PREDICTION OF DAYLIGHT AVAILABILITY FOR AN INDOOR SPACE BY OPTIMIZING WINDOW PARAMETERS UNDER CIE SSLD MODEL

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of the requirements for the degree of

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Submitted by
KALYAN PALIT
Examination Roll No.: M6ILT19011

Under the guidance of
Dr. Biswanath Roy
&
Dr.Arindam Kumar Sil

School of Illumination Science, Engineering and Design
Jadavpur University

Course affiliated to
Faculty of Engineering and Technology
JadavpurUniversity
Kolkata-700032
India

2019

M.Tech. (Illumination Technology and Design)
Course affiliated to
Faculty of Engineering and Technology
Jadavpur University
Kolkata, India

CERTIFICATE OF RECOMMENDATION

This is to certify that the thesis entitled **“PREDICTION OF DAYLIGHT AVAILABILITY FOR AN INDOOR SPACE BY OPTIMIZING WINDOW PARAMETERS UNDER CIE SSLD MODEL”** is a bonafide work carried out by **KALYAN PALIT, Exam Roll No.: M6ILT19011** under our supervision and guidance for partial fulfilment of the requirement of **M.Tech. in Illumination Technology and Design** in School of Illumination Science, Engineering and Design during the academic session 2018 -2019.

THESIS ADVISOR

Dr. Biswanath Roy
Professor,
Electrical Engineering Department,
and visiting faculty, SISED
Jadavpur university,
Kolkata-700 032

THESIS ADVISOR

Dr. Arindam Kumar Sil
Assistant Professor,
Electrical Engineering Department,
and visiting faculty, SISED
Jadavpur university,
Kolkata-700 032

Dr. Kamalika Ghosh
DIRECTOR
School of Illumination Science, Engineering and Design
Jadavpur University,
Kolkata-700 032

Dr. Pankaj Kumar Roy
DEAN -FISLM
JadavpurUniversity,
Kolkata-700 032

M.Tech. (Illumination Technology and Design)
Course affiliated to
Faculty of Engineering and Technology
Jadavpur University
Kolkata, India

CERTIFICATE OF APPROVAL

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All information in this document has been obtained and presented in accordance with academic rules and ethical conduct.

I also declare that, as required by this rules and conduct, I have fully cited and referred all material and results that are not original to this work.

NAME: **KALYAN PALIT**

EXAM ROLL NUMBER: **M6ILT19011**

THESIS TITLE: **PREDICTION OF DAYLIGHT AVAILABILITY FOR AN INDOOR SPACE BY OPTIMIZING WINDOW PARAMETERS UNDER CIE SSLD MODEL**

DATE: SIGNATURE:

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Date:
Place: (Kalyan Palit)

Dedicated to Eternal and Indelible loving memory of my parents
Late Sri Kanai Lal Palit
and
Late Smt. Manu Palit

Contents

Page No.

i.	Synopsis of the Thesis	1
ii.	Problem Identification	2
iii.	Objectives of the project	3
iv.	Planning behind the Project	3

Chapter 1
Daylight Integrated Indoor Lighting design – an overview 4

1.1 Photometric quantities and their units 5
1.2 Other relevant terms and design parameters 7
1.3 Indoor Lighting Design 10
1.3.1 Objectives 10
1.3.2 Design Criterion 10
1.4 Significance of Daylight Integration and Necessity of Daylight Prediction Tool 11
1.4.1 Importance of Daylight Based Design 11
1.4.2 Importance of Prediction tool 12
1.5 Daylight Prediction Methods 13
1.5.1 Daylight Factor Method 13
1.5.1.1 Computation of E_{sky} 15
1.5.1.2 Computation of E_{ext} 16
1.5.1.3 Computation of E_{ExR} 16
1.5.1.4 Computation of E_{InR} 16
1.5.1.5 Limitation of DF Method 17
1.5.2 Daylight Coefficient (DC) Method 17
1.5.2.1 Advantages of DC Approach 18

