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A SIMPLIFIED APPROACH FOR THE EVALUATION OF THE NON-VISUAL POTENTIAL OF DAYLIGHT IN SIDE-LIT ROOMS

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Abstract

This article reports on the development, validation, workflow and implementation of a simplified method for evaluating the non-visual (melanopic) potential of daylight in typical side-lit rooms. The method is suitable for climatic areas with a dominant occurrence of cloudy skies. The non-visual daylight evaluation tool is based on a modified average daylight factor method. A simplified daylighting model improves the calculation of the vertical daylight factor and the passage of daylight through a vertical lighting opening. The proposed calculation method makes it possible to determine the illuminance of a vertical plane in the interior. The method is based on the uniform sky and the external diffuse horizontal illuminance at the location of interest. The outputs of the tool can also be used to quickly estimate visual levels of daylight. The article also proposes a classification of the availability of melanopic daylight in side-lit rooms, which is based on the outputs of the proposed calculation method.

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Key words

- Daylighting,
- Non-visual potential,
- Evaluation tool,
- Circadian light,
- Healthy lighting.

1 INTRODUCTION

The availability of daylight in buildings and the built environment significantly affects the quality of life (Boyce, 2010; Aries et al., 2015). Landmark discoveries in the chronobiological research of novel blue light-sensitive photoreceptors in the human eye at the turn of the millennium (Provencio, 2000; Brainard et al., 2001; Berson et al., 2002) confirm the earlier empirical observation that light has non-visual effects that are involved in the regulation of several fundamental biological functions of the body; it also affects mood, reduces fatigue and stress, and increases work productivity (Pyeritz et al., 2019; Nagare et al., 2021). The basic reason for these effects is the fact that the production and oscillations of many hormones and enzymes are directly related to the alternation of night and day and to the spectrum and intensity of natural light. Recent research shows that non-visual responses are not only dependent on the blue component of light, but non-visual effects depend on the interaction of information from multiple photoreceptors in the human eye, while their processing depends on the spectral composition of light, its intensity, duration, time of exposure within a day and year, as well as other influences (Gooley et al., 2012; Schlangen and Price, 2021; Lucas et al., 2022).

There is currently a general consensus that light stimulates both visual and non-visual systems in the human body. The main practical questions for architects, lighting engineers, and other professionals are how to incorporate new medical knowledge about the non-visual effects of light into the everyday practice of designing buildings and their interiors. In response to these new challenges, research has been conducted, particularly in the field of artificial lighting, which has brought, among other things, several new color-based methods for assessing "circadian lighting" (Rea et al., 2010; CIE S 026/E, 2018; IWBI, 2022). Several metrics have also been proposed to guarantee "healthy" lighting in buildings. Using multi-spec-

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tral simulation software (Inanici, M. & ZGF Architects, 2015; Solemma&Alertness, 2018), many studies have been conducted that analyze photopic and melanopic ocular light exposure in cases of daylight, artificial, and combined lighting (e.g., Amundadottir et al., 2017; Acosta et al., 2019; Innanici et al., 2015; Saiedlue et al., 2019; Pierson et al., 2023).

The spatial distribution of daylight in both exterior and interior spaces, as well as its spectral composition, is constantly changing over time (Diakite-Kortlever and Knnop, 2021; Ezpeleta et al., 2021). Detailed simulations of "vertical circadian daylighting" over the course of a year indicate difficulties with a criteria-based evaluation of the data calculated. The movement of people and their behavior in space can only be predicted to a limited extent. The amount of daylight entering the eyes of users of indoor spaces with lateral daylighting depends to a large extent on the direction of their glance. When someone is looking towards the window, vertical daylight illuminance is several times higher than when looking at a wall. If the window is equipped with a shading device, which is usually the case, its brightness changes, depending on the type of shading device and the way it is used. The illuminance on the eyes of office workers from computer screens can be higher than from windows, especially in the deeper parts of rooms. The results of detailed simulations of "circadian" light environments in buildings are significantly dependent on the evaluation scenario, are complex, and difficult to interpret.

This article focuses on the global and practical assessment of circadian (melanopic) daylight availability in side-lit rooms. The assessment is based on the melanopic average daylight factor method and on the availability of local exterior diffuse daylight. The simplified assessment method proposed allows for a clear assessment of the impact of various geometric urban and architectural parameters and the optical properties of materials and building surfaces on the level of visual and non-visual (melanopic) side daylighting of buildings in the early stages of their design.

2 SIMPLIFIED CALCULATION METHOD OF THE AVAILABILITY OF NON-VISUAL DAYLIGHT IN SIDE-LIT ROOMS

After World War II, building regulations gradually changed, moving from a prescriptive approach based on past experience to performance-based building regulations and building design. The amount of daylight in individual interior spaces was assessed in many countries using the daylight factor (DF) at a point in the room; subsequently, in several countries, the average daylight factor (ADF) of a reference plane in the room began to be used (Crisp and Littlefair, 1984). DF is the ratio of the horizontal indoor to horizontal outdoor daylight illumination under standardized overcast sky conditions. DF is a performance indicator that allows for the specification of the impact of the size and configuration of a room, the size and distribution of transparent parts of a building envelope and their light transmittances, and the reflectances of all surfaces on the distribution of diffuse daylight in side-lit rooms. DF provided architects, designers, and stakeholders with information on compliance with daylight legislation in the early stages of building design. In the early 21st century, the climate-based daylight modeling (CBDM) method began to be widely used for the design and assessment of daylight in buildings (Mardaljevic, 2000).

CBDM provides for the possibility of assessing daylight throughout the year in dynamic conditions of the local daylight climate, including direct sunlight. This performance-based approach to daylight design has many benefits but also pitfalls. The CBDM method is not considered suitable for use in the early stages of design. In the early stages, conceptual designs often, and significantly, change. Architects and designers prefer simple and yet sufficiently reliable methods for determining the availability of daylight in buildings. Many practical designers consider the ADF method to be a sufficiently proven method for assessing daylight in buildings in locations with a dominant occurrence of cloudy days. For the assessment of both visual and non-visual daylight in side-lit rooms, we propose a modified mADF (melanopic Average Daylight Factor) method that respects the principles of daylight theory and captures the essential parameters determining the non-visual potential of daylight.

