method to determine the VDF on facades facing different external urban obstructions. It determines the daylight from the sky component and the reflected light from surrounding buildings and street surfaces. In this study, a uniform overcast sky condition has been assumed, as some researchers did previously (Li 2010). A simple calculation method was established and evaluated considering different daylight procedures obtained by other studies. It was found that the present method was in good agreements with those produced by simulating results from worked examples, as in Tregenza (P. R. Tregenza 1995), Tregenza and Wilson (P. Tregenza and Wilson 2011) and Li et al.(Li et al. 2009). In the early stage of the design process it involves layout exploration where creative strategies are tested. In current architectural practice the architect must be able to sketch, mostly on paper, and search for information in an easy and intuitive way. Based on formulating design guidelines (Littlefair 2001), (Brown and DeKay 2001) and other requirements the architect tests his work hypotheses by making many adjustments while designing and before undergoing the next design stage. The graphical presentation of the results represent different canyon characteristics. Thus, this can also assist designers in an early stage design when evaluating a prototype model and taking into account the availability of daylight in a non time-consuming process.

2. THEORETICAL AND GEOMETRICAL APPROACH

The daylight factor on a point (DF_p, in %) is estimated based on the relation between the received illuminance on the point (Ep, in lx) and the external unobstructed horizontal illuminance (Eh, in lx), for overcast sky conditions (Ramos and Ghisi 2010).

$$DF_p = \frac{E_p}{E_h} 100\% \tag{1}$$

An expression to estimate the average daylight factor (DF_{BRE}, in %) in an enclosed space was developed by the Building Research Establishment (BRE) that is widely used by several authors (P. Tregenza and Wilson 2011), (Simm and Coley 2011) and (Capeluto 2003):

$$DF_{BRE} = \frac{\theta A_g \tau_g}{A_r\left(1-\rho_r^2\right)} \tag{2}$$

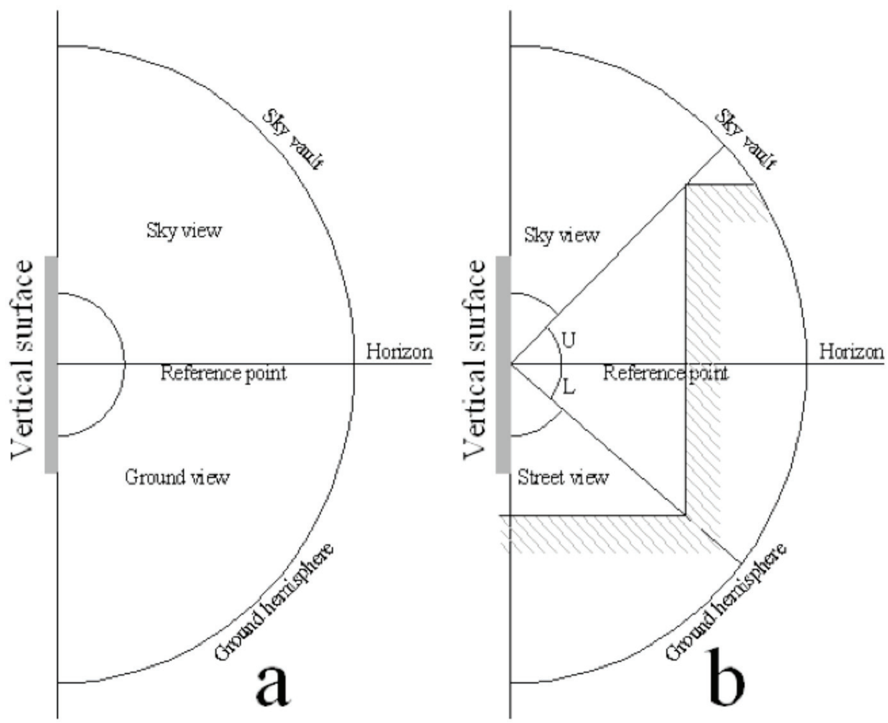
Where θ is the v angle of visible sky from the center of the window (degrees), A_g the glazing area (m^2), τg is the transmittance of glazing, A_r the total area of internal surfaces of the room (m^2) and ρr the area-weighted average reflectance of interior surfaces. The average daylight factor (DF_{VDF}, in %) can also be estimated based on the vertical daylight factor (VDF, in %) on the centre of the window (P. Tregenza and Wilson 2011), as:

$$DF_{VDF} = \frac{2VDFA_g \tau_g}{A_r(1-\rho_r^2)} \quad (3)$$

The total diffuse light received on any vertical surface without any obstacle to the hemispherical view of the sky and ground is the sum of the diffuse light from the sky and the reflected component from the ground. For an unobstructed vertical surface, the sky vault covers half of the hemisphere view while the other half is attributed to the ground, as shown in Figure 1a. Throughout this study it is assumed that the sky is isotropic, meaning that the vault has the same luminance in all directions. Under this assumption and given the horizontal illuminance (E_h, in lx), the illuminance from the sky vault on the vertical facade (E_d, in lx), is:

$$E_d = E_h F_s \quad (4)$$

FIGURE 1. Hemispherical view from the vertical facade.



And the reflected component from the surrounded ground (E_r, in lx), is:

$$E_r = E_h F_g \rho_g \quad (5)$$

Where, F_s and F_g, is the view factor of the sky and the ground to the vertical surface, and ρ_g, is the reflectance of the ground. Taking into account the geometric arrangement shown in Figure 1a and a reference point of the vertical surface, the normal to the surface, the sky and ground half hemisphere, F_s and F_g are calculated with a simple geometric formula as in Thevenard and Haddad (Thevenard and Haddad 2006) and Gueymard (Gueymard 2009), as:

$$F_s = \frac{1-\cos(s)}{2} \quad (6)$$

And

$$F_g = \frac{1+\cos(s)}{2} \quad (7)$$

Where, s, is the tilt angle of the surface from the ground (degrees). For a vertical surface (s = 90°) the F_s and the F_g are 0.5, respectively, meaning that half of the hemispherical view from the surface is attributed to the sky vault and the other half to the infinite foreground. The sky illuminance that falls onto a vertical surface is half of that received on an unobstructed horizontal one. Similarly, the illuminance that falls onto the vertical surface from the ground is half of the reflected illuminance.