Chapter 2
Literature Survey on Daylight Simulation for Indoor Lighting Design 19

2.1 Daylight Utilisation for Sustainable Development 20
2.2 Daylight Simulation 21
2.3 Daylight Prediction Tool 22

<u>**Chapter 3**</u>
Development of Daylight Prediction Model 25

3.1 Introduction 26
3.2 Room Dimension and Window Specification 27
3.3 Relative Luminance of Sky Element based on CIE SSLD model 29
3.4 Solar Geometry 33
3.5 Computation of Zenith Luminance 34
3.6 Computation of Sky Element Luminance 35
3.7 Grid Specifications 36
3.8 Computation of point specific Illuminance within a room having single window 37
3.9 Computation of point specific Horizontal Illuminance on Work Plane due to sky luminanace 38
3.10 Computation of Vertical Illumination on the room walls due to sky luminance 41
3.10.1 Point Specific Vertical Illuminance on the lower part of 1st wall 42
3.10.2 Point Specific Vertical Illuminance on the lower part of 2nd wall 45
3.10.3 Point Specific Vertical Illuminance on the lower part of 3rd wall 47
3.11 Computation of point specific Horizontal Illuminance on the Floor due to sky luminanace 50
3.12 Computation of Ground Luminance 52
3.13 Computation of Vertical Illumination on the room walls due to Ground luminance 53
3.13.1 Point Specific Vertical Illuminance on the upper part of 1st wall 54
3.13.2 Point Specific Vertical Illuminance on the upper part of 2nd wall 56
3.13.3 Point Specific Vertical Illuminance on the upper part of 3rd wall 59
3.14 Computation of point specific Horizontal Illuminance on the Ceiling due to Ground luminanace 61
3.15 Computation of Average Inter reflected Illuminance (IRC) 64
3.16 Computation of point specific total Horizontal Illuminance on the Work Plane. 66

<u>**Chapter – 4**</u>
Model Validation through Case Study 67

4.1 Case Study 1: Design Considerations 68
4.2 Comparison of Light Distribution Pattern with Output of the DIALux Software for the same design. 71

4.3 Variation of Daylight distribution for different sky condition
and different window orientation throughout the day on
different dates at Kolkata 78
4.4 Variation of Daylight distribution for particular window
orientation and particular Sky type on particular date
but for different location 86
4.5 Comparison of Hourly Daylight Variation obtained from
proposed Model with DIALux output 89

Chapter – 5
Application of the Proposed Model to Window Design 92

5.1 Relevant Recommendations from National Building Code'2016 93
5.2 Case Study 2: Window Optimisation with two variables 95
5.2.1 Window Optimisation 98
5.2.2. Dynamic Window 99
5.3 Case Study 3: Window Optimisation with Three Variables 101
5.3.1. Window Optimisation 104
5.3.2 Smart Window 105

Chapter – 6
Conclusion 108

6.1 Conclusion 109
6.2 Scope of Future Work 110

Bibliography: 111

Synopsis of the Thesis

In present era of human civilisation the concept of sustainable development needs to be introduced in every corner of the technological advancement. This kind of approach always demands minimum utilisation of artificial energy. But, we know a large amount of electrical power is generally utilised in the interior lighting design, particularly in the countries having huge population like our country India. In order to reduce the use of electrical energy, use of natural daylight must be enhanced in the daytime. But, daylight depends on various factors and is completely dynamic in nature. Therefore, to develop daylight integrated interior lighting design a daylight prediction tool is required, which may further be used in lighting control or even in optimized window design. The tool can be wisely utilised in the design of energy efficient building architecture.

The method of daylight prediction is broadly classified under two main categories – Daylight Coefficient (DC) and Daylight Factor (DF). The first approach is much more realistic instead of conventionally used Daylight Factor (DF) method for this purpose. The former one uses the real time sky luminance value, which depends on location, date, time and even sky type also. The aim of this project is to compute and develop a realistic daylight prediction model in MATLAB environment by using CIE Standard Sky Luminance Distribution. The results of developed model are also verified with the result of other available software (DIALux). The model has also been applied in optimizing the window dimension to achieve the best result.

Problem Identification

Daylight was always an integral part of Building architecture. Now its significance has newly re-established to enhance the energy efficiency of the building design. But daylight integrated interior design needs a reliable daylight prediction tool.

The conventionally used models are mostly based on available data base and are limited to broadly classified sky types – Overcast, Mixed and Clear sky. The models developed on Daylight Factor (DF) method are only applicable for purely overcast sky. But if a model is developed on the basis of predicted sky luminance for 15 CIE standard sky types, then the result of this tool is expected to be more realistic and reliable and widely applicable also.