2.1 Computational procedure

A well-known average daylight factor method will be modified to account for external obstacles with different reflectance factors and the vertical daylight component on the window. The proposed mADF method also includes several computational procedures, which improve the calculation of both melanopic and photopic daylight illuminance. During the year, a wide range of luminance patterns occur in the sky. We assume that the variability of luminance patterns noticeable in the annual average better reflects a uniform luminance sky model than a standard heavily overcast sky model. In mADF, the sky illuminance is determined from a sky of constant brightness. The interreflection of daylight in the outdoor and indoor environments is calculated under overcast sky conditions (an overcast sky is used in the ALFA software (Solemma & Alertness, 2018)) and standard overcast sky (CIE, 1955). mADF is a simplified flux-type method. Lynes (1979) proposed a formula for calculating the average illuminance over all interior rectangular indoor space in order to simplify the computational assessment of daylight in buildings based on point daylight factors. This formula was later modified (Crisp and Littlefair, 1984) based on measurements in a classroom model under an artificial standard overcast sky, so that the calculation results were the average illuminance on the reference plane according to the formula:

$$\mathrm{ADF} = A_w\ \tau_o\ \theta/(A_t\,(1-\rho^2))\ \ [\%] \qquad (1)$$

where

- A_W is the area of the window (m^2),
- θ is the vertical angle subtended by the visible sky in degrees (Fig. 1),
- τ_o is the overall loss factor for diffuse light passing through the daylight opening (-),
- A_t is the total area of the room surfaces (ceiling, floor, walls, windows) (m^2),
- ρ is the area weighted mean reflectance of all the interior surfaces (-).

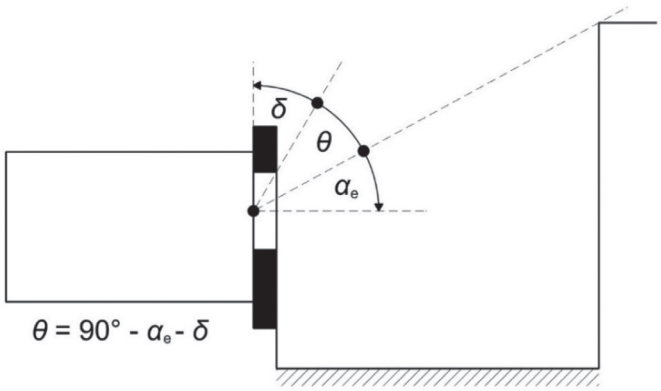


Fig. 1 *Angle θ*

Angle α_e in Fig. 1 is the equivalent obstruction angle, which can be determined for any obstructing geometry by using the method described by Hraška and Štujber (1997) and Hraška (2000). Later, several other authors analyzed and tested equation (Eq.) (1) (Naeem and Wilson, 2007; Bonaiuti and Wilson, 2007; Reinhart and LoVerso, 2010), primarily using the Radiance simulation program (Radiance, 2023). These authors concluded that the ADF method is adequate for the initial design of daylight provision in buildings. The ADF method has gained significant popularity in practice due to its simplicity and relatively loose interpretation of criteria. The ADF method is suitable for the work of architects because it simply and clearly relates the geometric and spatial characteristics of the creation of a building's environment to the requirements for daylight provision, especially in climatic conditions with a dominant occurrence of overcast skies.

From a practical point of view, the ADF method has the advantage of restricting the possibility of "creative manipulation" with computation parameters so that it can be used by the majority of designers and not only by specialists. On the other hand, the ADF is a certain mathematical construct, which is only valid for small rooms under a strict set of parameters. One of the disadvantages of the ADF is that it does not allow for the consideration of different reflectance factors of surfaces in front of a window. The proposed mADF method is based on the vertical daylight factor (VDF) on the window D_w. The value of D_w takes into account the range of external obstructions of the window as well as the reflectance factors of light from external surfaces. In mADF, the photopic and melanopic photometric properties of materials and surfaces are determined by the D65 light source, which represents the spectral composition of "average daylight".

D_w is the sum of the sky component of daylight factor D_s and the exterior reflected factor D_ρ, due to the interreflection of daylight between the terrain and the external surfaces of buildings, or other objects located in front of a window:

$$D_w = D_s + D_\rho \quad [\text{- or \%}] \tag{2}$$

The sky component of the daylight factor on a window is determined by the following formula:

$$D_s = 0.000051\,\alpha_U^2 - 0.01037\;\alpha_U + 0.51 \quad [-] \tag{3}$$

Where α_U is obstruction angle, according to Fig. 2, in degrees.

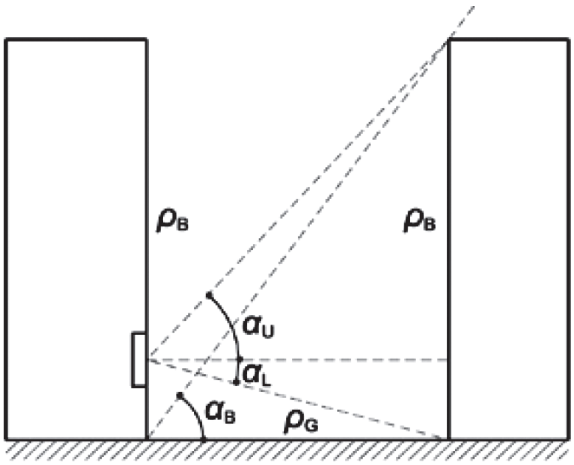


Fig. 2 *Angles α_U, α_L and α_B*

According to (Li et al., 2009), the ratio of the ground-reflected component of the daylight factor at a vertical window $D_{\rho T}$ to the unit horizontal ground illumination can be calculated from the equation:

$$D_{\rho T} = \rho_G\, E_G\, (1 - sin\,\alpha_L)/2 \quad [-] \tag{4}$$

Where

ρ_G average light reflectance of the ground (melanopic or photopic) [-],

$E_G = 0.9 - 0.009\,\alpha_B$ [-],

α_L and α_B are the angles marked in Fig. 2 [degrees].

The reflected component of the daylight factor on a vertical window from a shading building, $D_{\rho B}$, is determined as follows:

$$D_{\rho B} = \rho_B\, D_B\, S\, cos\,\delta/\pi \quad [-] \tag{5}$$

Where

D_B is the average vertical daylight factor on the obstacle according to (Li et al., 2009)

$$D_B = (0.92 - 2.7 \times 10^{-3}\alpha_U - 1.1 \times 10^{-4}\alpha_U^2) \times \times 0.935^{\left(\frac{\alpha_L}{10}-1\right)} \times 0.5,$$

ρ_B average light reflectance of obstructing building (melanopic or photopic).

