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OPTIMIZATION OF DAYLIGHT FACTOR DISTRIBUTION USING STANDARD DEVIATIONS BASED ON SHIFTING WINDOW POSITION

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Abstract

Natural lighting is an important factor affecting the comfort of building users and requires a window area of at least 1/6 of the floor area. This research was conducted to obtain the distribution of Daylight Factor (DF) as a natural lighting factor during the day in the room, based on changes in the position of the window on the wall. In this research, we optimally calculate the distribution of lighting in a room through window openings and compare the best window position in the spread of illumination with DF calculations based on Sky Component (SC). The method used by shifting the window position is analyzed by standard deviation and the mean based on the DF distribution. Optimization of the DF distribution in a shifted window position if it has the largest average DF value and the smallest DF variant value. The results of the research in the room showed the optimal DF distribution was in the middle window position with an average value of 2.59%. The relationship of shifting the position of the window and the distribution of DF is useful for architects to determine the position of the window in the room's architectural design.

Key words: Natural lighting, DF Distribution, Window Position, Sky Component, Optimization, Standard Deviation (S), Mean (μ) values.

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INTRODUCTION

The relationship between humans, natural lighting and architectural design is very closely related to each other. Lighting has the greatest influence on human life in physical, physiological and psychological [1]. Human activity in buildings is inseparable from the need for the importance of natural lighting to increase user productivity and visual comfort [2]. Many studies have proven the importance of natural light in buildings. Natural light significantly influences the balance of energy use in buildings and actual human activities. Accurate estimation of daytime lighting in a room is important in saving lighting energy because daytime lighting data in a room can be used to predict the lighting energy of a building and improve energy efficiency [3].

Natural lighting is used in architectural and building designs which aim at giving a more evaluation of the level of internal natural lighting, and determining whether they will be sufficient for occupants of space to carry out their normal activities [4]. The distribution of natural light in a room depends on three factors: Geometry of space, placement and orientation of windows and other openings and internal surface characteristics [5]

One of the lighting sources in the room is natural lighting that comes from sunlight. Natural lighting utilizes openings or windows, the wider the openings, the more light will enter the space [6]. The quality of natural lighting is also influenced by the layout of the openings towards the direction of the arrival of sunlight [7]. The position of laying a window that affects natural lighting can also affect the user's visual interests, where those visual interests can be felt [8]. Windows are a key element in architecture, as they represent the most basic resource for enabling natural light in buildings. The right window design also increases visual comfort and results in energy savings in the use of artificial lighting.

The Daylight Factor (DF) is the simplest and most common measure of quantifying daylight permitted by a window, because it reveals the potential lighting in a room in the worst-case scenario, under cloudy conditions when there is little exterior light [9]. At present, the daytime factor is the most widely used metric in daytime lighting evaluations [10].

In the research of Mohelnikova and Jiri Hirs, mentioning external factors and reflection factors in influencing lighting levels during the day 2-12% at the point of measurement, then from that statement the sky factor is the most significant component and has the most factors, a considerable influence on the point measurement [11].

In this research, the component used in DF is SC. Eliminating ERC and IRC in this study aims to test the space in the worst conditions without any reflection factors that affect the distribution of lighting in the room. The value of DF at each measurement point in the room is called the DF distribution.

The research gap in this paper is related to the distribution of lighting in the room based on the SC estimation approach [12], to find the optimization of the DF distribution in the room against shifting the horizontal window position on the wall. The aims and motivations of this paper are 1) to apply the calculation of the estimated SC on each window shift towards the measurement point; 2) test the DF distribution based on SC on three window position shifts.

Based on the explanation above, this paper looks for DF optimization by shifting the window opening position horizontally in the room, to get the best window position. The optimization calculation process uses the average distribution of each window shift in the room by comparing the variance values. By using statistical mathematical analysis, the value of the object that has the highest mean value with the ratio of the lowest variance value, the object that has optimization will be considered the best.

This paper is organized as follows. The Material and Methods section, explains the DF based on SC, the position of the measurement point against the window position shift and the optimization of DF. In the Results and Discussion Section, test the distribution of 3 types of window position shifts in the room. Finally, Section 5 summarizes the results of the optimization of the DF distribution from testing all three sample spaces.