When a vertical facade is in an urban environment, the opposite building creates an obstacle to the hemispherical view of the sky and ground, as illustrated in Figure 1b. This reduced view of the sky happens when the skyline of the opposite building is higher than the reference point or the normal to the surface, which in this case is a window. Therefore, this reduced view of the sky from the surface can be given as a configuration factor of the sky view (cf_s) referred to in Tregenza (P. R. Tregenza 1995):

$$cf_s = \frac{\sin(90)-\sin(U)}{2} = 0.5 - \frac{\sin(U)}{2} \quad (8)$$

Where, U, is the altitude angle of the skyline above the horizon, measured perpendicular to the facade (degrees). The first term is the view factor of the sky from eq. (6) and the second is the reduced part due to the opposite facade. The same procedure is followed later on by Wa-Gichia (Wa-Gichia 1998) and Li et al (Li et al. 2010). A similar approach is possible when it considers the reduced view of the infinite ground, as:

$$cf_g = \frac{\sin(90)-\sin(L)}{2} = 0.5 - \frac{\sin(L)}{2} \quad (9)$$

Where, L, is the altitude angle of the opposite building below the horizon, measured perpendicular to the facade (degrees). To find the illuminance onto the vertical surface in a street canyon from the sky and from the ground, equations (4) and (5) can be rewritten as:

$$E_d = E_h cf_s \quad (10)$$

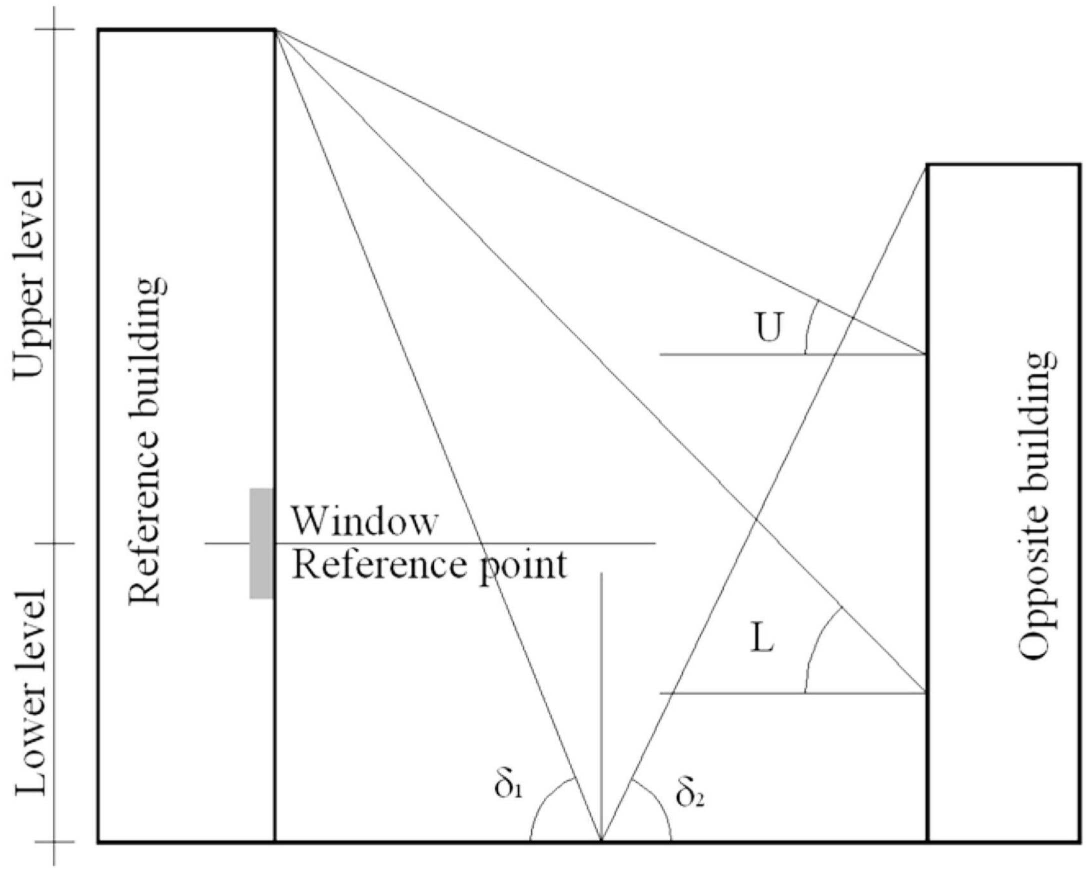
And,

$$E_r = E_h cf_g \rho_g \quad (11)$$

Considering a street canyon, it may be important to know the downward and upward flux that reaches a window in order to determine the indoor illuminance. A split-flux method is then desirable. Taking this into consideration, the vertical canyon is divided into zones (upper and lower). These are related to a window under study. Therefore, from the mid height of the window, the opposite building has upper and lower angles, as shown in Figure 2.

For each of these angles a configuration factor is determined according to the eq. (8) and (9) where the illuminance from the sky is through eq. (10).The sky view from the street surface is also reduced by the buildings on both sides. However, the light that first falls on the street is a special case according to Robinson and Stone (Robinson and Stone 2004). Besides the light from the sky, the contribution from both sides of the street is required. Therefore the illuminance that falls onto the street is:

FIGURE 2. Street canyon geometry and worked angles.

