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OPTIMIZATION OF THE WORKING PLANE FOR DAYLIGHT USE IN WINTERS THROUGH THE SOUTH FAÇADE WITH OVERHANG WIDTH VARIATION IN MID WESTERN INDIA

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Abstract

For the past few years daylight design of buildings that is one of the essential techniques of passive solar architecture has gained much attention. This contribution tries to depict the quantitative performance of illuminance on the working plane through a computer model, which was developed using established sky luminance and interior illuminance models. Computations have been performed through a window on the South façade with overhang width variation in winter at Indore. Daylight contours of both direct and diffuse illuminance have been plotted. Optimized position of the working plane for illuminance on various tasks has been determined with optimum overhang width.
Keywords: Sunlight, Skylight, Daylight, luminous efficacy, illuminance

Introduction

It has been established that work productivity of humans increase if the working plane is day lit. The concept of daylight design of buildings is not new as our historical buildings exhibit excellent design elements. In the modern context of daylight design by incorporating prediction techniques through mathematical models a reduction in energy costs can be achieved.

The first research work on daylight was attempted by Moon & Spencer [1] and on other than overcast or clear skies i.e. for 'average skies' by Littlefair [2] and 'intermediate' skies by Nakamura et al [3]. Perez et al [4] developed the 'all weather' model using three parameters of sky clearness, sky brightness and the zenith angle based on the global and direct irradiance measurements. Recently S. Darula and R. Kittler [5] presented new method of sky luminance estimation based on luminance gradation and indicatrix function, which was chosen to predict the sky luminance at Indore.

In the Northern hemisphere the Sun sweeps the south façade in winters and north façade in summers and therefore if windows are placed in these orientations daylight can be efficiently utilized but daylight contains both the diffuse and direct parts called skylight and sunlight respectively and sunlight can produce lot of glare especially in the south façade in winters. By predicting sunlight contour levels and placing the appropriate overhang the task position can be determined so that glare is eliminated. In this paper both sunlight and skylight contours are plotted through a window in South with change in overhang width and thus the optimized working plane for different tasks has been determined.

Location and climatic conditions

The city identified for the study was Indore (latitude 22.7^0 N and a longitude of 75.9^0 E, altitude of 556 msl) located in mid western part of India. 10^{th} day of December month was considered for calculations. Used hourly horizontal irradiance for the month of December is tabulated in table 1.

Table 1: Hourly horizontal irradiance for December month at Indore, W/m^2

	Hour												
Month	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Dec. (global radiation)	0	47	225	418	590	710	753	710	590	418	225	47	0
Dec. diffuse radiation)	0	29	104	136	131	126	133	126	131	136	104	29	0

Mathematical modeling for illuminance distribution inside a room

The horizontal illuminance of the daylight entering in a room has three components: the beam illuminance $E_{b,r}$, the diffuse illuminance $E_{d,r}$, and the reflected illuminance $E_{r,r}$. In this paper for calculation purposes the reflected illuminance was not considered.

Beam illuminance : To calculate the interior horizontal beam illuminance $E_{b,r}$ of the daylight, equation (1) has been used.

$$E_{b,r} = \tau_w(\theta_i)E_b \quad (1)$$

Where θ_i is the angle of incidence and $\tau_w(\theta_i)$ is the light transmittance through the window.

To calculate the light transmittance of the window, equation (2) has been used.

$$\tau_w(\theta_i) = 1.018\tau_w(0)\cos\theta_i\left(1+\sin^3\theta_i\right) \quad ...(2)$$

where $\tau_w(0)$ is the light transmittance of window with the 0 angle of incidence.

The outdoor horizontal beam illuminance E_b is calculated from the outdoor horizontal beam irradiance G_b.

$$E_b = K_b G_b \qquad ...(3)$$

where K_b (lm/W) is the luminous efficacy of the beam radiation calculated through [9,10].

To findout whether the sun is visible to the point of reference, first the solar altitude α_s and solar azimuth angle γ_s are calculated and then the altitude and azimuth angles of the edges of the window seen by the observer O inside the room are calculated.