Luminance values vary over a wide range depending on location, date, time and sky types. Again, interior daylight distribution also depends on room dimension, window dimension and window orientation and many other factors like room surface reflection property, transmittance of window glazing material, work plane dimension etc. To consider all of those factors, MATLAB program can be used to develop such a model of daylight computation, which helps in deriving a daylight distribution in any place, on any date of the year, at any time for any plane of any room of variable dimension with variable window opening and for different window orientation also.

Further, this model can be used to optimize the window dimension, properties and even orientation to get the best result of day lighting for a particular room. Finally, this model can be fully upgraded or developed as a useful tool for architectural design of building as a whole.

Therefore, it is obvious that, the success of daylight simulation, prediction and application depends to a large extent on the effective and proper techniques to consider all the above mentioned factors, on which interior daylight illumination depends. To develop such a simulation algorithm in MATLAB environment is the prime objective of this project. Further, validation of the outcome of the proposed model and suggesting the ways to apply the same in architectural design are also the objectives of the project.

Objectives of the Project

- To develop a reliable simulation model for daylight prediction based on CIE standard sky luminance distribution (SSLD) model.
- To use the model for optimizing the window dimension.

Planning behind the execution of the Project

❖ To have a thorough literature survey on the relevant topics.
❖ To consider the room dimensions window specifications and other necessary factors.
❖ To compute the zenith and sky luminance values.
❖ To compute point specific illuminance on the different planes of the room.
❖ To compute Inter-reflection component.
❖ To derive the lighting distribution on the work plane and develop the corresponding Iso-Lux plot.
❖ To compare and verify the outcomes of the model in all possible ways for checking its reliability.
❖ To use the model for optimized window dimension to achieve the best possible energy efficient design.

Chapter – 1

Daylight Integrated Indoor Lighting Design – an overview

1.1 Photometric Quantities and their Units

Light

It is the radiant energy which can cause visual sensation on standard human eye. It is generally denoted by ‘Q’ and is measured or expressed in lumen-hour, which is analogous to watt-hour of electrical energy.
It is propagated in the form of electro-magnetic wave. Generally EM wave, that ranges from 380 nm to 780 nm can produce visual sensation on human eye and hence is considered as light.

Luminous Flux

It is the rate of flow of luminous energy i.e. the total quantity of light energy emitted per second from a luminous body.
It is denoted by 'F’ and F = Q/t where, t is the time in second. Its unit is Lumen.
It helps to specify the output or luminous efficacy of any light source.

Luminous Intensity

Luminous intensity in any given direction is the luminous flux emitted by the source per unit solid angle in the direction, in which it is mentioned.

It is denoted by the symbol ‘I’ and I = F/ω, where ω is the solid angle in steradian. It is expressed in Lumen/Steradian or Candela.

It helps in understanding and quantifying the photometric distribution of any light source.

Illuminance

It is defined as the luminous flux falling on any surface per unit area.

It is generally denoted by symbol ‘E’ and E = F/A, where A denotes the area of the surface where light falls. Its unit is Lumen/m^2 or Lux.

Sufficient illuminance is required for any visual as well as physical work.

Luminance

It is defined as Luminous Intensity per unit projected or apparent area of either a surface source of light or an illuminated (reflecting) surface.

It is denoted by 'L' and L is given by $L = I/A_a$ where A_a represents the apparent area in m^2. Unit of Luminance is Candela/ m^2 or nit.

It is somewhat analogous to the term Brightness. But Brightness is subjective perception and it is quantified by the Luminance value of the surface.

Lumen

It is the unit of Luminous Flux.

$I = F/\omega$ or $F = I^* \omega$. If I =1 Candela and ω = 1 Steradian, then F = 1 Lumen.

Hence, Lumen is defined as the amount of flux in a space represented by one unit solid angle given out by a source having an intensity one candela.

Candela

It is the unit of Luminous Intensity. It is the number of lumens given out by the source per unit solid angle.

It is the standard unit of Illumination Science. It is defined as 1/60 th of the luminous intensity per cm^2 of a black body radiator at the temperature of solidification of platinum (2043 K).

Lux

It is the unit of illuminance.

$E = F/A$. If F =1 and A =1 then E = 1 Lux.