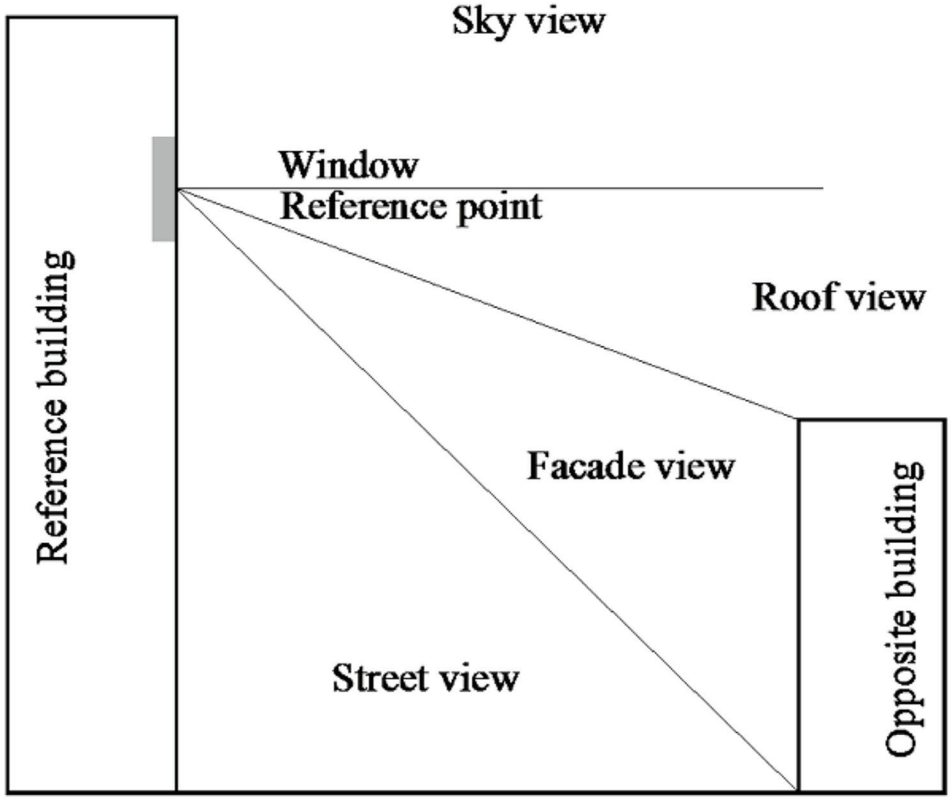


$$E_g = E_h \frac{\cos(\delta_1)+\cos(\delta_2)}{2} + E_1\rho_1 \frac{1-\cos(\delta_1)}{2} + E_2\rho_2 \frac{1-\cos(\delta_2)}{2} \quad (12)$$

Where, δ, is the angle formed between the normal to the street and the top of each building on both sides of the street (degrees), E is the illuminance received on each building from both sides of the street (lx) and ρ is the reflectance of each building on both sides of the street. The obstruction geometry angles as viewed from the street are shown in Figure 2. When the window is above the level of the skyline of the opposite buildings, another surface that reflects light onto the window must be added, therefore corresponding to the visible roofs (Carlos and Martins 2014). This component is treated within this study as an unobstructed ground. It is a simplification of several possible shaped roofs as seen from the window. The reference angles at the midpoint of the window, for the referred scenario, are shown in Figure 3.

The reflected illuminance received from the opposite wall above and below the horizontal plane at midpoint of the window, for given illuminance, is estimated according to Robinson and Stone (Robinson and Stone 2004) from:

FIGURE 3. The angles used at the midpoint of the window.



$$Er_o = E_o cf_o \ {}_o \tag{13}$$

Where, Er_o, is the reflected illuminance from the opposite wall (lx), E_o, is the given illuminance on the opposite wall (lx), ρ_o, is the reflectance of the wall and cf_o, is the configuration factor given by:

$$cf_o = \frac{\sin(\theta_o)}{2} \tag{14}$$

Where, θ_o, is the obstruction angle as seen from the midpoint of the window (degrees). For the upper wall, the angle is measured from the normal to the window and onto the skyline of the opposite building. For the lower wall, the angle is from the normal to the window and onto the street level. The received illuminance from the street level is from:

$$Er_g = E_g cf_g \rho_g \tag{15}$$

All that remains is to determine the inter reflected illuminance in the street canyon that reaches the window. The total flux on the window coming from reflected light originally incident on the obstructing buildings and ground is given by (Li et al. 2009):

$$Er = (Er_o + Er_g)\frac{1}{1-\rho} \tag{16}$$

Where, ρ, is the effective mean external reflectance given by (P. Tregenza and Wilson 2011):

$$\rho = \frac{2h\rho_f + w\rho_g}{2h + 2w} \tag{17}$$

Where, h is the height of the building (m) w, is the width of the street (m). The vertical daylight factor (VDF) is defined as the ratio of the percentage of the total daylight illuminance amount falling onto a vertical surface to the horizontal illuminance which excludes direct sunlight. In an urban context, light coming directly from the sky and reflected from the surrounding environment is taken into account, where the latter derives from the opposite buildings and the street level. Finally, the VDF can be written as (Li et al. 2009):

$$VDF = \frac{E_d + E_r}{E_h} 100\% \tag{18}$$

3. COMPARISON WITH EXISTING WORKED EXAMPLES

The presented procedure has been compared analytically with worked examples from two studies. The first oneby Tregenza (P. R. Tregenza 1995) who estimates the mean illuminance on a window in a street canyon via a configuration factor related to the window. The second by Tregenza and Wilson (P. Tregenza and Wilson 2011) who present a methodology to calculate the skylight in the urban canyon. This involves the form factors that replace the configuration factors presented in equations (10) and (11). Although using different methods, these examples study a street canyon with continuous buildings of the same height on both sides of the street. The methodology now proposed uses a configuration factor to determine the overall illuminance on different surfaces as well as the reflected component. This is less time consuming than the method using the form factors, particularly on urban canyons with buildings of different heights on both sides of the street.

The level of precision reached by the present procedure is being compared to those obtained by the two worked examples (P. R. Tregenza 1995) and (P. Tregenza and Wilson 2011), as a ratio between the calculated illuminance on each surface and the horizontal illuminance. The characteristics of the street canyon on both examples are shown in Table 1. These are the width of the street (width), the height of the facade from the street to the window centre (height 1), the height of the facade from the window centre to the top of the building (height 2), the reflectance of the street (ground - ρ_g), the reflectance of the buildings (building - ρ_b) and the used horizontal illuminance (E_h, in lx).

TABLE 1. Characteristics of the worked examples.