Parameter S expresses the size of the obstacle (an infinite-length urban canyon), and δ is the angle between the window normal and the height center of the obstacle:

$$S = 2\,\beta\,\pi/180$$
$$\beta = \alpha_U + \alpha_L$$
$$\delta = \arctan(v_p - tan\,\alpha_L)$$
$$v_p = (tan\,\alpha_L + tan\,\alpha_U)/2$$

The effective reflectance of daylight, ρ_o, of the cavity among buildings and the ground can be approximately determined from the following equation:

$$\rho_o = 0.009 \times \alpha_B \times (\rho_B + \rho_T)/2 \quad [-] \tag{6}$$

We can estimate the reflected component D_ρ of D_w using the following formula:

$$D_\rho = \left(D_{\rho T} + D_{\rho B}\right) \times (1/(1-\rho_o)) \quad [-] \qquad (7)$$

The daylight illuminance in the room is determined by the value of the daylight flux falling on the window, whoch is reduced by light losses when passing through the window. The mADF on the reference plane is directly proportional to the D_w according to the following equation:

$$mADF = k \times D_w \quad [-] \qquad (8)$$

Chaiyakul (2005) presents a relationship for determining the value of k, which has the following form after our correction factors are added:

$$k = 2\, A_w\, \tau_o\, \psi\, \mu / (A_t\,(1-\rho^2)) \quad [-] \qquad (9)$$

The parameter τ_o takes into account the loss of diffuse light when it passes through the daylight opening:

$$\tau_o = \tau_d \,.\tau_2\,.\tau_3\,.\tau_4 \quad [-] \qquad (10)$$

Where τ_d is the light transmittace of glazing. For ordinary glazing $\tau_d = 0.9 \times \tau_1$.

The meaning of τ parameters is:

- τ_1 light transmittance when light hits the glazing perpendicularly (melanopic or photopic),
- τ_2 correction factor for the window framing,
- τ_3 correction factor for glazing dirt,
- τ_4 correction factor for elements that permanently shade the window glazing (e.g., fixed window grilles).

The parameter ψ takes into account the loss of daylight due to the thickness of the window wall. The meaning of the parameters in Eq. (11) is obvious from Fig. 3.

$$\psi = (1 - e^{-0.624\,x})(1 - e^{-0.614\,y}) \quad [-] \qquad (11)$$

Where

$$x = \frac{h_w}{th} \quad and \quad y = \frac{w_w}{th}$$

If $x > 10$, then $x = 10$; and if $y > 10$, then $y = 10$.

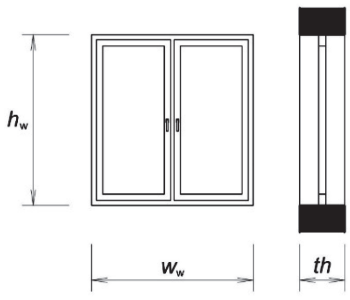


Fig. 3 *The dimensions in Eq. (11)*

The correction factor μ takes into account the leakage of light through the window due to the internal interreflection of light (Meshkov, 1957, p. 201).

$$\mu = 1 - \varphi$$
$$\varphi = (\rho\,(A_w/A_t) / (1 - \rho\,(1 - (A_w/A_t)))\,\tau_o \quad [-] \qquad (12)$$

In smaller rooms with bright interior surfaces and large windows, light leakage from a room can be noticeable.

Using Eq. (13), we can calculate the required size of the window to achieve the desired mADF (or photopic pADF) on the reference plane:

$$A_w = mADF\; A_t\,(1-\rho^2) / (2\, D_w\, \tau_o\, \psi\, \mu\,) \quad [-] \qquad (13)$$

Whether it is a photopic or melanopic daylight factor depends on whether the light transmission factors through the glazing and the light reflectance factors from the outer and inner surfaces are entered as photopic (pADF) or melanopic (mADF). In the mADF and pADF methods, the same D65 light source is considered.

The parameter k includes the geometry of the room and the daylight opening, as well as the photometric properties of the glazing and interior surfaces, and the interreflection of light in the room. The parameter k is significantly more suitable for predicting the average illuminance of a side-lit room than the commonly used wall-to-window ratio (WWR) or the ratio of the window area to the floor area (WFR), which only considers the geometry.

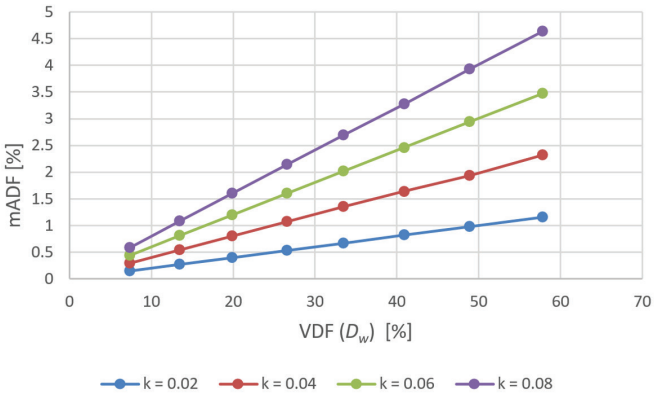


Fig. 4 *Melanopic average daylight factor (mADF) values plotted as a function of the vertical daylight factor at a window (Dw) and smaller values of the parameter k*

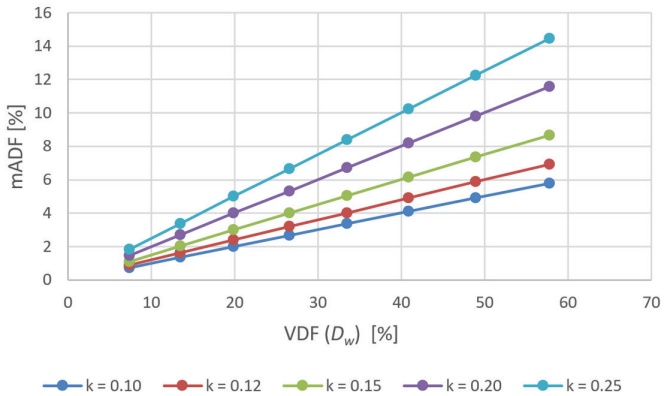


Fig. 5 *Melanopic average daylight factor (mADF) values plotted as a function of the vertical daylight factor at a window (Dw) and larger values of the parameter k*

The mADF method can be used to assess the side daylighting of smaller rooms, whose shape can be approximated by a prism, the length of which is not significantly larger than twice the height. The limiting size of a side-lit room can be considered to be a room with floor dimensions smaller than 7 × 7 m, whose ceiling height is up to 3.5 m.