The sun is visible to the observer O if:

$$\theta_1 < \alpha_s < \theta_2$$

and $\gamma_1 < \gamma_p < \gamma_2$

where $\gamma_p = \gamma_s - \gamma_w$

where γ_w is the azimuth of the normal to the window in radians.

and θ_1 is the altitude angle of the lower edge of the window relative to the observer O.

(Radians)

θ_2, is the altitude angle of the upper edge of the window relative to the observer O.

(Radians)

γ_1 is the azimuth angle of the left edge of the window relative to the observer O.

(Radians)

γ_2, is the azimuth angle of the right edge of the window relative to the observer O.

(Radians)

Internal diffuse illuminance: The interior horizontal diffuse illuminance at the viewpoint of the observer O depends upon the sky luminance and the solid angle of the window seen by the observer.

If the sky luminance seen by the observer O through the window is assumed to be constant over the window area, then the interior horizontal diffuse illuminance $E_{d,r}$ at O is calculated through:

$$E_{d,r} = \int_0^{w_l}\int_0^{w_h} \frac{\tau_w L z y dx dy}{\left(x^2+y^2+z^2\right)} = \frac{\tau_w L}{2}\left(\tan^{-1}\left(\frac{w_l}{z}\right) - \frac{z}{\sqrt{{w_h}^2+z^2}}\tan^{-1}\left(\frac{w_l}{\sqrt{{w_h}^2+z^2}}\right)\right) \qquad ...(4)$$

where w_l is the length of the window in meters and
w_h is the height of the window in meters as shown in figure.

A general case of equation (18) is given by (Vartiainen & al., 2000) [11]

$$E_{d,r} = \frac{\tau_w L}{2}\left\{\begin{array}{l}\frac{z}{\sqrt{{h_O}^2+z^2}}\left(\tan^{-1}\left(\frac{w_x+w_l-x_O}{\sqrt{{h_O}^2+z^2}}\right)+\tan^{-1}\left(\frac{x_O-w_l}{\sqrt{{h_O}^2+z^2}}\right)\right)- \\ \frac{z}{\sqrt{(h_O+w_h)^2+z^2}}\left(\tan^{-1}\left(\frac{w_x+w_l-x_O}{\sqrt{(h_O+w_h)^2+z^2}}\right)+\tan^{-1}\left(\frac{x_O-w_x}{\sqrt{\sqrt{(h_O+w_h)^2+z^2}}}\right)\right)\end{array}\right\} \qquad ...(5)$$

where w_x is the distance between the left edge of the window and left wall in meters.
x_O is the distance between the point of observation O and the left wall in meters.
h_O is the height of point O from the window sill in meters.
z is the distance of the point O from window in meters.

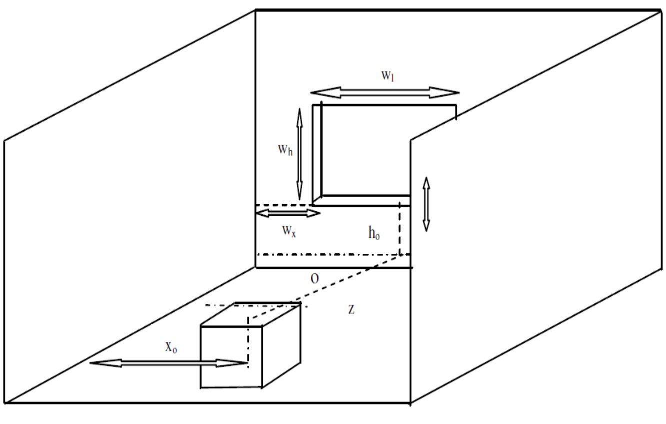

Fig. 1 : The interior geometry for calculating the internal horizontal diffuse illuminance

Daylight prediction with an overhang

A mathematical model was developed for the estimation of internal illuminance if an overhang as placed on the window.

If an overhang is placed on the window the sky seen through the window would decrease.

Figure 3 illustrates the methodology adopted.