Examples from	width (m)	height 1 (m)	height 2 (m)	ground ρ_g	building ρ_b	E_h (lx)
Tregenza(P. R. Tregenza 1995)	15.00	1.34	8.66	0.20	0.40	15.200
Tregenza and Wilson(P. Tregenza and Wilson 2011)	8.50	4.75	2.75	0.20	0.50	45.38

From the first example there is a uniform obstruction angle of 30º above the horizon seen from the midpoint of the window. One may say that the midpoint of the window is about to 1.34 m above the street level and 8.66 m from the top of the building. The illuminance on the window from the sky, considering the referred study, is found to be about 25% of the horizontal illuminance. This depends on the window level of the façade in relation to the opposite building. Therfore, it relies on the obstruction angle above the horizon seen from the midpoint of the window. The method now proposed presents the same value. The illuminance on the street beneath the facade of the building assumed the same value as the unobstructed horizontal surface. According to eq. (12) this would be reduced to 62% due to the reduced sky view. In the second example the window has an obstruction angle of about 18º. The illuminance on the window from the sky is 35% of the horizontal illuminance, being the same value now proposed. Form factors are used to find the mean illuminance from an area source onto another area in a split-flux method. In this example the mean illuminance on the lower facade zone below the midpoint of the window is of 25%, while using the proposed configuration factor of 24%. The upper zone of the facade is 42% using both methods.

A comparison with another study is presented. Li et al. (Li et al. 2009) presented a new technique for determining the vertical daylight factor (VDF). The performance of their method was evaluated taking into account other computer simulations. It deals only with illuminance under an anisotropic sky. The obtained VDF from the methodology proposed in this manuscript was compared to those that resulted from the worked examples of the referred study. Those examples considered heavily obstructed environments. The obstruction angle above the midpoint of the window was 60º at various obstruction angles below the midpoint of the window, from 10º to 50º. Strømann-Andersen and Sattrup (Strømann-Andersen and Sattrup 2011) stated that a VDF prediction by RADIANCE simulation demonstrates that an upper obstruction at 60º and a lower obstruction at 10º reduces the daylight level by up to 85%. An upper obstruction angle of 70º and lower angle of 10º was also analysed. The reflectance of the buildings is 0.4 and of the street it is 0.2 as well as 0.15. From the several compared simulations presented by Li et al. (Li et al. 2009), the results from RADIANCE were the ones closest to their proposed technique. The results from the remaining compared simulations are much lower than those from RADIANCE, being then excluded from this

TABLE 2. Comparison of VDF and DF obtained from different methods and the one proposed in this study.

Upper obstructing angle (º)	Lower obstructing angle (º)	Li et al.(Li et al. 2009) RADIANCE (ρ_g=0.2)	Li et al.(Li et al. 2009) RADIANCE (ρ_g=0.15)	Li et al.(Li et al. 2009) method (ρ_g=0.2)	Proposed method (ρ_g=0.2)	Proposed method (ρ_g=0.15)	Sky visible angle (º)	DF (BRE) (ρ_g=0.2)	DF (VDF) (ρ_g=0.2)	DF (BRE) (ρ_g=0.15)	DF (VDF) (ρ_g=0.15)
60	10	14.76	13.89	14.99	15.54	14.37	30	1.7	1.8	1.7	1.6
60	20	14.41	13.74	14.59	14.91	13.98	30	1.7	1.7	1.7	1.6
60	30	14.07	13.59	14.27	14.31	13.60	30	1.7	1.6	1.7	1.5
60	40	13.77	13.43	13.96	13.75	13.23	30	1.7	1.6	1.7	1.5
60	50	13.51	13.28	13.47	13.22	12.87	30	1.7	1.5	1.7	1.5
70	10	8.20	7.61	8.15	10.01	8.91	20	1.1	1.1	1.1	1.0

comparison. Table 2 presents the comparison of VDF revealed through RADIANCE, a specific technique (Li et al. 2009) and the ones obtained with the present method. Columns 3 to 5 present the VDF obtained from the referenced literature, while columns 6 and 7 present the results obtained by the proposed method. Colums 9 and 11 presents the DF obtained by the BRE method (P. Tregenza and Wilson 2011), (Simm and Coley 2011), and (Capeluto 2003) through equation (2). Columns 10 and 12 presents the DF obtained with equation (3) using the VDF values from columns 6 and 7.

The relative difference of the VDF between the results obtained by different methods shown in Table 2 and the proposed method, according to:

$$\frac{results\_from - analyzed\_study}{proposed\_method} 100\% \tag{19}$$

Most of the results from Li et al. (Li et al. 2009) overestimated the ones that were obtained from RADIANCE. For a street reflectivity of 0.2 the difference reached 1.6%. For a street reflectance of 0.15 the difference was higher as referred in the study. The other two methods not shown in Table 2 were based on the Tregenza split-flux method. They were underestimated at least by 30% of the RADIANCE results. The proposed method presents a difference from -2.2% to 5.0% from RADIANCE and from -1.9% to 3.5% from Li et al. (Li et al. 2009) for a street reflectance of 0.2. The exception is the example with heavy obstruction angles, which differs by about 18%. Table 2 also presents the average DF estimated with equations (2) and (3). While the BRE method relies only on the angle of the visible sky, the proposed method takes into account the reflectance of the street canyon. The results of the different comparisons are very close to the proposed method.

4. RESULTS AND DISCUSSION

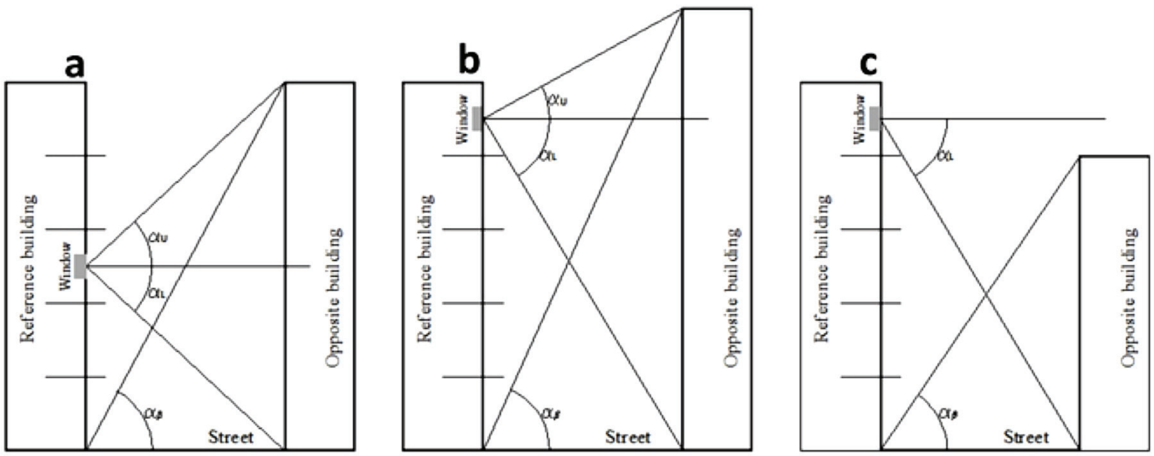
The research was carried out using a proportional urban canyon based on types of urban spaces presented by Strømann-Andersen and Sattrup (Strømann-Andersen and Sattrup 2011). The urban patterns defined six different canyons by their height/width ratio (H/W) ranging from 0.5 to 3 (Table 3). The highest ratio is usually found in the centre of the cities and are therefore more compact. On the contrary, the lowest is found in the suburbs.