Hence, Lux can be defined as the illuminance on any surface, if 1 m^2 of the surface receives the luminous flux of 1 Lumen.

1.2 Other Relevant Terms and Design Parameters

Utilisation Factor (UF)

It is defined as the ratio of lumens reaching the working plane to total lumens given out by the lamp. It is unit less quantity. Its value is less than unity. By using properly designed luminarie or lighting scheme the value of UF can be controlled as per requirement.

Maintenance Factor (MF)

It is defined as the ratio of the illumination on the work plane under normal working conditions to that, when everything is in ideal condition. It is also unit less and less than unity. Its value depends on the dust, dirt, smoke deposited on walls, ceiling and glazing surface etc.

Actually, MF = LLMF*LSF*LMF*RSMF

Where, LLMF is Lamp Lumen Maintenance Factor

LSF is Lamp Survival Factor

LMF is Luminaire Maintenance factor

RSMF is Room Surface Maintenance Factor

Glare

Glare may be defined as the brightness within the field of vision of such a character as to cause discomfort or interference with vision. It may be of two types – (i) Disability and (ii) Discomfort. Normally it is measured in Unified Glare Rating (UGR).

In daylighting application where, windows act as source of daylight, discomfort glare may be created to the occupant's eye because of much higher luminance of the visible sky than the average room surface luminance. Daylight Glare Index (DGI) is the measure of this kind of discomfort glare. Solid angle subtended is limited for UGR model. But in window it is much higher, that's why UGR model is not valid in day lighting design.

DGI depends on – (i) Direction of observer's line of sight

(ii) Observer's position w.r.t. window opening

(iii) Background Luminance

(iv) Luminance of window opening.

Uniformity

It is the measure of how much the illumination on any surface is uniformly distributed. Overall Uniformity is the ratio of Minimum Illuminance to the Average Illuminance. It is also unit less and its value is less than unity.

Overall Uniformity (U_O) = Emin / Eavg

Light Power Density (LPD)

It is the electrical power consumed in watts for interior or exterior illumination purpose per unit floor area in any place. It is expressed in watts/m^2. It should be as minimum as possible for energy efficient design but not sacrificing the desired illuminance level.

Colour Rendering Index (CRI)

It is the measure of colour rendering ability of any light source i.e. the ability of the source to express the true colour of the object, when illuminated by the source. It entirely depends on the Spectral Photometric Distribution (SPD) of the source.

For example, Incandescent or Halogen lamp has very high CRI value, nearly 95 to 100. CRI of Halo Phosphor and Tri Phosphor Cool White Fluorescent Lamp is 65 to 70 and 80 to 90 respectively. On the other hand, High Pressure Sodium Vapour Lamp (SON) is of very low CRI nearly 25 while, Standard LED lamp is of quite improved value, in the range of 80 to 85.

Correlated Colour Temperature (CCT)

It is the temperature or nearest related temperature at which a perfectly black body radiator generates the same colour, which the source produces. CCT is the colour temperature of a black-body radiator to which human colour perception most closely matches the light from the lamp. It is the measure of the colorimetric property of light source. Normally, higher the CCT value more is the bluish composition in SPD of the lamp.

For example, CCT of Cool White Fluorescent Lamp is nearly 5000K to 6000K, where as that of Warm White Fluorescent lamp is nearly 2700 K to 4000K. CCT of standard incandescent lamp is nearly 2400 K and that of high pressure sodium vapour lamp (HPS or SON) is 1900 K.

The Sun closely approximates a black-body radiator. The effective temperature, defined by the total radiative power per square unit, is about 5780 K. The colour temperature of sunlight above the atmosphere is about 5900 K. Daylight of overcast sky offers a CCT of nearly 6500 K whereas, that of pure clear blue sky may have the CCT which ranges from 15000 K to 27000 K.

Window Sill

A window sill (also written as windowsill or window-sill) is the surface at the bottom of a window. A dictionary of architecture categorically defines the characteristics of a window sill as: The lowest form of window casement.

Visible Light Transmittance

Visible transmittance is the amount of light in the visible portion of the spectrum that passes through a glazing material. Normally, it varies from 30% to 70%.