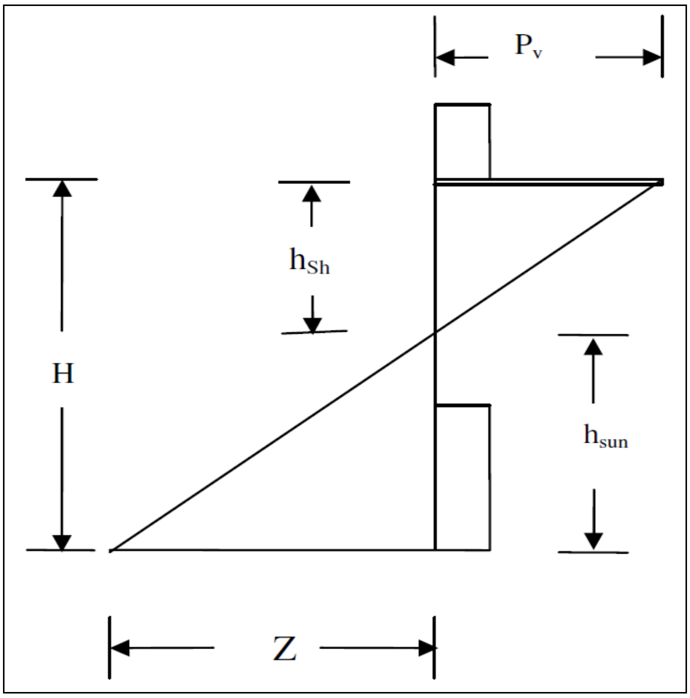

Fig. 2: The shaded and sunlight area of fenestration for interior Illuminance determination

Let H be the total height from the top of the window to the floor, h_{sh} be the portion in shadow, h_{sun} be the portion in sun. Let P_v be the overhang length and Z be the distance of point of observance from the plane of the window.

From similar triangles A and B

$$\frac{P_v}{Z} = \frac{\sqrt{h_{sh}^{2} + P_v^{2}}}{\sqrt{h_{sun}^{2} + z^{2}}} \quad \text{and } H=h_{sh}+h_{sun} \tag{6}$$

Solving and rearranging we get $h_{sun} = \dfrac{H}{1+\dfrac{P_v}{z}}$ and

$$h_{sh}=H-h_{sun} \quad ...(7)$$

Results and discussion

Room size and Input data

For a typical window of dimensions 2.0m x1.2m, area 2.4 m^2 the hourly interior illuminance at desk level was estimated for December average day 4 hours before and after noon (8:00hrs through 16:00 hrs for a typical office room of size 6.0m x 4.5m x 3.0m, desk level was fixed at 0.6375m and the sill height was fixed at 0.75m the solar radiation data was taken from [12]. As the interior horizontal illuminance decreases rapidly with the distance from the window therefore it is not sufficient to estimate the daylight availability at a single point in the room so it was decided that the room be divided into grids of 20cm x 30 cm resulting in 450 grid points in the interior. Further for calculation accuracy the window was divided into 10 x 10 patches resulting in 100 grid points on the window. The normal light transmittance of window was fixed at 0.85.

Daylight contours with no overhang width variation

Composite time averaged contours were plotted for sunlight and skylight from 8am to 4pm, which are, depicted in figures 3 and 4.