TABLE 3. Urban canyon typology under study.

Street width	5 m	7.5 m	10 m	15 m	20 m	30 m
Height/Width ratio (H/W)	3.0	2.0	1.5	1.0	0.75	0.5

Each canyon was defined for a 5 storey building with a height of 15 m on both sides of the street. As these urban canyons always represent buildings of the same height on both sides of the street, two more typologies are included in this study. For the previous canyon, the opposite building will also be 18 m and 12 m high, corresponding to a 6 and 4 storey buildings, respectively (Figure 4). This represents street canyons of cities where the uniformity of the urban design, meaning skylines, is not constant.

FIGURE 4. Obstruction angles and canyon typologies under study.



The analysis of the available diffuse light on the canyons is presented, comparing the VDF on windows of diverse urban scenarios and on different levels of the facade. Since the reference building is a 5 storey building, the windows under study are located on the ground, 2nd and 4th floors. Li et al. (Li et al. 2009) has defined three major angles to define the shading effect of the urban canyon. The upper obstructing angle (α_U) and the lower obstructing angle (α_L) to the reference point of the vertical window (Figure 4). The overall facade of the obstruction angle (α_β) is related to the previous ones, as $\tan(\alpha_\beta)=\tan(\alpha_U)+\tan(\alpha_L)$. However, this does not represent the different levels of the window on the facade. Another geometric relationship is found to define the whole hemisphere view of the urban canyon in relation to the reference point, as in Fig 1a. The same angles (α_U) and (α_β) are used. The hemispheric view from a specific window in an urban canyon is defined through $\cos(\alpha_U)\cos(\alpha_\beta)$. When the product is 1 it means that the window does not have any vertical obstacle but an infinite sky and also an infinite ground below the horizon.

The VDF on the window is analysed in terms of correlation with the hemispheric view of the window regarding its level. The analysis is done in terms of the:

(i) floor level;
(ii) canyon reflectance (building = 0.45 and street = 0.2);
(iii) sky view.

Despite the canyon ratios, the window on the 4th floor is the one that obtains the highest VDF values. It has a higher sky view at its higher location. In the narrow canyon, with a sky view of 73º the VDF is about 43% while for the wide canyon with a sky view of 87º the VDF is about 58% as seen in Fig. 5. At a window on the ground floor of a narrow street the sky view falls to about 20º and the VDF to about 11%. Curiously, the window on the second floor does not obtain any intermediate values as it stands in the middle of the facade. This is due to the combination of the obstruction angles. While the facade obstruction angle is the same (71.6º), the obstruction angle of the window is about 70º on the ground floor and about 56º and 17º on the second and fourth floor, respectively.

For the narrowest streets the reflected component would correspond to the biggest component of daylight being the window on the ground floor. The light coming directly from the sky represents only about 3% of the VDF. With an overcast sky, the reflected light from the

FIGURE 5. VDF against canyon sky view.