Reflectance

Reflectance of the surface of a material is its effectiveness in reflecting radiant energy. It is the fraction of incident electromagnetic power that is reflected at an interface. The values for Floor, ceiling and walls of office building are generally recommended as 0.1 to 0.5, 0.6 to 0.9 and 0.3 to 0.8 respectively.[1]

1.3 Indoor Lighting Design

1.3.1 Objectives

- **Safety and Security** – The design must provide adequate illumination to ensure safe movement and security from unwanted criminal activities.
- **Visual Performance** – The illumination both in quantity and quality must fulfil the requirement of the particular visual task.
- **Environmental integration** – The lamps or luminaries must be suitable for the building architecture and it should not disturb the aesthetical view of the interior.
- **Energy Usage** – The design must ensure the minimum usage of artificial electrical energy by proper demand side management.

1.3.2 Design Criterion

Average Maintained Illuminance

Average illumination level must be as per recommendation for the particular visual task. In India, it normally follows the IS 3646 part-1, 1992 (table: 1). The actual value of illuminance is wisely judged depending on some other factors also like occupant’s age, speed or accuracy of the task and reflectivity of room surface. For general office building the minimum value is 300 lux. [1, 2]

Uniformity

The lighting distribution should be as uniform as possible throughout the working plane. The illuminance values are measured or computed on several grid points. Emin is the minimum value and Eavg is the average value considering all grid points. Then overall uniformity is given by U_O = Emin / Eavg. In India, as per recommendations in NLC for indoor design in office building it should be equal or greater than 0.7 for visual task areas and 0.6 for immediate surrounding areas. [1]

Glare Limit

During indoor design, it is highly recommended to consider both disability and discomfort glare. As per CIE, it is computed in UGR scale. Maximum glare index is recommended for different kinds of interiors.

CCT

Recommendation in terms of CCT is as follows:

Class	Range of CCT	Lamps
Warm	< 3300 K	GLS, SON
Intermediate	Between 3300K & 5300 K	TFL
Cool	> 5300 K	Cool CFL

CRI

Recommendation in terms of CRI is as follows:

Class	Range of CRI	Place
IA	90	Studio, Textile Industry, Picture Gallery
IB	80 - 90	Shop, Chemical Industry
II	60 - 80	Class Room, Office, Light Industry
III	40 - 60	Heavy Industry
IV	20 - 40	Outdoor

1.4 Significance of Daylight Integration and Necessity of Daylight Prediction Model

1.4.1 Importance of Daylight Based Design

Almost 19% electrical energy is utilised for illumination purpose in India. The electrical energy utilised for indoor illumination can be considerably saved through daylight integrated artificial lighting systems. In this system attempt is made to achieve desired illuminance level, both in amount and distribution, on the working plane by the combination of daylight and artificial light. Since quantity (Lux) and quality (CCT) of daylight is highly dynamic in nature, an adoptive control strategy for installed artificial lighting system is essential.

But, now daylight consideration has become an integral part of building architecture design. The proportionate amount of window opening with respect to the total area of building envelope and the orientation of window must be pre determined to allow sufficient amount of daylight entry within the interior to ensure energy efficient building design.

Daylight integrated design increases the wise utilisation of natural energy and thereby saves the artificial electrical energy. Moreover recent research proves that dynamic quantity and quality of daylight helps to maintain the mood and as a whole the psychological health of human beings.

1.4.2 Importance of Prediction model

The dynamic behaviour of daylight depends on various factors – like location (latitude and longitude), calendar date, and time and sky types. On the other hand daylight integration within the interior of the building largely depends on the orientation and dimensions of window and also on the optical properties of glazing material of the window. The colour and surface quality of the room walls and even Light Loss Factors also play important role. Therefore a reliable and user friendly daylight prediction tool or model is essential, which can predict to a satisfactorily good extent the amount and distribution pattern of daylight on any plane at a given location on given date and time for a particular room and window dimension. It will help significantly in the field of energy efficient building design particularly to optimize the dimensions and other specifications of window and/or other opening on the building envelope.

1.5 Daylight Prediction Methods

There are conventionally two computational methods for daylight prediction –

(a) Daylight Factor (DF) Method

(b) Daylight Coefficient (DC) Method.

1.5.1 Daylight Factor (DF) Method

Daylight Factor (DF) is given by

DF % = (E_p / E_{ext}) * 100

where, E_p is point specific illuminance and

E_{ext} is Horizontal external illuminance due to unobstructed sky.