MATERIAL AND METHODS

In this section, *DF* is a percentage value of the lighting distribution and is the sum of the three components that influence it, namely *SC*, *IRC*, and *ERC*. *DF* is closely related to the position of the window and the size of the window opening with the distribution of lighting in the room. When *IRC* and *ERC* do not have an effect value or zero, then *DF* = *SC*. The SC estimate is measured perpendicular to the window. Thus, there will be several possible measurements of the measuring point with respect to the position of the window.

Daylight Factor (DF)

Daylight Factor (DF) is the ratio between the value of lighting in the room with the value of outdoor lighting in daytime conditions and the sum of the three-component factors that affect DF, namely Sky Component (SC), External Reflection Component (ERC) and Internal Reflection Component (IRC). DF can be defined by equation (1) [13,14,15].

$$DF = SC + IRC + ERC \tag{1}$$

DF calculations are generally based on daytime factors regardless of prevailing weather conditions. The daylight conditions in question are evenly distributed lighting conditions or cloud conditions.[16].

Sky Component (SC) Calculation

Sky Component (SC) is the influence factor of the outer sky, where SC relates to the measuring point with the window. The most significant percentage in DF is influenced by SC [12,17]. The SC value can be determined by measuring the width (L) and height (H) of the effective light hole (window) visible from the measuring point (p), relative to the distance (d) of the measuring point to the where the light hole is located.

Based on the CIE test [18] and SNI 03-2396-2001 [19]. The effective vertical light hole with dimensions (L × H) as illustrated in Fig.1.

$$DF = SC \tag{3}$$

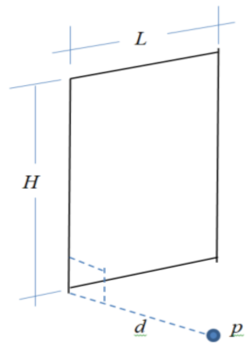

Fig 1.Position of p, with d, window size $L\ x\ H$.

SC at the measuring point (p), perpendicular to the window position is shown in equation (2).

$$(L,d,H) = \frac{1}{2\pi}\left(\arctan\left(\frac{L}{d}\right) - \frac{1}{\sqrt{1+\left(\frac{H}{d}\right)^2}}\, arctan\left(\frac{\frac{L}{d}}{\sqrt{1+\left(\frac{H}{d}\right)^2}}\right)\right) \tag{2}$$

where g is SC at a distance (d) perpendicular to the window between the measurement point (p) and the window opening area, H is the window hole height above the measurement point, and L is the window hole length.

DF based on SC

ERC and IRC in equation (2), ERC is defined as a fraction of the sky component, depending on the distance from the exterior geometry and its reflection [20]. IRC is a factor that is influenced by reflections of objects indoors as a result of reflections from objects lighting outdoors and ceilings [18].

In this study, ERC and IRC are negligible, because it is assumed that in the worst conditions, there are no reflection factors from outside buildings that block daylight and there are no objects that can be reflected in the room, so it is assumed that the ERC and IRC values are zero. Then only SC affects DF. Equation (3) defines DF based on SC.

SC Estimation Based On Window Position In The Room

SC estimation is measured perpendicular to the window position [21]. In Fig.2, SC point p (x, y, z) which is located at a distance d perpendicular to the window with size $L \times H$ on the axis z , where H is the height of the window at points $(x_0, 0, z_0)$ and L is the width of the window at the point $(x_0 + L, z_0)$

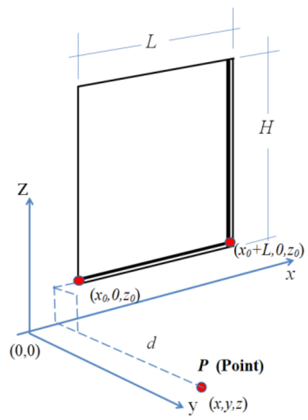

Fig 2. Estimated Sky Component (SC) at the measuring point(x, y, z).

Based on Fig.2, there is an estimation of the SC, which can only be calculated perpendicular to the window. Then, there are six possible conditions for the position of the measuring point against the position of the window.