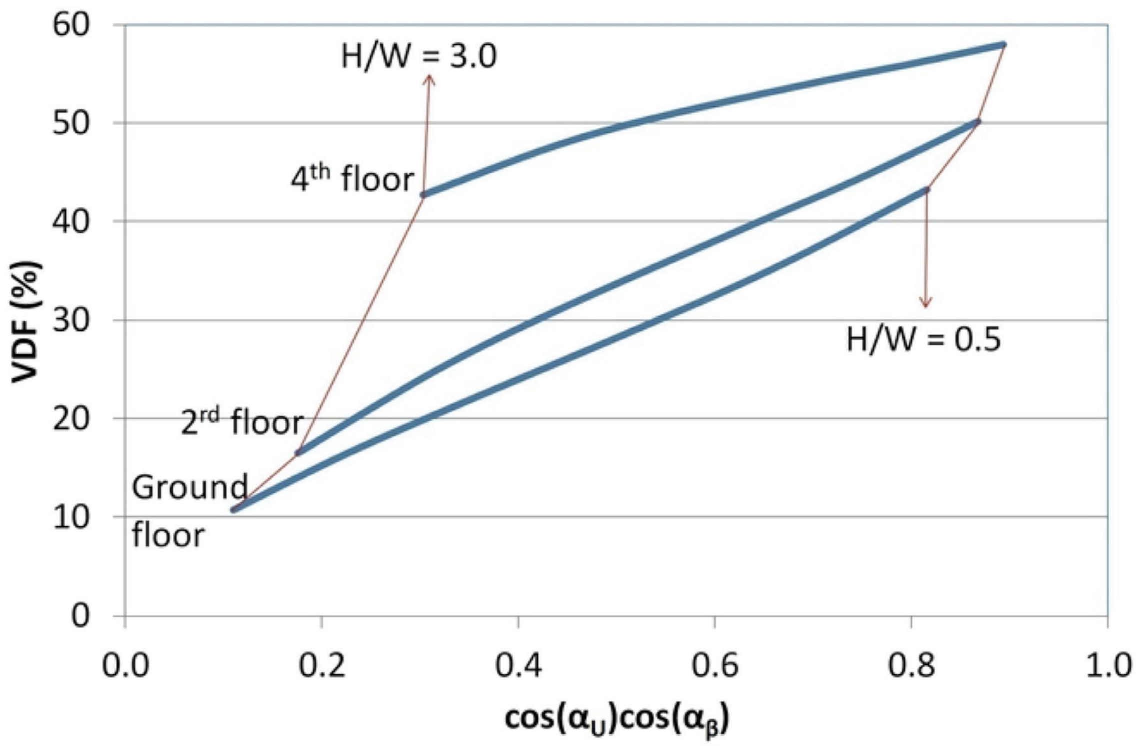


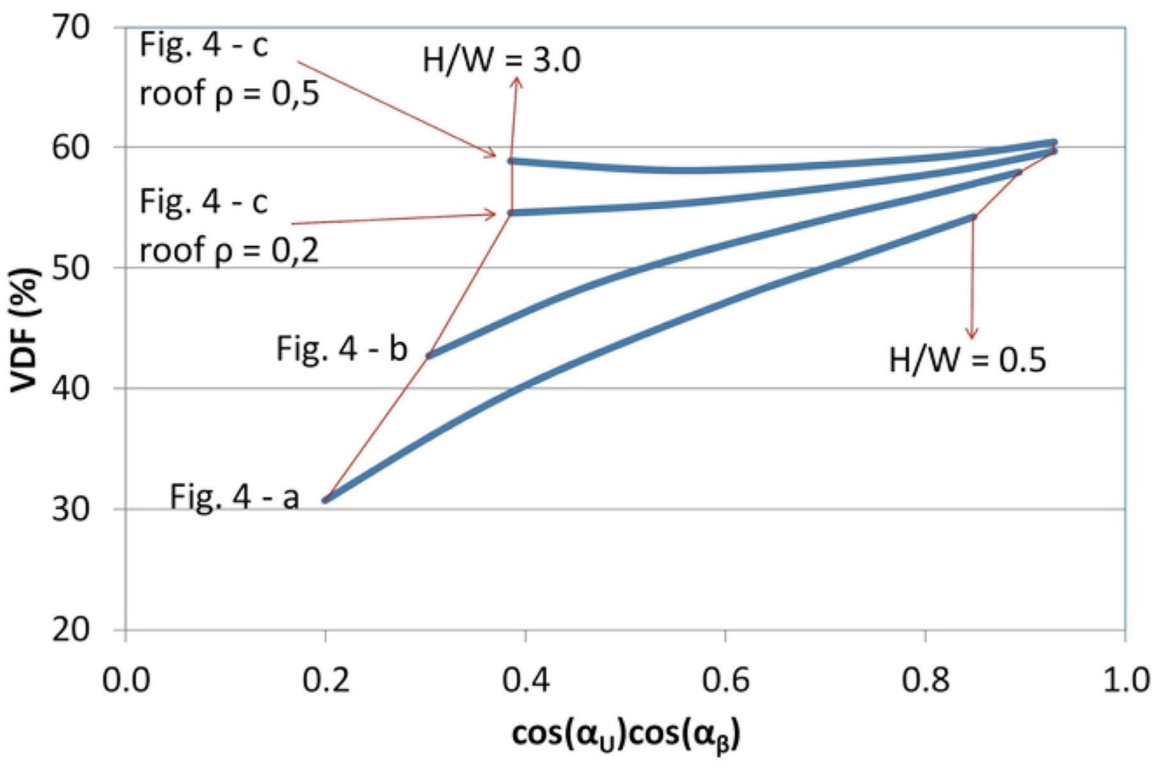
TABLE 4. Average DF comparison.

Street width		5 m	7.5 m	10 m	15 m	20 m	30 m
4th Floor	Sky view (°)	73	79	81	84	86	87
	DF_{BRE}	3.1	3.3	3.4	3.5	3.6	3.6
	DF_{VDF}	3.6	4.0	4.2	4.5	4.7	4.8
2th Floor	Sky view (°)	34	45	53	63	69	76
	DF_{BRE}	1.4	1.9	2.2	2.6	2.9	3.2
	DF_{VDF}	1.4	2.1	2.6	3.3	3.7	4.2
Ground	Sky view (°)	20	29	37	48	56	66
Floor	DF_{BRE}	0.8	1.2	1.5	2.0	2.3	2.7
	DF_{VDF}	0.9	1.3	1.8	2.4	3.0	3.6

ground adds about 5% to the light that reaches a window (P. Tregenza and Wilson 2011), but in the present case, the reflected component adds about 8%. Knowing VDF, DF may be estimated based on equation (3). A room as in Tregenza and Wilson (P. Tregenza and Wilson 2011) with a total surface wall of 107.5 m^2 and a room with a mean reflectance of 0.404, a glazing area of 6.25 m^2 with a glass transmittance of 0.6. For a visible sky angle of 48º the DF_{BRE} is 2.0 estimated through equation (2). This corresponds to a room on the ground floor, for a street width of 15 m, as seen in Table 4, with a DF_{VDF} of about 2.4%.

When the reference building faces an opposite building of different height, the sky view from the street canyon is subject to change. Figure 6 represents the results of VDF obtained at the top floor, considering the opposite building of the same height as the reference one, 3 m high and 3 m shorter (Figure 4). The sky view from the street canyon is reduced with a higher obstacle and vice versa. Considering the window on the fourth floor and at the narrowest street (H/W=3. 0; H represents the reference building) the sky view is about 73º when the opposite building is at the same height, against 48º and 90º when the opposite building is 3 m high and 3 m shorter than the reference building, respectively. For a wider street (H/W=0.5) the sky view from the window, and by the same order, is 87º, 81º and 90º. This represents a VDF of about 42.70% (H/W=3.0) and 57.96% (H/W=0.5) when both buildings are at the same height. For scenarios" b" and "c" (Figure 4) the VDF is about 30.71% and 54.58% (H/W=3.0) and 54.25% and 59.70% (H/W=0.5), respectively. When the window faces opposite buildings with high reflectance roofs (scenario "c" – Figure 4) the VDF on the window is about 58.89% (H/W=3.0) and 60.45% (H/W=0.5).The VDF on the window of the fifth floor is about 55% to 60%, and nearly constant. This is due to the fact that the sky view of such a window is at its maximum without any obstacle above the horizon. Due to this particular location, it stands out from the previous scenarios.

FIGURE 6. Top floor window VDF with different opposite building and different roof reflectance.