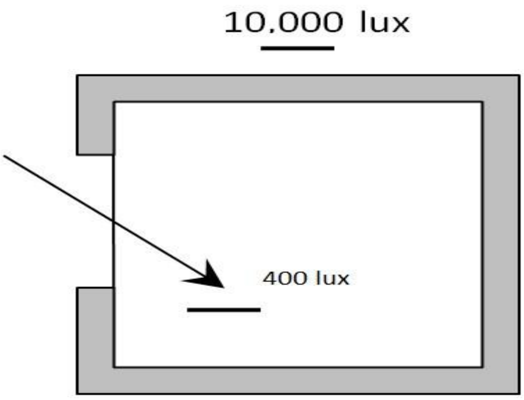


Fig. 1.1: Diagram for Presentation of Daylight Factor (DF)

For example, (from Fig. 1.1) if E_{ext} is 10000 Lux and DF is 4% then point specific illuminance on the surface E_p is 4 x 10000 / 100 = 400 Lux.

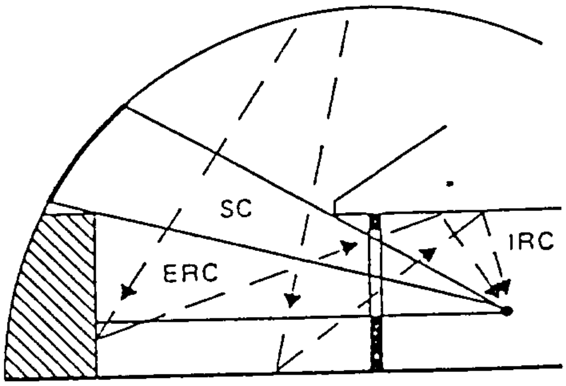


Fig. 1.2: Different components of % Daylight Factor (DF)

Now, $E_p = E_{sky} + E_{ExR} + E_{InR}$

where, E_{sky} is point specific horizontal illuminance due to visible sky patch only.

E_{ExR} is reflected illuminance from external surface

E_{InR} is reflected illuminance from internal surface

$$DF\% = \frac{E_{sky}}{E_{ext}} * 100 + \frac{E_{ExR}}{E_{ext}} * 100 + \frac{E_{InR}}{E_{ext}} * 100$$

= SC + ERC +IRC (as shown in Fig. 1.2)

Where, SC is Sky Component

ERC is External Reflection Component

IRC is Internal Reflection Component

If the absolute value of average daylight illuminance in any zone is less than 100 Lux, then the zone is not considered as useful daylight zone.

1.5.1.1 Computation of E_{sky}

Let us consider α and γ are the horizontal and vertical angles for a sky element respectively and Z is the zenith angle i.e. the angle subtended at the point between the zenith and the sky element. So $Z + \gamma = \pi/2$.

Therefore, for unobstructed sky vault α varies from 0 to 2π and γ varies from 0 to π/2.

$L_{\gamma\alpha}$ is the luminance of the sky element of elementary area dA and dI_p is the luminous intensity in the direction towards point P, where illuminance is to be measured.

Then, $L_{\gamma\alpha} = \frac{dI_p}{dA}$ or $dI_p = L_{\gamma\alpha} * dA$................................(1.1)

If we consider the entire sky vault approximately as a hemisphere of radius R, then

$dA = R^2.sinZdz.d\alpha$ or $dA = R^2.cos\gamma d\gamma.d\alpha$............(1.2)

Now point specific illuminance at point P is given by dE_p.

So, $dE_p = \frac{(dIp * \cos Z)}{R^2}$

or, $dE_p = \frac{(L\gamma\alpha * dA * \cos Z)}{R^2}$.........................[from equation 1.1]

or, $dE_p = \frac{(L\gamma\alpha * R2.\cos\gamma d\gamma.d\alpha * \cos Z)}{R^2}$.............[from eqn.1.2]

or, $dE_p = (L_{\gamma\alpha} * \cos\gamma d\gamma d\alpha * \sin\gamma)$..... .[since, $Z + \gamma = \pi/2$]

or, $dE_p = (L_{\gamma\alpha} * \sin\gamma\cos\gamma d\gamma d\alpha)$..............(1.3)