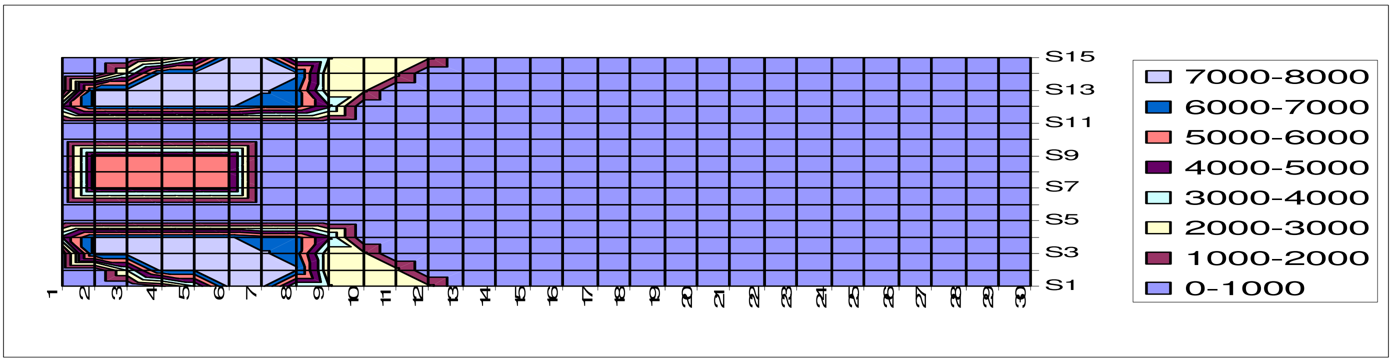

Fig. 3: Composite time averaged contours of sunlight with no overhang

It can be interpreted from the above graph that the maximum accessibility of the sunlight is up to the depth of 2.5m grid (13, S1), (13,S15) which is of the order of 1000 lx so the working plane could be after 2.5m from the window plane. In the mornings and evenings the average illuminance is higher as compared to afternoon because more beam component enters the room during morning and evening hours.

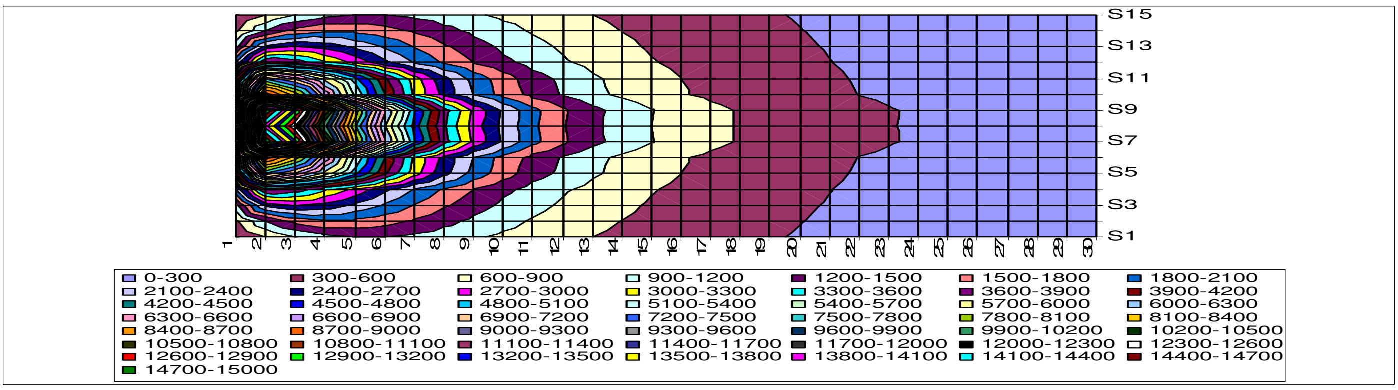

Fig. 4: Composite time averaged contours of skylight with no overhang

It is evident that for an office building where positioning the working plane 3.6m away from the South facing window plane can fulfill the lighting requirement of 300-500lx, grid (18, S1), (18, S15).

Daylight contours with overhang width variation

For the aforesaid window the overhang width was varied from 0.3m to 0.9m with 0.3 m increments and again the composite time averaged contours were plotted for sunlight and skylight from 8am to 4pm, which is depicted in figures 5 to 10.