A. Condition 1: The position of the measurement point (x, y, z) lies in between $(x_0, 0, z_0)$ and $(x_0 + L, 0, z_0)$ perpendicular to the window. The position of the window lies in the x_0, z_0 coordinates, while the length of the window denotes L, the height of the window denotes H, if $x_0 < x < x_0 + L$ and $z = z_0$, then,

B. Condition 2: The position of the measurement point (x, y, z) is in front of the point$(x_0, 0, z_0)$, perpendicular to the window. The position of the window lies in x_0, z_0 coordinates, window length (L), window height (H), if $x < x_0$, and $z = z_0$, then

$$SC_2(x, y, z; x_0, z_0, L, H) = g(x_0 - x, y, z_0 + H) - g(x_0 - x, y, z_0 + H)(x_0 + L, y, z_0 - z) + g(x_0 + L - x, y, z_0 - z` \tag{5}$$

C. Condition 3: The position of the measurement point (x, y, z) is at $(x_0, 0, z_0)$, and $(x_0+L,0,z_0)$. The position of the window located in the x_0, z_0 coordinates, window length (L), window height (H), if $x_0 + L < x$ and $z = z_0$, then,

$$SC_3(x, y, z; x_0, z_0, L, H) = g(x - x_0, y, z_0 + H - z) - g(x - x_0 - L, y, z_0 + H - z) - g(x - x_0, y, z_0 - z) + g(x - x_0 - L, y, z_0 - z) \tag{6}$$

D. Condition 4: The position of the measurement point (x, y, z) is between $(x_0,0,z_0)$ and $(x_0+L,0,z_0)$ below the window. The position of the window located in the x_0, z_0 coordinates, window length (L), window height (H), if $x_0 < x < x_0 + L$ and $z < z_0$, then,

$$SC_4(x, y, z; x_0, z_0, L, H) = g(x - x_0, y, H) + g(x_0 + L - x, y, H) \tag{7}$$

E. Condition 5: The position of the measurement point (x, y, z) is to the left of the point $(x_0,0,z_0)$ near the point (0,0). The position of the window located in the x_0, z_0 coordinates, window length (L), window height (H), if $x < x_0$, and $z < z_0$, then,

$$SC_5(x, y, z; x_0, z_0, L, H) = g(x_0 + L - x, y, H) - g(x_0 - x, y, H) \tag{8}$$

F. Condition 6: The position of the measurement point (x,y,z) is to the right of the point $(x_0+L,0,z_0)$. The position of the window located.

$$SC_1(x, y, z; x_0, z_0, L, H) = g(x - x_0, y, z_0 + H - z) + g(x_0 + L - x, y, z_0 + H - z) - g(x - x_0, y, z_0 - z) - g(x_0 + L - x, y, z_0 - z) \quad (4)$$

In the x_0, z_0 coordinates, window length (L), window height (H), if $x_0 + L < x$ and $z < z_0$, then

$$C_6(x, y, z; x_0, z_0, L, H) = g(x - x_0, y, H) - g(x - x_0 - T, y, H) \quad (9)$$

Equations (7), (8), (9) and conditions 4,5,6 are special conditions of conditions 1,2,3, with equations (4), (5), (6), where $z = z_0$, From equation (4-9) above we get a new function from combining SC in a room, with equation (10):

$$SC(x, y, z; x_0, z_0, L, H) = \begin{cases} SC_3(x, y, z; x_0, z_0, L, H) & if\ z_0 + L < x, z = z_0 \\ SC_4(x, y, z; x_0, z_0, L, H) & , if\ x_0 < x < x_0 + L, z \le z_0 \\ SC_5(x, y, z; x_0, z_0, L, H) & , if\ x < x_0, z \le z_0 \\ SC_6(x, y, z; x_0, z_0, L, H) & , if\ z_0 + L < x, z \le z_0 \end{cases} \quad (10)$$

By using space testing criteria in conditions without any reflection factors from the exterior and interior of the building which affect the distribution of DF in the test room, then IRC and ERC are zero, and the equation can be written as equation (11).

$$DF(x, y, z; x_0, z_0, L, H) = SC(x, y, z; x_0, z_0, L, H) \quad (11)$$

Based on equation (12), the total DF in the room is in equation (12). where T is the total DF in the room.

$$T(x_0, z_0, L, H) = \int_x \int_y DF\ (x, y, z; x_0, z_0, L, H)\ dx\ dy \quad (12)$$

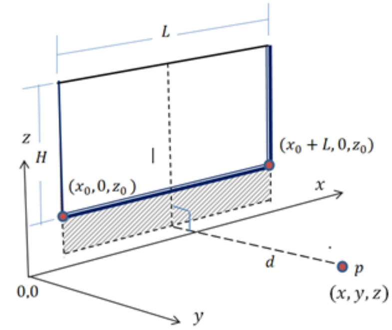

Fig 3. Position of the measuring point (p) in condition 1, $x_0 < x < x_0 + L$ and $z = z_0$.