As van Esch et al. (van Esch, Looman, and de Bruin-Hordijk 2012) concluded, *"Street width has significant influence on the total global radiation yield of the canyon; the wider the street, the higher the global radiation yield."* The proposed trigonometric functions would be time consuming to apply to any given situation. Thus, a series of graphs are shown in figures 7 through 9, so any building designer may consult them during the first phase of the design stage (sketch) and estimate the VDF and consequently the DF within minutes. This will help make decisions for the project in an early design stage that develops the desired daylit building. The same H/W ratio defined in Table 3 is maintained, using H as the height of the reference building, the one with a window under study. Street canyons with the reference building of the same height of 15 m as in the previous analysis and also a reference building of 9 m are analysed. The latter is used in a less density urbanization. Three different opposite height buildings are defined. The first of the same height as the reference building, the second 3 m higher and the third 3 m lower. The latter canyon geometry, the window on the top floor will see the roofs (Figure 3). High wall reflectance (0.75), compared to one with low wall reflectance (0.45) since the street reflectance of 0.20 is going to be used as Strømann-Andersen and Sattrup (Strømann-Andersen and Sattrup 2011).

FIGURE 7. Street canyon with buildings of the same height.

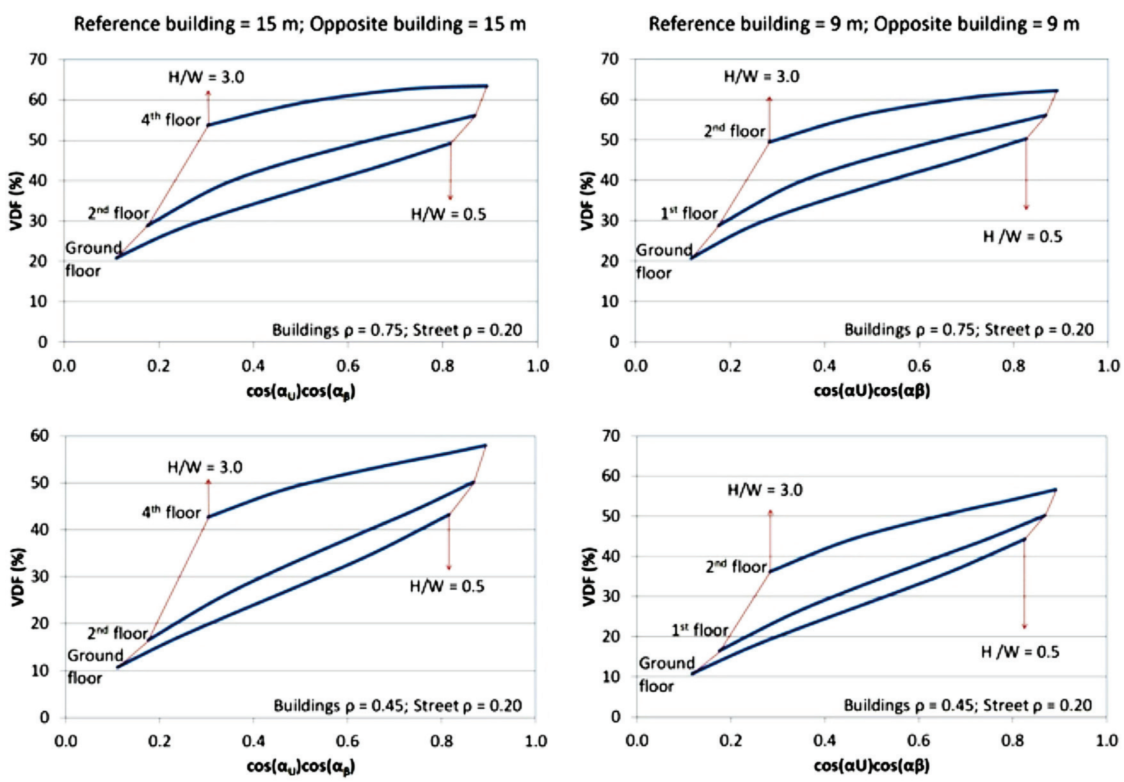


FIGURE 8. Street canyon with the opposite building 3 m higher than the reference building.