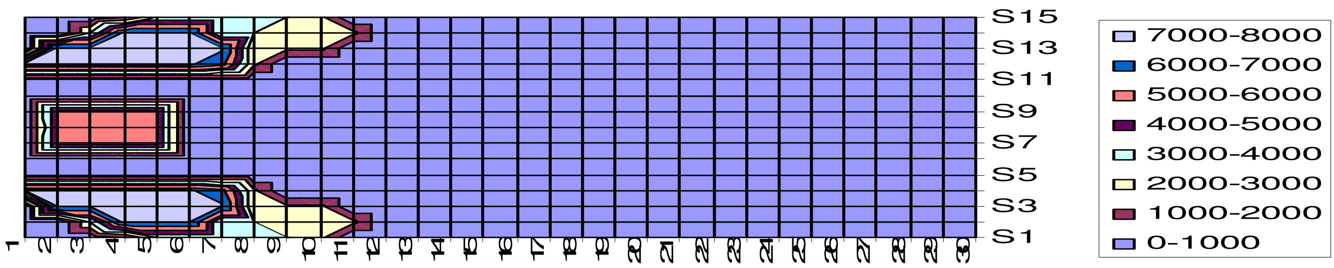

Fig. 5: Composite time averaged contours of sunlight with 0.3m overhang width

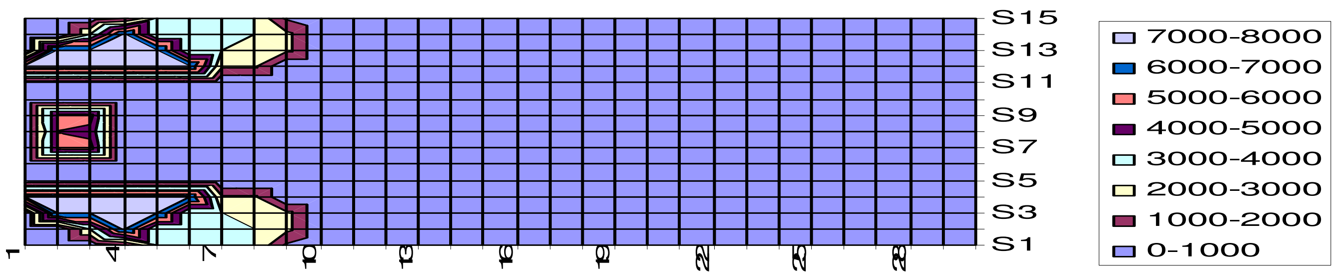

Fig. 6: Composite time averaged contours of sunlight with 0.6m overhang width

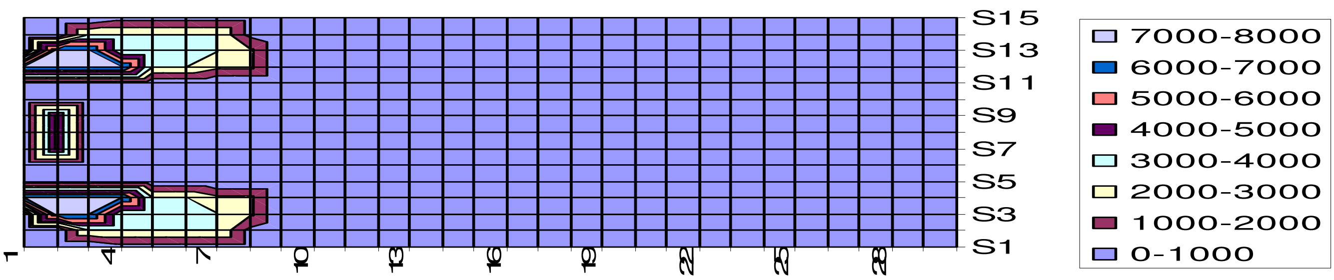

Fig. 7: Composite time averaged contours of sunlight with 0.9m overhang width

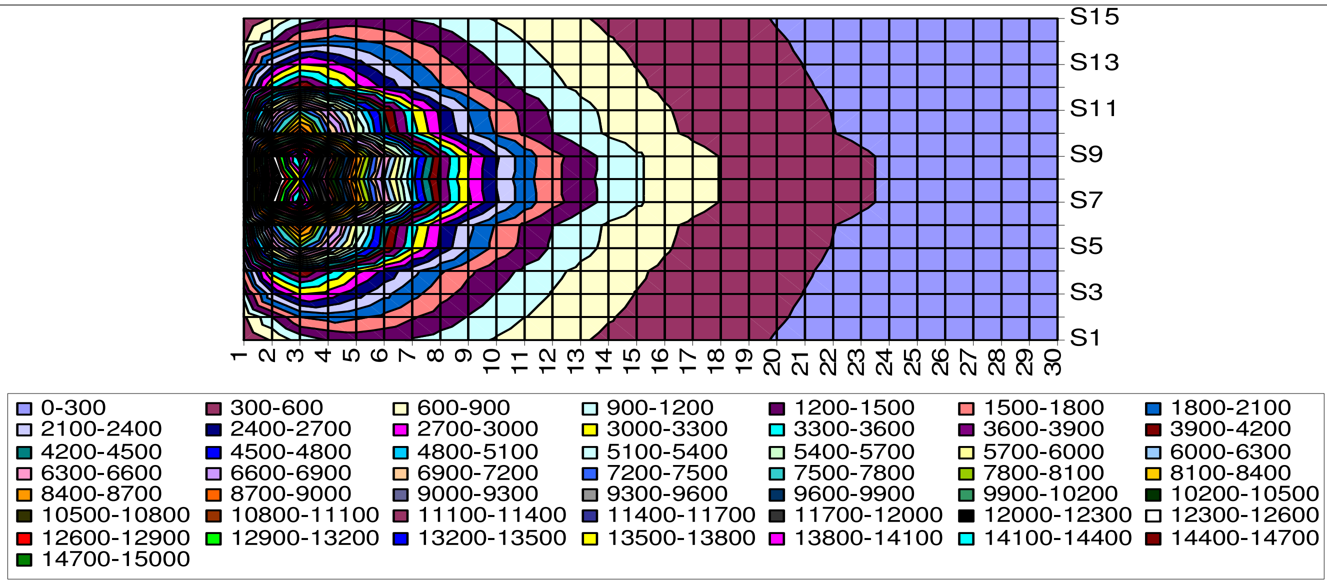

Fig. 8: Composite time averaged contours of skylight with 0.3m overhang width

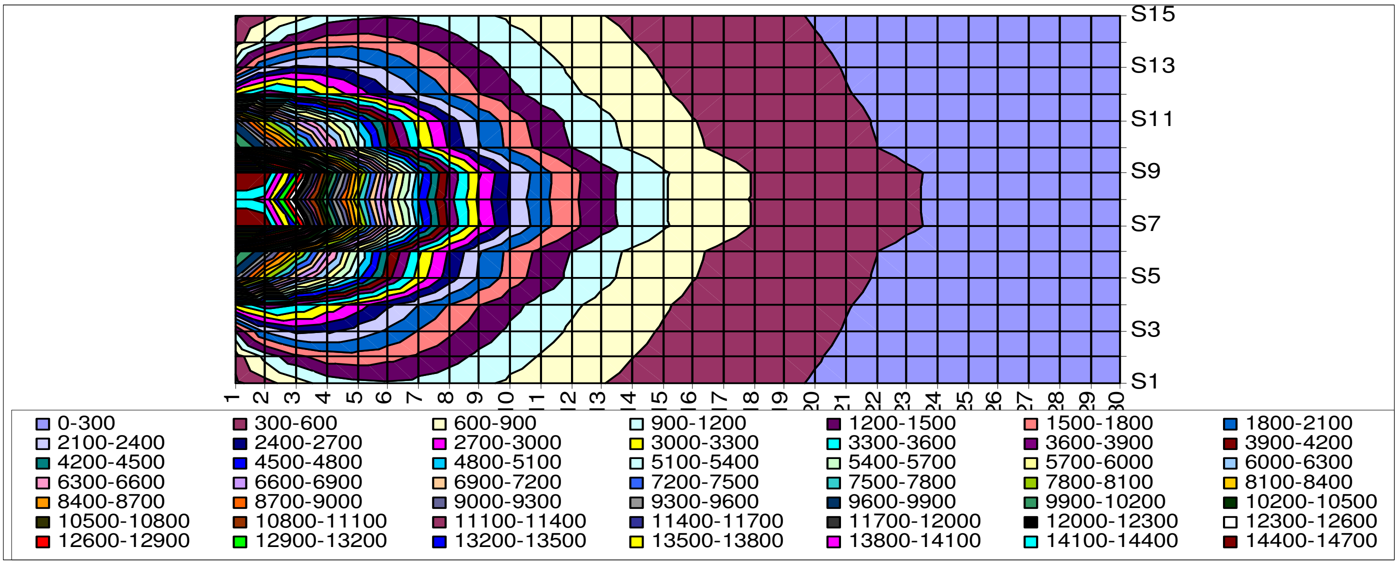

Fig. 9: Composite time averaged contours of skylight with 0.6m overhang width

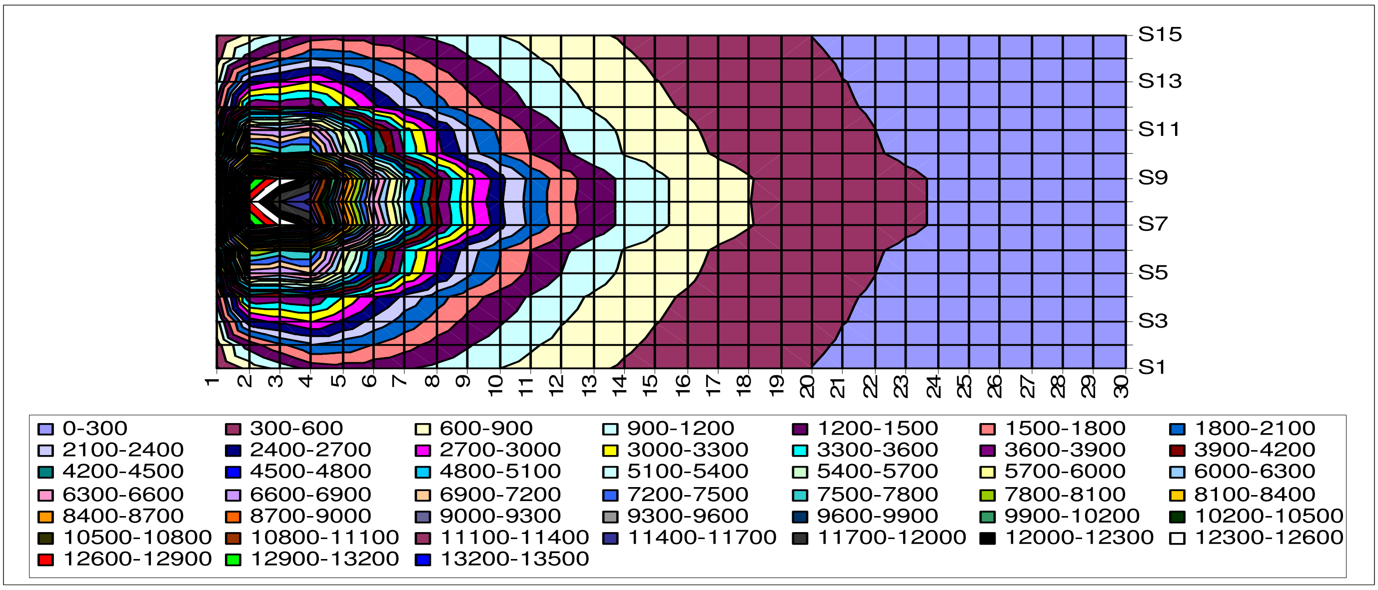

Fig. 10: Composite time averaged contours of skylight with 0.9m overhang width

With increase in overhang width the sunlight is reduced which is evident from figures 3-7. It can be seen that the decrease in illuminance contours during mornings and evenings is 20cms for an overhang of 0.3 m as