2.2 Comparison of the mADF method with measurements under an artificial sky and with simulations by the ALFA software

The ALFA (Adaptive Lighting for Alertness) circadian lighting software (Solemma, 2017) was used for numerical modeling of non-visual (circadian) daylighting potential. Circadian lighting simulations in ALFA were compared to measurements on a model room (Fig. 6) under a hemispheric artificial CIE uniform sky (Fig. 7). The calculations in ALFA were carried out on December 21, at 12 o'clock in Bratislava (Lat 48°08', Lon 17°10') under a cloudy sky. Under these conditions, the orientation of the room to the cardinal points does not affect its daylighting. The ALFA software uses its own sky models (Mayer and Kylling, 2005), which differ from the standardized models by CIE (CIE, 2003). In the vicinity of the window in the model room, the measured values of the horizontal and vertical illuminance were significantly higher than the ALFA outputs for all the obstruction angles. In the middle of the room, the calculated and measured illuminances were almost equal, and the software-calculated illuminance values were slightly higher than the measured values in the back of the model room. One of the reasons for the large differences between the measured and ALFA-calculated DF values is likely the difference in sky models. Due to the fact that we do not know the luminance distribution on the cloudy sky in the software used, we cannot

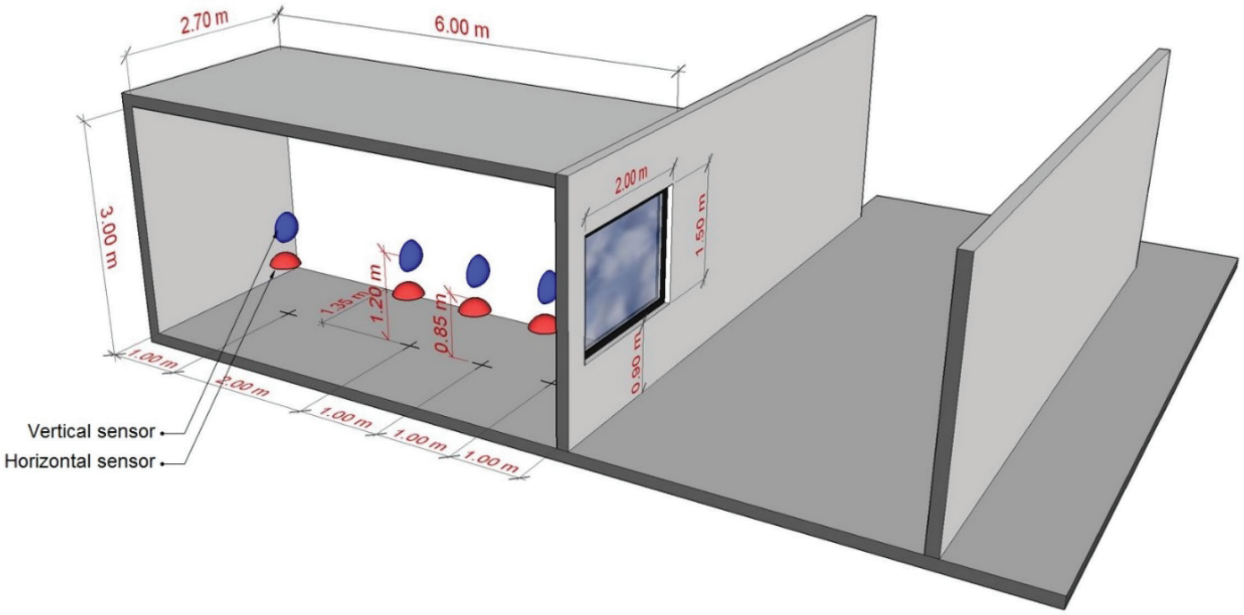


Fig. 6 *A room model and obstruction that was used to test a simplified calculation method by measurements under an artificial sky*

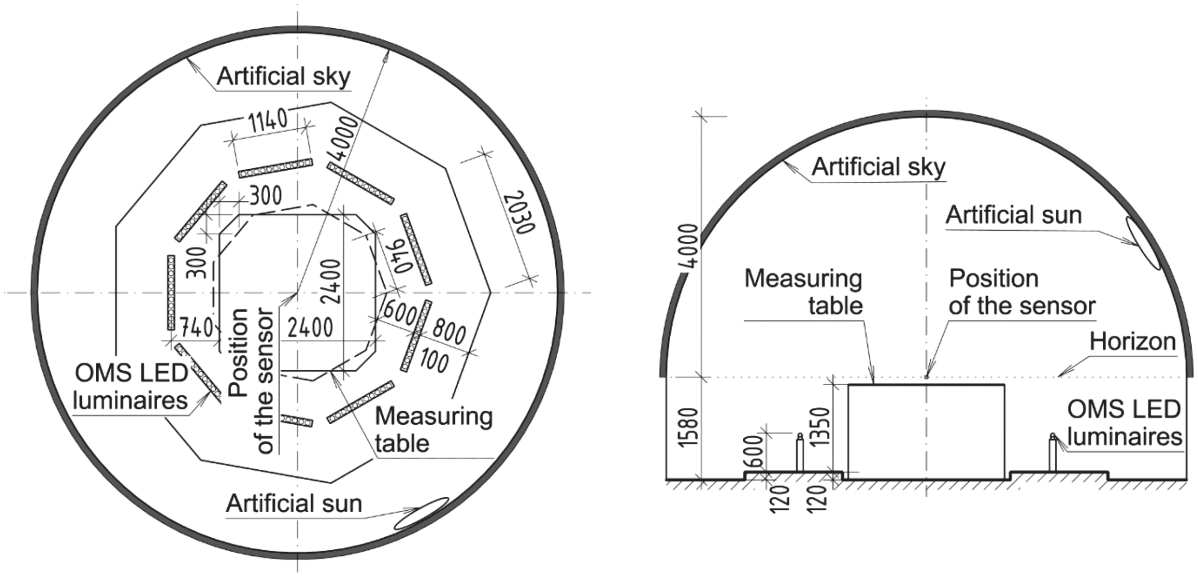


Fig. 7 *Scheme of the artificial sky of the Slovak Academy of Sciences in Bratislava (Slovak Republic)*

analyze the differences between the measured and calculated DF in more detail. ALFA sky models have not been validated against measured data (Diakite-Kortlever, 2022). The determination of the interreflection component of daylight illuminance in the proposed simplified calculation tool mADF is based on the results of the ALFA simulations.