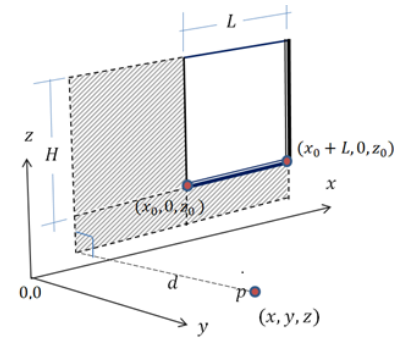

Fig 4. Position of the measuring point (p) in condition 2, $x < x_0$, and $z = z_0$.

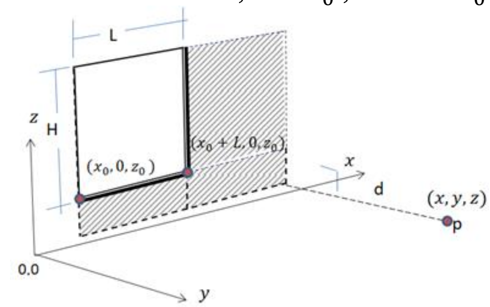

Fig 5. Position of the measuring point (p) in condition 3, $x_0 + L < x$ and $z = z_0$

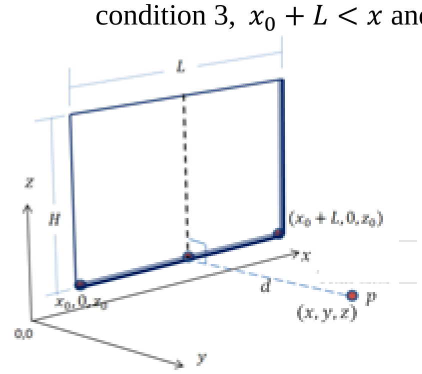

Fig 6. Position of the measuring point (p) in condition 4, $x_0 < x < x_0 + L$ and $z < z_0$.

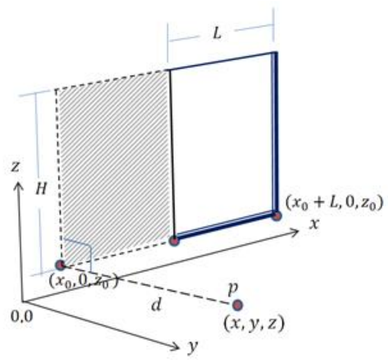

Fig 7. Position of the measuring point (p) in condition 5, $x < x_0$, and $z < z_0$.

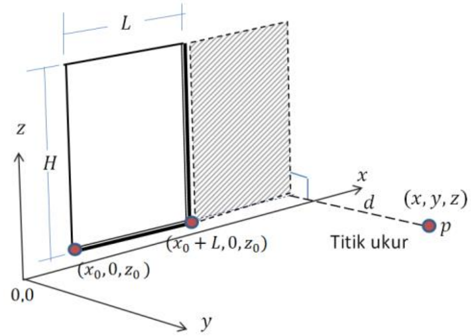

Fig 8. Position of the measuring point (p) in condition 6, $x_0 + L < x$ and $z < z_0$.

Optimization of DF Distribution Estimates

The final step, after getting the value of the DF distribution based on SC, next analyzes the distribution of DF in each room to find out the optimal window variant position when shifted horizontally in each room. Estimation of optimization of DF distribution is a way to find the most optimal optimization of window openings from DF distribution in each room with different window positions The process of estimating the optimization of daylight factor distribution is processed using the equation of variance (equation 13) and mean (equation 14).