compared to no overhang which increases to 40cms with an overhang of 0.6m as compared to 0.3m and reduces to 20cms for an overhang width of 0.9m as compared to 0.6m overhang. Further between 11am to 1 pm the decrement is 20cms from 0.3m to 0.6m and there is no appreciable shift from 0.6m to 0.9m-overhang width. Hence it can be inferred that the optimum overhang width should be in between 0.3 and 0.6m. It can be envisaged from figures 5 and 9 that overhang has no appreciable effect on diffuse illuminance farthest of the window since the optimum value of 300-500lx is still in the grid (17, S1), (17, S15) 3.4m away from the South facing window plane. However the effect on skylight reduction can be seen nearer to the window.

Comparing figures, it is evident that an overhang width has no significant effect on the diffuse light where the desired lighting requirement is needed in the room therefore choice of 0.45m overhang width is beneficial as far as cost is concerned.

Having determined the overhang width the position of working plane for different tasks was determined. Table 2 [3] shows the requirement of illuminance level for different tasks.

Table 2: Illuminance level requirements for different tasks

Location	Illuminance levels (lx)
Library/classroom	300
General office	500
Work bench	500
Drawing office	500-750
High precision tasks	1500

The requirement of 300lx for a library, 500 lx for general office building, 700 lx for drawing area and 1500 lx for high precision task can be achieved at a distance of 4.6m grid (S1, 23), 3.8m grid (S1, 19), 3.4m grid (S1, 17), 2.4m grid (S1, 12) respectively from the window plane and the necessary requirement of illuminance after this distance can be augmented by artificial light. Further the placement of desk can be either on the east grid (8, S15) or west grid (8, S1) facing as far as day lighting is concerned.