Fig. 8 shows a comparison of the vertical daylight factors D_w on the window of the room in Fig. 6 calculated by the mADF method and the ALFA program with measured values under the artificial sky with uniform luminance. The values of D_w were measured and calculated for the light external surfaces and various angles of obstruction, at which the mADF method slightly overestimated the vertical illuminance of the vertical window.

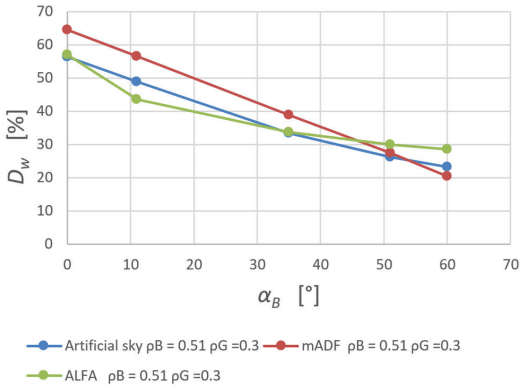


Fig. 8 *Measured and calculated values of D_w, depending on the obstruction angle α_B*

The ALFA software and the proposed simplified method were used to calculate the ADF in the room in Fig. 6 on a horizontal reference plane 0.85 m above the floor. The calculation parameters of the room and the window were defined as follows: room width 2.7 m, room depth 6 m, room height 3 m, window width 2 m, window height 1.5 m, sill height 0.9 m, wall thickness 0.18 m, ratio of glazing area to window area 0.82, glazing transmittance $\tau_1 = 0.88$, and correction factor for glazing dirt $\tau_3 = 1$. The values of the surface reflectance factors were determined as follows: gray floor and exterior terrain $\rho_v = 0.30$, light gray interior walls and obstacle $\rho_v = 0.51$, white ceiling $\rho_v = 0.72$, and reflectance of the inner side of the window $\rho_v = 0.25$. In the case considered, the value of the parameter k is 0.0586. A comparison of the results of the ADF calculations on the horizontal reference plane using the simplified mADF method and the ALFA program for multiple obstruction angles is shown in Fig. 9.

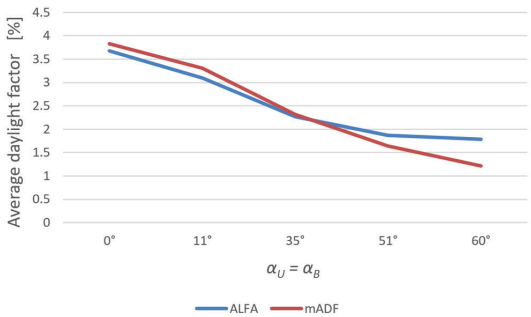


Fig. 9 *Average daylight factors in a model room calculated by the mADF method and the ALFA software for different obstruction angles*

Fig. 9 shows a relatively good agreement between the average illuminance of the reference plane of the above-characterized model room calculated by the numerical simulations using the ALFA software and calculated using the proposed simplified mADF method. This is quite surprising, given that the methods use different sky models.

Additive glazing in loggias, the occupant's use of shading devices, dark carpets on the floor, dusky wall and ceiling paints, trees and other plants in front of buildings, furniture, the user's behavior, etc., influence the daylighting of a room much more than a slight degree of uncertainty in a calculation method.

2.3 Calculation example

In the room shown in Fig. 6, with the photometric properties of the materials and surfaces listed in Tab. 1, we calculated the mADF and photopic ADF (pADF) on the reference plane. In Tab. 2, the values of mADF and pADF and their ratios were calculated using the proposed calculation method for several obstruction angles. The orange and yellow surfaces are spectral filters of blue light. For this reason, the values of mADF are lower than pADF. The impact of the pale orange obstacle on the reduction of mADF increases with the increasing obstruction angle.

Tab. 1 *Melanopic and photopic photometric characteristics of glazing and surfaces*

Surface (material) / color		Light reflectance / transmittance		M/P ratio [-]
		Melanopic (M) ρ_{mel} [-]	Photopic (P) ρ_v [-]	
Walls / pale yellow		0.54	0.79	0.68
Ceiling / white		0.79	0.84	0.94
Floor / grey		0.33	0.34	0.97
Glazing	reflectance	0.24	0.25	0.96
	transmittance	0.66	0.65	1.02
Obstacle / pale orange		0.28	0.57	0.49
Terrain / dark grey		0.20	0.20	1.00

Tab. 2 *The average melanopic (mADF) and photopic (pADF) daylight factors on the reference plane in the room assessed with different melanopic and photopic surface reflectances*

Obstruction angles $\alpha_B = \alpha_U$	mADF [%]	pADF [%]	M/P ratio [-]
0°	2.98	3.89	0.77
10°	2.53	3.41	0.74
20°	2.12	2.97	0.71
30°	1.74	2.56	0.68
40°	1.38	2.15	0.64
50°	1.04	1.70	0.61
60°	0.71	1.21	0.59
70°	0.40	0.68	0.59

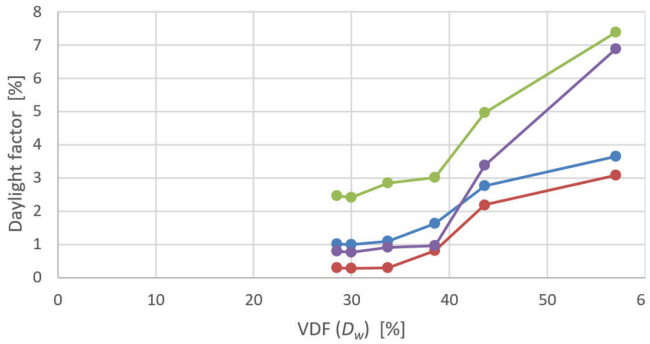
The calculation example shows that the difference between the melanopic and photopic daylight illuminance is significant in the case considered. The decrease in the M/P ratio with the increasing obstruction angle of the window is caused by the low reflectance of melanopic light from the orange obstructing obstacle. The data in Tab. 2 show that the optimization of daylighting in terms of non-visual effects can differ from the evaluation, taking into account only the visual effects of light.

The proposed method makes it possible to evaluate daylight by photopic measures and, at the same time, to evaluate the non-visual potential by melanopic ADF, which can be converted into melanopic illumination.