Equation (13) is an equation to find the value of the DF variance of each sample with its window opening position.

$$S_{Ei} = \sqrt{\frac{\sum(DF - \overline{DF})^2}{n-1}} \tag{13}$$

where,

S_{Ei} = Variance total DF
DF = DF Value
$\overline{DF}$ = Mean Value of DF
n = Reference Total

Equation (14) is an equation to find the mean DF of each sample for the window opening.

$$A_{Ei} = \frac{\sum DF}{n} \tag{14}$$

where,

A_{Ei} = Mean total DF
DF = DF Value
n = Reference Total

RESULT AND DISCUSSION

In this paper, there are differences when compared with some studies that have been done. 1) the process of finding the best window position by shifting the window opening position on the wall plane to produce the optimization of the Daylight Factor distribution; 2) The process of optimization calculations using mathematics, statistical analysis, the value of objects that have the highest mean value with the lowest variance value ratio, the object that has optimization will be considered the best. This section will examine the three window shift positions commonly found in architectural designs.

Three Samples Shift Window Position

Window openings are on one of the shortest walls of the room. The room has an area of 12 m² (4 m long and 3 m wide) and has a window area of 1/6 of the room area of 2 m² (1.50 m x 1.33 m). In this paper, the three window opening positions that have a distance to the left wall, namely the window position (a). 0,1 m, (b). 0,5 m and (c). 0,85 of the wall.

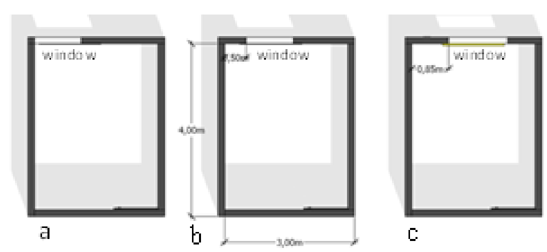

Fig 9. a. window position 0,1 m.; b. window position 0,5 m; c. window position 0,85 m.

Before doing the estimation of the DF distribution using the calculation of one element of the daylight factor, Sky Component (SC). The first step to do is to create a grid of reference points in the plane of space. The purpose of giving this reference point is to give a value of daylight factor distribution so each point represents the average of the area of the grid box created. The reference point is as high as 0.75 m, with a grid distance of 0.1 m. The average outdoor illuminance (Eo) value available for data collection is 3000 lux. From each grid that has been made from each of these rooms will be given a SC value.

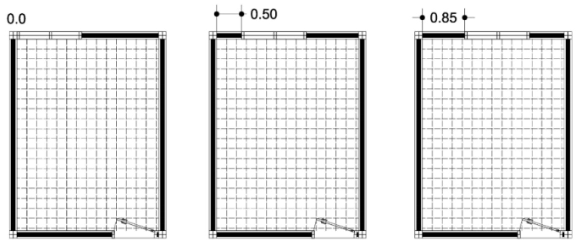

Fig 10. Grids on each floor 0.1 m

Distribution of DF

Testing on three sample spaces is accompanied by shifting the position of the window in the same plane and resulting in the total DF distribution. Shifting the window parallel to the x-axis, then the DF distribution can get the window's optimization position, which will be displayed graphically.
Based on the DF distribution in Fig. 12-14, it is analyzed that each direction of the window shifting from room affects the value of the DF distribution in the room. The process of sliding the window is 0.1 m from the left side of the window to the right side of the window. From the results of the distribution value, the search process calculates using Equations (1) to (14) according to the methodology.

The DF distribution shown in Figure.12-14 has color in each distribution. The degree of contrast color in the DF distribution in Fig.11 can be defined. Dark blue shows the smallest presentation of DF value 0%, light blue shows presentation of DF value 0.6% -1.2%, green shows DF value 1.3% -3.1%, yellow shows presentation of DF value 3.2% -5.3%, and red represent the highest DF value presentation of 5.4% and above. From these colors, it can represent and make it easier to see the distribution of DF with variations in the window shift.

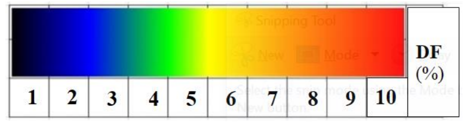

Fig 11. Color contrast levels in DF

The window position 0.1 m from the left wall (Fig.12), there are three areas of the lowest DF distribution has an interval of 0.1-2.5% (60.3% area dark blue - blue), the value of DF has an interval of 2.6% - 5.5% (18.2% 40 areas in blue), the value of DF has an interval of 5.6% - 6.9% (4.6% in green), and the highest DF has an interval of 7% - 10% (6.3% of the area is bright orange - bright red) with the illumination of the window opening being positioned 0 m from the wall, p this is also valuable when it is on the right-hand side (1% of the plane) because it has the same distribution.