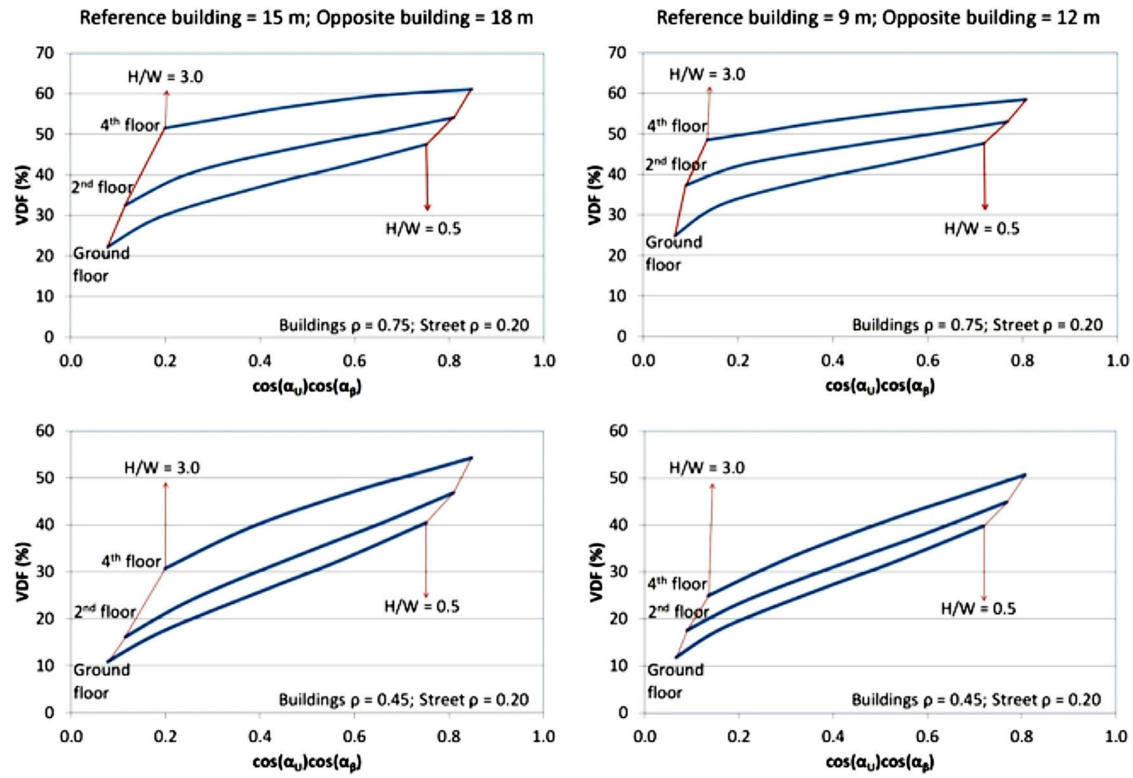
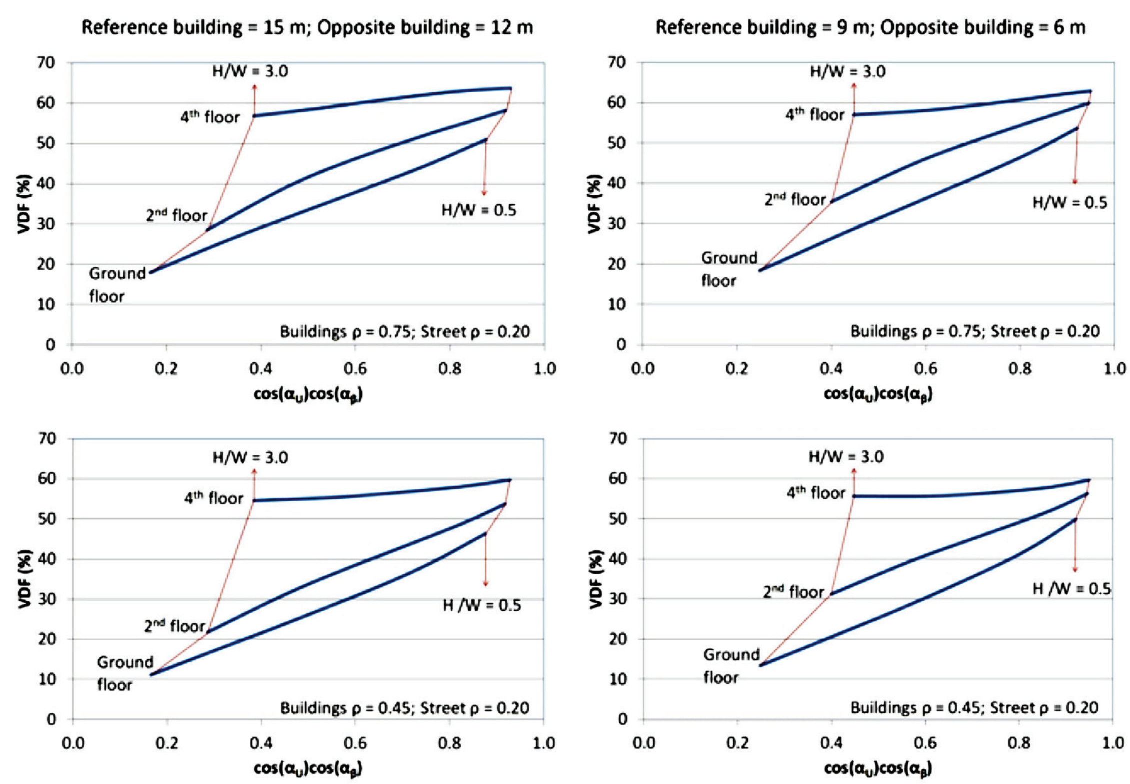


FIGURE 9. Street canyon with the opposite building 3 m shorter than the reference building.



5. CONCLUSIONS

A study on the calculation of vertical daylight factor (VDF) under an isotropic overcast sky was used. The analysis aimed at a vertical window from an infinitely long street canyon model located on the ground floor), middle and top floors.The performance of the proposed method was assessed by comparison with results from different published worked examples. These resulted, basically, from the RADIANCE simulation software and the Tregenza's modified split-flux formulae. It was found that the VDFs prediction based on the proposed approach showed good agreement with the different simulated data under comparison.

Street geometry, width and height among its reflectance characteristics, has significant influence on the illuminance of the canyon. The wider the street, the higher the sky view and received illuminance. The research is carried out investigating the contribution of the externally reflected component of daylight in different canyon geometries. It started with the building reflectance of 0.5 and 0.2 on the streets. The wider the street, the lower the reflectance within the canyon. The building reflection was reduced to 0.3 by keeping the street reflectance unchanged. The street reflectance was also augmented to 0.4 by keeping the initial reflectance of the buildings. This gives a general indication of the importance of opposing facades and street reflectance in an overcast sky condition.

Different H/W (height/width) ratios of the canyon were verified. Different building heights and several window levels were used for this study. The H/W ratio was from 0.5 to 3.0 (widest – narrowest). A sky view of the canyon regarding the window level was established. Generally, the higher the sky view, the higher is the obtained VDF; the lower the sky view or high H/W ratio showed a decrease in the VDF at all levels of the window. The reflected light has increased on the obtained VDF. At a lower level of the window, it even overcame the illuminance from the sky. The differences in the VDF increase as the level of the window rises is due to a higher sky view. This difference is bigger among higher floors. The results increase as one moves higher because of a larger sky view of the window. Differences in the VDF are mostly marked in the high H/W ratio scenarios rather than in the low H/W ratio ones.

The analyses show that the opposing facades and street level in overcast sky conditions are potentially seen as reflective light devices. Roofs have also a significant influence on the reflected light when the opposite buildings are lower than the window. The reflectance of opposing facades, the street level, the H/W ratio, the canyon sky view and in certain conditions the roofs, altogether, play an important role on the obtained VDF. It was found that the geometry of urban canyons has a relative impact on the total illuminance of the windows and where the reflected light makes an important contribution on the lower floors in high urban densities. It was shown that the reflectance has a relative effect on the diffuse illuminance. Even though the VDF might be very low, therefore increasing the size of facade openings especially on the lower floors, it is a way to increase indoor illuminance, when the architect is not in control of the existing canyon geometry and characteristics.

"Developers and planners need to address it if solar energy is to play a major role in the cities of tomorrow" (Littlefair 2001). However, estimating its value can be time consuming to building designers and different methodologies in use or even software tools may not be easily accessible. The presentation of the VDF through graphical presentations that correspond to different street canyons can, without difficulty, give the the designer a good approach of its

value during an early design stage. In consequence, the next step of the design may be developed with consciousness that a minimum level of daylight is achievable before testing the final architectural model with a proper tool or a more sophisticated methodology.

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