Therefore, Illuminance $Ep = \int_\gamma \int_\alpha L\gamma\alpha \sin\gamma\cos\gamma d\gamma d\alpha$.......(1.4)

For overcast sky, $L_{\gamma\alpha} = (L_Z / 3) * (1 + 2\sin\gamma)$

$E_p = E_{sky} = (L_Z / 3) * \int_\gamma \int_\alpha (1 + 2\sin\gamma) * L\gamma\alpha \sin\gamma\cos\gamma d\gamma d\alpha$.....(1.5)

1.5.1.2 Computation of E_{ext}

E_{ext} is the point specific horizontal illuminance due to unobstructed sky. In this case γ varies from 0 to π/2 and α varies from 0 to 2π.

Therefore, for overcast sky from Eqn. 1.5,

$$E_{ext} = \frac{L_z}{3}\int_{\gamma=0}^{\pi/2}\int_{\alpha=0}^{2\pi} (1 + 2\sin\gamma) * L\gamma\alpha \sin\gamma\cos\gamma \, d\gamma d\alpha$$

Or, $E_{ext} = \frac{7*\pi}{9} * L_z$..............................(1.6)

1.5.1.3 Computation of E_{ExR}

E_V = Average Vertical Illuminance on the external Wall

ρ_{avg} = Area weighted average reflectance of the walls

L_{avg} = average luminance on the wall

Then, $L_{avg} = \frac{E_V}{\pi} * \rho_{avg}$..........(1.7)

So, $E_{ExR} = L_{avg} * \int_{\gamma}\int_{\alpha} L_{\gamma\alpha} \sin\gamma\cos\gamma d\gamma d\alpha$.........(1.8)

1.5.1.4 Computation of E_{InR}

$Flux_w$, $Flux_f$, $Flux_c$ are the fluxes on walls, floor and celling respectively.

A_w, A_f, A_c are the areas of walls, floor and celling respectively

ρ_w, ρ_f, ρ_c are the reflectance of walls, floor and celling respectively.

FRF = First Reflectance Flux = $Flux_w*\rho_w + Flux_f*\rho_f + Flux_c*\rho_c$

ρ_{avg} = Area Weighted Average Reflectance

$\rho_{avg} = [A_w * \rho_w + A_f * \rho_f + A_c * \rho_c] / [A_w + A_f + A_c]$

E_{InR} = Average Inter Reflection Illuminance

$E_{InR} = \frac{FRF}{[(1-\rho_{avg})*(A_w+A_f+A_c)]}$.................................(1.9)

1.5.1.5 Limitation of DF Method

- In this method point specific illuminance is predicted with respect to external horizontal illuminance due to unobstructed sky. So it is less realistic and that's why it is called relative prediction method.
- DF is constant only for purely overcast sky. So the application of this method is limited to only the overcast sky.

1.5.2 Daylight Coefficient (DC) Method

Point specific illuminance is given by $\Delta E_p = D_{\gamma\alpha} * L_{\gamma\alpha} * \Delta_{\gamma\alpha}$..........(1.10)

Where, $D_{\gamma\alpha}$ is Daylight Coefficient (DC) corresponding to the sky element at γ and α.

$L_{\gamma\alpha}$ is Luminance of the sky element at γ and α.

$\Delta\omega_{\gamma\alpha}$ is solid angle subtended by the element at γ and α at point 'P'.

But, Horizontal Point Specific Illuminance is dE_p^H and it is given by

$dE_p^H = L_{\gamma\alpha} * \sin\gamma\cos\gamma d\gamma d\alpha$..................[From Eqn. 1.3]

Again elementary area $dA = R^2\cos\gamma d\gamma d\alpha$, where R is radius of the hemispherical sky vault.