The window position 0.5 m from the left wall (Fig.13), there are three areas of the lowest DF distribution has an interval of 0,1-2,5% (57,2% of the area is dark blue-blue), the value of DF has an interval of 2,6% -5,5% (21.6% of the blue area), the value of DF has an interval of 5.6% - 6,9% (4% in green), and the highest DF has an interval of 7% -10% (6,3% of the bright orange-bright-red area) with the lighting of the window opening being 0,5 m from the wall the left (25% of the wall area).

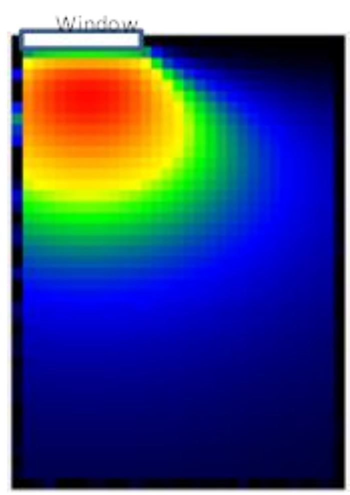

Fig 12. DF distribution at window position 0,1 m

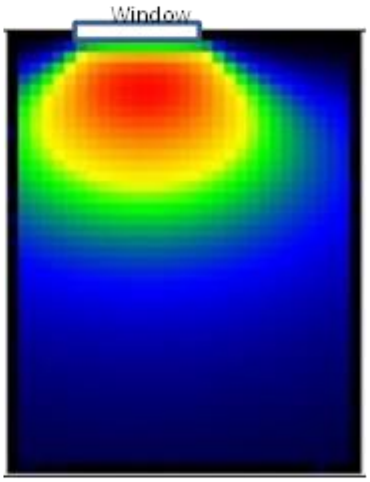

Fig 13. DF distribution at window position 0,5 m.

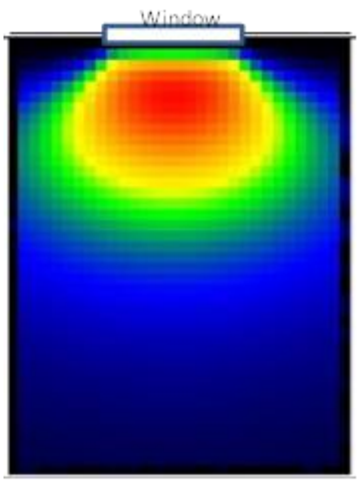

Fig 14. DF distribution at window position 0,85 m.

The window position is 0,85 m from the left wall (Fig.14), there are three distribution areas, namely, the lowest DF has an interval of 0.1-2.5% (54% of the area is dark blue - blue), the DFvalue has an interval of 2.6% - 5.5% (25.3% of the blue area), the value of DF has an interval of 5.6% - 7% (4.9% in green), and the highest DF has an interval of 7.1% - 10% (6.3% of the bright orange - bright red) area with the illumination of the window opening at 0,85 m from left wall (50% of the wall area).

The results can be seen in the distribution condition after 50%, namely in the window opening position 50% - 100% towards the wall area, where the distribution results are 50% - 0.1%. This can happen due to the condition of the rectangular room so that the window shifts when more or less than 50%, the result will be the same as the reduction.

Results of Optimization of DF Distribution Distance.

After the stage of shifting the window position in the y-axis direction (horizontally) every 0.1m according to the distance distribution of the grid in the room to find the average value of the DF distribution based on Sc has been done.

The next step is to look for optimizing the position of laying the window horizontally by using mean and variance. This is done to determine the most optimal position of window placement in one area of the wall.

For every window position shift, the DF distribution will be calculated using the mean and variance equation (equations (13) and (14)). The best window position in the distribution DF is that which has the highest DF and the lowest mean value. From this statement, we get the graph of the window position shift with the distance of the DF distribution in the room in Fig 15.

In Fig.15, the red line shows the variance value on the DF and shows the inverse comparison of the mean value at the distance of the DF distribution, when the mean daylight factor value is high, the value of the daylight factor variant is small and vice versa.