Conclusions

The optimum illuminance level on work plane for common tasks have been determined through a window placed on South façade at Indore of width to height (w/h) ratio of 1.66 and area 17.7 % of the façade area with overhang width variation. The optimal overhang width at the orientation has been also determined. It has been observed that an overhang width of 0.45m would be optimum for both daylight and cost considerations. It was also seen that the effect of overhang width on skylight and sunlight is more prominent nearer to the window plane and after a distance of 2.4m and farther visual comfort for various tasks can be achieved. For the aforesaid overhang width, length of the working plane from the window plane to breadth of the room (l/b) ratio of the placement of task area should be 1.02, 0.84, 0.75, 0.53 respectively for library, general office, drawing office, high precision task areas respectively. The areas under visual comfort were found to be 20.7 m^2, 17.1 m^2, 15.3 m^2, 10.8 m^2 respectively which is of the order of 76.6%, 63.3%, 56.6%, 40% of the room area respectively provided the areas where the illuminance falls less than the required number, and are supplemented with artificial light.

References

[1] Moon, P. and Spencer, D.E. (1942). Illumination from a non-uniform sky, Illumination Engineering (N.Y.), 707–726.

[2] Littlefair, P.J. (1994). A comparison of sky luminance models with measured data from Garston, United Kingdom, Solar Energy, 53: 315-322.

[3] Nakamura, H.; Oki, M.; Hayashi, Y. (1985). Luminance distribution of intermediate sky, Journal of Light and Visual Environment, 9(1): 6–13.

[4] Perez, R.; Seals, R.; Michalsky, J. (1993). An all-Weather Model for Sky Luminance Distribution, Solar Energy, 50(3): 235-245.

[5] Kittler, R.; Darula, S.; Perez, R. (1998). A set of standard skies, characterizing daylight conditions for computer and energy conscious design, American–Slovak grant project, US–SK 92 052.

[6] Perez, R.; Ineichen, P.; Seals, R.; Michalsky, J.; Stewart, R. (1990). Modeling daylight availability and irradiance components from direct and global irradiance, Solar Energy, 44: 271-289.

[7] Kasten, F. (1993). Discussion on the relative air mass, Light Res Technol, 25:129.

[8] Navvab, M.; Karayel, M.; Ne'eman, E. and Selkovitz, S. (1984). Analysis of atmospheric turbidity for daylight calculations, Energy and Buildings, 6: 293-303.

[9] Wright, J.; Perez, R.; Michalsky, J.J. (1989) Luminous efficacy of direct irradiance: variations with insolation and moisture conditions, Solar energy, 42: 387.

[10] Joshi, M.; Sawhney, R.L.; Buddhi, D. (2007). Estimation of luminous efficacy of daylight and exterior illuminance for composite climate of Indore city in mid western India, Renewable energy, 32: 1363-1368.

[11] Vartiainen, E.; Peippo, K. Lund, P. (2000). Daylight optimization of multifunctional solar facades: Solar Energy, 68(3): 223-235.

[12] Mani, A.; Rangrajan, S. (1980). Handbook of solar radiation data for India. New Delhi, Applied Publishers Pvt. Ltd.; 1980.

[13] Muneer, T. (1997). Solar radiation and daylight models for the energy efficient design of buildings, Architectural Press: UK. 1997.

[14] Turan, I.; Chegut, A.; Fink, D.; Reinhart, C. (2020). The value of daylight in office spaces, Building and Environment, Volume 168/15, 2020.

[15] Dieste-Velasco, M.I.; Díez-Mediavilla, M.; Alonso-Tristán, C.; González-Peña, D.; Rodríguez-Amigo, M.C.; García-Calderón, T. (2020). A new diffuse luminous efficacy model for daylight availability in Burgos, Spain, Renewable Energy, 146: 2812-2826.

[16] Fang, Y. and Cho, S. (2019). Design optimization of building geometry and fenestration for daylighting and energy performance, Solar Energy, 191: 7-18.

[17] Das, A. and Paul, S.K. (2015). Artificial illumination during daytime in residential buildings: Factors, energy implications and future predictions, Applied Energy, 158/15: 65-85.