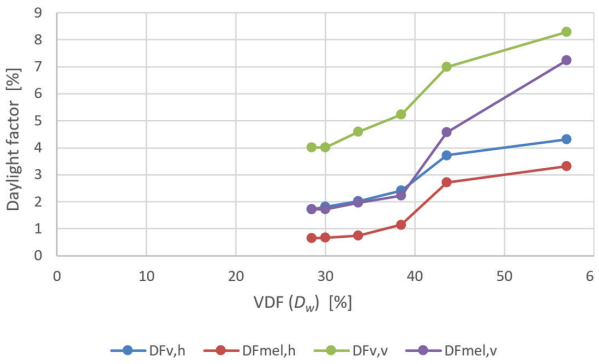
2.3 Indicator of the non-visual potential of daylight in side-lit rooms

The latest metrics of non-visual effects are mostly based on the melanopic illumination of the eyes (Lucas et al., 2012). Melanopic illuminance is currently typically calculated using the melanopic action spectrum according to the CIE standard (CIE S 026/E, 2018). For practical reasons, melanopic illuminance is usually calculated on a vertical plane, typically at a height of 1.2 m above the floor level. Various studies have shown that exposure to melanopic illuminance levels of 100-300 lux can have a significant impact on non-visual effects of light. For example, in (Brown et al., 2022), a large group of experts recommended a minimum indoor melanopic light exposure of 250 mlx ("melanopic lux") vertically at eye level during the day in indoor environments.

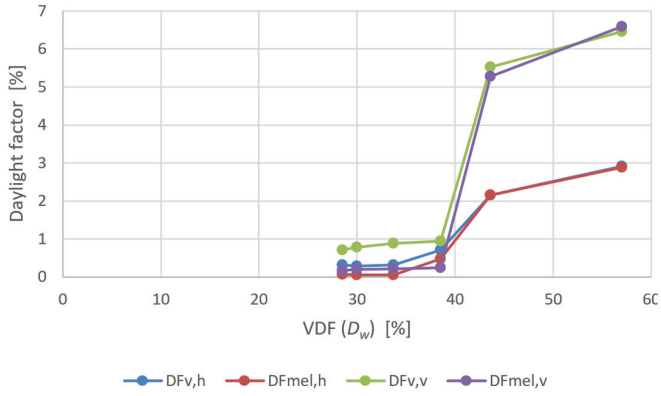
Unfortunately, this recommendation does not specify either the time of day nor the places in the interior where the stated level should be achieved, nor the type of lighting. This recommendation also does not specify at what angle viewing the vertical illuminance of 250 mlx should be achieved. The direction of the view is of key importance for the evaluation of vertical illuminance in the case of lateral daylighting. Many authors and practitioners use the WELL Building Standard v2 methodology (IWBI, 2022) to assess circadian lighting. In section "L03: Circadian Lighting Design", Tier 1 requires a vertical illuminance of at least 136 melanopic equivalent daylight illuminance D65 (m-EDI) for artificial lighting in regularly occupied spaces. In the case that a physically unspecified level of daylight illuminance in the interior space is provided in the WELL method, Tier 2 requires a minimum of 109 mlx. In Tier 2, in the case of "enhanced daylight access", a minimum of 163 mlx is required for such a solution to receive 3 points in the evaluation system. During the several years of the existence of the WELL method, the criterion values for circadian lighting and the corresponding professional terminology have changed several times. In most cases, vertical illuminance is significantly lower than horizontal illuminance in artificially lit interiors. On the other hand, in



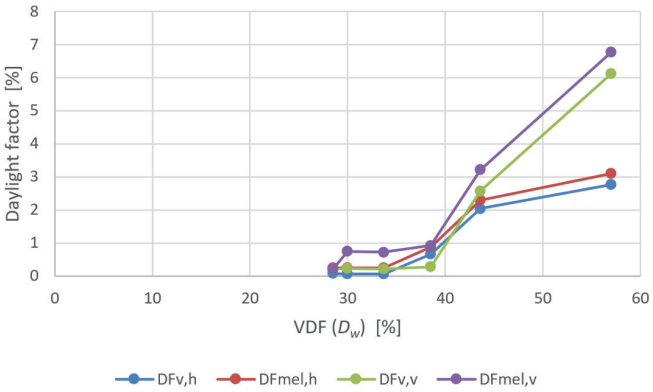
All the surfaces are orange except for the grey terrain.
$\rho_v = 0.48$, $\rho_{mel} = 0.17$, $\rho_G = 0.20$



All the surfaces are orange except for the grey terrain.
$\rho_v = 0.48$, $\rho_{mel} = 0.17$, $\rho_G = 0.20$



All the surfaces are dark red except for the grey terrain.
ρv = 0.16, ρmel = 0.04, ρG = 0.20



All the surfaces are dark blue except for the grey terrain.
ρv = 0.05, ρmel = 0.15, ρG = 0.20

Fig. 10 *Vertical photopic and melanopic daylight factors (DFv,v and DFmel,v) and horizontal daylight factors (DFv,h and DFmel,h) plotted against the daylight factor on a window (Dw) at a position 2 m from the window in the room in Fig. 6*

the case of lateral daylighting, vertical illuminance is typically twice as high as horizontal illuminance at the same point, when looking towards a window with little external shading.

In general, it can be stated that daylight in buildings is the most suitable for circadian lighting in terms of its intensity, spectral quality, and the timing of the exposure. The intensity and spectral composition of daylight are constantly changing. The spatio-temporal distribution of daylight in a room is constantly changing at each point during days and over years.

A detailed assessment of the non-visual potential of daylight in short time periods throughout the year has many challenges. In addition to dynamic changes in the local light climate and its spectral composition, it is necessary to take into account the difficult-to-predict dynamics in the use of shading devices and the behavior of the users of the spaces.

Using the ALFA simulation software, melanopic and photopic illuminance on vertical surfaces at a height of 1.2 m above the floor and horizontal illuminances at a height of 0.85 m above the floor were calculated in the same positions in side-lit rooms. The calculations were carried out under a cloudy sky in the location of Bratislava, Slovakia. At the same time, the average photopic and melanopic illuminances on the reference planes of rooms at a height of 0.85 m above the floor were calculated. In the calculation variants, the colors of the exterior and interior surfaces were changed. The colors of the surfaces were either the same on all the surfaces or the colors and light reflectances on the individual surfaces of the room were combined. Fig. 10 illustrates a part of the calculation results for a position 2 m from a window, with vertical photopic and melanopic daylight factors ($DF_{v,v}$ and $DF_{mel,v}$) and horizontal daylight factors ($DF_{v,h}$ and $DF_{mel,h}$) plotted against the daylight factor on the window (i.e. D_w). The graphs shown apply to the room in Fig. 6 and for the same colors of the exterior and interior surfaces, whose photopic and melanopic reflectances are shown in Fig. 10. As expected, both the $DF_{v,v}$ and $DF_{mel,v}$ values were higher than $DF_{v,h}$ and $DF_{mel,h}$. The size of the obstruction and surface reflectances significantly affected the distribution of light in the room, the average DF value on the reference plane, and the ratios of the vertical and horizontal illuminance in virtually every location in the room.