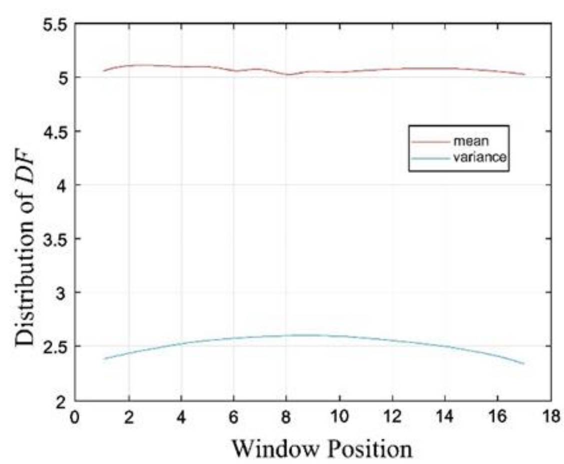

Fig 15. Mean and Variance graph in DF distance distribution

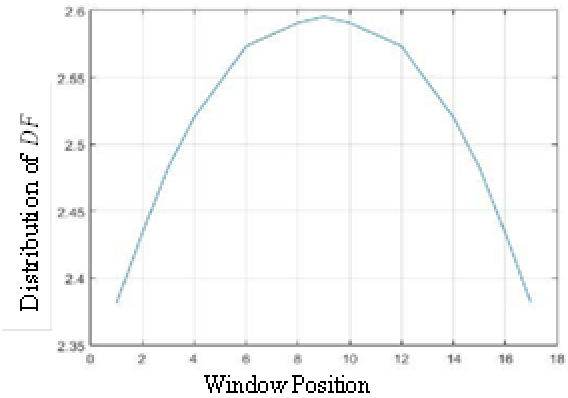

Fig 16. Mean Graph in DF Distance Distribution

The graph in Fig.16 shows the highest mean shift in the window position 0,85 m from the left wall or the window position in the middle position. The highest value at the window opening position in the middle (50%) has a mean DF of 2.59 %. The more the window opening is at the edge of the window wall, the DF mean value will decrease, in Fig.15 the smallest value is at position 1 and position 17 with the DF value is 2.38 %.

Based on the results of Fig 15. Mean and variance graphs, obtained comparisons of mean and variance values at the three window positions against the wall. A comparison of mean and variance is shown in Table 1.

Table 1. Comparison table for all three samples.

Window Samples	Window Position (m)	Mean %	Variance %
Window 1	0,1	2,38	5,10
Window 2	0,5	2,53	5,22
Window 3	0,85	2,59	5,05

Optimization of the DF distribution calculation between the mean and variance is the best window opening shift when the window opening position has the largest average value with a small variance ratio. The maximum optimization is in the position of the window opening in 0,85 m (position 9 to the window position in Fig 16.).

CONCLUSION

The position of the window shift can affect the value of the DF distribution in the room. As was done in the above experiment that the window position changes horizontally from each room and the most optimal value is based on the average value and variance based on the DF distribution in the room. In this study, the factors used to look for DF are only in the Sky Component *(SC)* because other factors are ignored or considered 0, this is to test the worst spatial conditions without the influence of IRC and ERC.

Optimization of DF Distribution can be determined by using mean and variance in the mathematical analysis of Standard Deviation. The statistical value used to determine how the data is distributed in the sample, and how much it approaches the mean.

Testing the sample window position shifting on the wall plane in this paper, using standard deviations, shows the comparison of DF spread based on the window position shift on the wall. In the three sample window position shifts in the window sample with a size of 1.3 m x 1.5 m and a wall width of 3 m, show the window position which is 0,85 m from the most angular wall, achieving optimization in the window position shift towards the DF distribution. The best window position or optimization value in the DF distribution is if it has the highest DF distribution value and the lowest mean value.

The mean DF distribution graph shows a shift in the position of the window in the center of the wall, having an average DF value of 2.59%. On the graph shifting the window position in numbers 1 and 17 shows the value of DF distribution of 2.38%. The more the window opening is on the edge of the wall, the lower the DF distribution value.

The results of this study can be used as further studies to find out the DF distribution optimization based on the position of the window in the variation of the wall plane and the number of window openings.

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