As the size of the obstruction increases, the difference between the values of the horizontal and vertical illuminance decreases, but the vertical illuminance always remains higher. In a very unlikely scenario of extremely dark interior surfaces, a larger dark obstruction and dark interior surfaces will cause a rapid decrease in both the vertical and horizontal illuminances to very low values. In the case of dark blue surfaces, the favorable ratio of the melanopic to photopic reflectance has only a small impact on the value of the melanopic illuminance. Spectrally neutral light surfaces are more effective in terms of melanopic illuminance than darker blue colors, even though they have a much more favorable ratio of melanopic to photopic reflectance (about 2.6).

Fig. 11 shows the ratios of vertical to horizontal illuminance calculated by ALFA at a distance of 2 m from the window in the room shown in Fig. 6 for ordinary spectrally neutral surfaces. The reflectances of the floor of the room and the external terrain were assumed to be $\rho_v = 0.31$, the reflectances of the walls of the room and obstacles to be $\rho_v = 0.51$, and the ceiling reflectance of the room to be $\rho_v = 0.72$. If we compare the values of the photopic average daylight factor (pADF) and $DF_{v,h}$ at a distance of 2 m from the window, their values are similar throughout the range of the D_w values. The vertical illuminance $DF_{v,v}$ is significantly higher than the horizontal illuminance, which is also due to the relatively bright external obstruction. With a small obstruction, the vertical illuminance towards the window is twice as high as the horizontal illuminance in a cloudy sky. As the obstruction increases, this difference decreases, but it is still significant.

The ratio of the vertical illuminance to the average illuminance on a reference plane in a side-lit room in a zone near a facade is nonlinear and is significantly affected by the size of the obstruction and its reflectance.

We propose to assess the non-visual potential of daylight in side-lit rooms using an indicator, which is the melanopic vertical illuminance of a sensor at a height of 1.2 m above the floor at a distance of 2 m from a window; this sensor is oriented perpendicular to a window. After analyzing the results of the simulations using the ALFA software in the case of light reflectance of the terrain in front of a window of around 0.20 and the light reflectance of an obstacle in the range of 0.25 – 0.55, we can approximately determine the ratio of the vertical illuminance to the average illuminance on a reference plane R at a distance of approximately 2 m from the window from the formula:

$$R = \frac{DF_{ver,2\,m}}{ADF} = 70.69 \times D_w^2 \times \rho_B + 5.87 \times D_w^2 - 49.01 \times D_w \times \rho_B + 0.099 \times \rho_B^2 - 6.555 \times D_w + 6.79 \times \rho_B + 3.701 \quad [-] \quad (14)$$

Where D_w and ρ_B are dimensionless numbers.

The functional dependence of the value R on the daylight factor at the vertical window D_w and the light reflectance of the obstruction ρ_B according to Eq. (14) is shown in Fig. 12.

3 THE AUTONOMY OF THE NON-VISUAL POTENTIAL OF DAYLIGHT IN SIDE-LIT ROOMS

The intensity of daylight and the amount of time it is available throughout the year varies greatly from location to location on the Earth. At mid-latitudes and in locations with predominantly overcast skies, daylighting criteria have traditionally been linked to the availability of diffuse natural light. We assess the autonomy of the non-visual potential by the availability of melanopic daylight on the potential non-visual indicator, which is defined above.

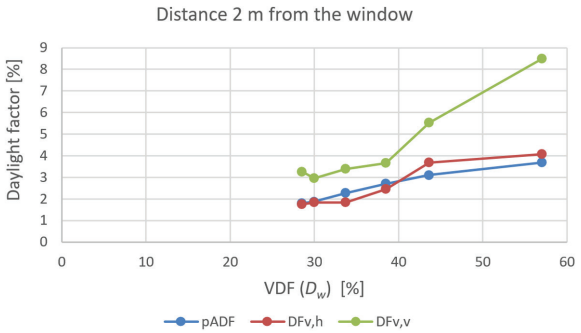


Fig. 11 Vertical and horizontal daylight factors (DFv,v and DFv,h) at a distance of 2 m from the window in the room in Fig. 6 and the average photopic daylight factor (pADF) on the reference plane of the room

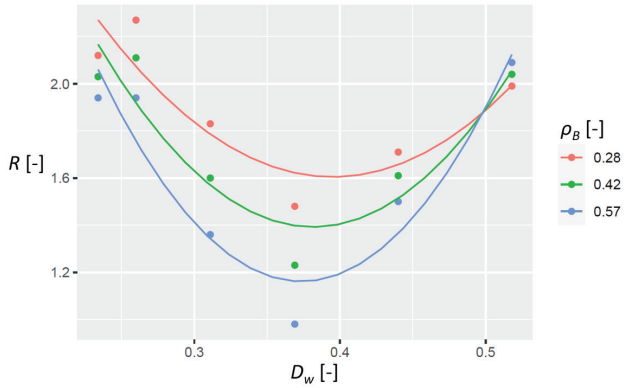


Fig. 12 *Dependence of the parameter R on the daylight factor at the vertical window Dw and the light reflectance of the obstruction ρB*

The occurrence of diffuse horizontal illuminance in Bratislava is variable throughout the year, see Fig. 13. Fig. 13 shows the cumulative frequency distribution of the exterior diffuse horizontal illuminance E_{vd} in Bratislava (Ferenčíková and Darula, 2019). In the winter, the levels of illuminance are significantly lower than in the other seasons. While on average throughout the year, horizontal illuminance above 10 klx occurs 60 % of the time of days, in the winter months it is less than 30 %. Relatively high intensities of diffuse illuminance in the summer months increase the average annual illuminance. Due to the purpose and method of the proposed simplified assessment of the non-visual potential of daylight in buildings, we consider that assessing it on the annual occurrence of diffuse daylight is a reasonable choice. However, the availability of diffuse light can be easily determined from Fig. 13, even in individual months of the year.

The illuminance at the window is calculated from the given exterior horizontal diffuse illuminance E_{vd} as follows:

$$E_W = E_{vd} \times D_w \quad (lx \text{ or } klx) \text{ [-]} \tag{15}$$

The average illuminance on the reference plane is:

$$E_{aver} = k \times E_w \quad (lx \text{ or } klx) \text{ [-]} \tag{16}$$

The average daylight factor (melanopic or photopic) on the reference plane is:

$$ADF = k \times D_w \quad (- \text{ or } \%) \text{ [-]} \tag{17}$$

We can assess the vertical illuminance of the virtual sensor (melanopic or photopic) approximately 2 m from the window (i.e., the indicator) using the following formula:

$$E_{ver,2\,m} = R \times E_{aver} \quad (lx \text{ or } klx) \text{ [-]} \tag{18}$$

The percentage probability of exceeding a certain value of the annual average diffuse horizontal illuminance E_{vd} in Bratislava P is determined by the following formula:

$$P = -8 \times 10^{-6} \times E_{vd}^{4} + 5 \times 10^{-4} \times E_{vd}^{3} + 4 \times 10^{-2} \times E_{vd}^{2} - 4{,}4 \times E_{vd} + 100 \text{ [\%]} \tag{19}$$

Assume that the mADF in a room in Bratislava is 1.5 %. The vertical daylight factor at the window is D_w = 0.45, and the melanopic light reflectance of the obstacle is ρ_B = 0.30. According to (EN 17037, 2018), the median exterior diffuse

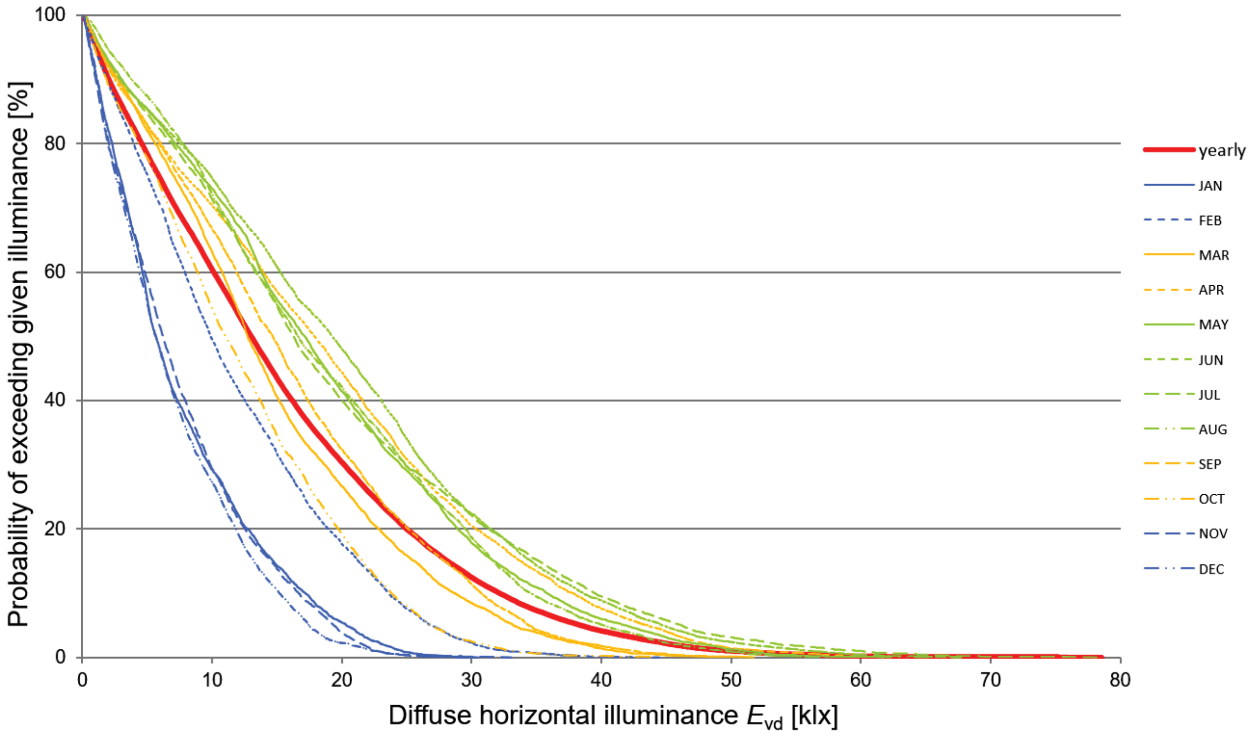


Fig. 13 *Cumulative frequency distribution of available exterior diffuse horizontal illuminance in Bratislava, Slovakia (Ferenčíková and Darula, 2019)*

horizontal illuminance in Bratislava is E_{vd} = 16,300 lx. The average median illuminance of the reference plane in the given hypothetical room will be E_{aver} = 244.5 mlx. From Eq. (14) under the given conditions, we can determine R = 1.66. From Eq. (18), we find $E_{ver,2\ m}$ = 406 mlx. The value of 406 mlx or higher will be achieved only half the time of the year with daylight. The median autonomy of the non-visual potential is 50 % in this case. The probability of exceeding 7,500 lx within the average annual availability of diffuse horizontal lighting E_{vd} in Bratislava is P = 69 %. In this case, the value of *Ever,2 m* will be above 187 mlx during 69% of all hours in the year with daylight.

4 CONCLUSIONS

This article describes a simple analytical method for assessing the non-visual potential of rooms with lateral daylighting. The proposed assessment method is based on the well-known average daylight factor method and was tested using model measurements under an artificial sky with constant luminance and simulations of photopic and melanopic horizontal and vertical illuminance in laterally lit rooms in the ALFA simulation software. Although approximate, this method is suitable for assessing the non-visual potential of the lateral daylighting of regular interior spaces in the initial stages of their design. The proposed method is applicable in concrete urban and architectural conditions. The computational method takes into account the size of the room, the size of the windows, external shading, and the photometric characteristics of materials and external and internal surfaces for both photopic and melanopic conditions. A user-friendly computational tool was also developed in the LabVIEW (2023) environment, which allows for the optimization of the design of both photopic and melanopic daylighting. This method also makes it possible to assess the photopic and melanopic autonomy of lateral daylighting, taking into account the available outdoor diffuse horizontal illuminance in locations with a year-round prevalence of cloudy skies. This easy-to-use tool can be used by people who are not specialized in the assessment of light environments in buildings.

Acknowledgments

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