So, $\frac{dA}{R^2} = solid\ angle = d\omega_{\gamma\alpha} = \cos\gamma d\gamma d\alpha$ ....(1.11)

Therefore, $\Delta E_p = L_{\gamma\alpha} * \sin\gamma * \Delta\omega_{\gamma\alpha}$.......................(1.12)

Now comparing Eqns 1.10 & 1.12 we get

$D_{\gamma\alpha} = \sin\gamma$

So, point specific Horizontal illuminance due to visible sky having altitude angle ranging from γ_1 to γ_2 and surface azimuth angle ranging from α_1 to α_2 is given by

$E_p = \Sigma_i \Delta E_{pi} = \Sigma D_{\gamma\alpha}^i * L_{\gamma\alpha}^i * \Delta\omega_{\gamma\alpha}^i$............................(1.13)

Or, $E_p = \int_{\gamma 1}^{\gamma 2} \int_{\alpha 1}^{\alpha 2} L_{\gamma\alpha} \sin\gamma\cos\gamma d\gamma d\alpha$ ....(1.14)

But, for point specific vertical illuminance, DC = $D_{\gamma\alpha}$ = cosγcosβ

$$E_p = \int_{\gamma 1}^{\gamma 2} \int_{\alpha 1}^{\alpha 2} L_{\gamma\alpha} \cos\gamma \cos\gamma \cos\beta \, d\gamma d\alpha \text{....................(1.15)}$$

Where, β is the angle between the normal at the point on the surface and the direction of incoming beam both projected on the horizontal surface or in other words, angular orientation of vertical plane with respect to incoming light beam.

1.5.2.1 Advantages of DC Approach

- In this method point specific illuminance is computed by using value of absolute values of sky luminance and it is not mapped with the relative value of illuminance like DF method and hence it is more realistic approach.
- It can be applied to all types of sky and hence the prediction tool based on this method is expected to be much more generalised in nature.

Chapter 2

Literature Survey on Daylight Simulation for Indoor Lighting Design

2.1 Daylight Utilisation for Sustainable Development

Statistics by United Nation (2001) indicated that the percentage of population living in urban areas has been increased from 30% in 1950 to 40% in 2000. It is expected to reach 60% by 2030. [3] It is estimated that by 2056, global economic activity will have increased fivefold, global population will have increased by over 50%, global energy consumption will have increased nearly threefold, and global manufacturing activity will have increased at least threefold. [4]

Urbanisation causes rapid development of high-rise buildings in cities all over the world. A high-rise building, particularly the big office buildings has always been categorised as a high-energy-consumption building type due to its dependency on artificial indoor environment. Therefore, sustainability in high-rise building design can never be overlooked. [3]

A conceptual framework aimed at implementing sustainability principles in the building industry is based on the sustainable triple bottom line principle, which includes resource conservation, cost efficiency and design for human adaptation. [4]

A result of the survey on existing high-rise offices and field measurement in different locations indicates the evidence of underuse of daylight, due to the glare and thermal problem, despite the high external daylight availability. A proper control of the dynamic daylighting using shading device and window glazing was needed for effective use of daylight for energy saving as well as visual comfort. [3]

Daylighting has been proven as an effective strategy to provide energy saving for electric lighting, as well as visual comfort for users. In the tropical climate, global illuminance can go as high as 100,000 lux or more. Yet, some researchers (Mohd Hamdan, 1996; Ossen, 2005) concluded that the excess of daylight in the tropics has not been utilised to the maximum since it is usually associated with intense solar heat gain. Therefore, the balance between the prevention of sunlight radiation heat gains and utilisation of natural daylight is very crucial in order to achieve building energy efficiency. [3]

2.2 Daylight Simulation

The source of all daylight is the sun. Scattering of sunlight in the atmosphere by air, water vapour, dust, and so on gives the sky appearance of a self-luminous source of light. The illumination produced by the sky depends on its luminance. Sky luminance varies according to a series of meteorological, seasonal, and geometric parameters that are difficult to specify. Characterizing the sun and sky for lighting simulation is equivalent to light source photometry for electric luminaires.[5]

Continuous monitoring of the sky brightness began in earnest in the 1950s. There are now many locations in the industrialized world where 10 or more years of daylight data have been recorded and archived.[5]

Basic daylight components are (a) global horizontal I_{gh} (sky and sun), (b) diffuse horizontal I_{dh} (sky only), and (c) direct normal I_{dn} (sun only). They are related as $I_{gh} = I_{dh} + I_{dn}\sin\theta$, where θ is Sun altitude.

Daylight which results an indoor illumination, has four components. – (a) Direct Sun, (b) Direct Sky, (c) Externally Reflected and (d) Internally reflected.

Both Daylight Factor (DF) and Daylight Coefficient (DC) approaches can be applied for daylight simulation. The former one has its own limitations, which has been already described in Chapter 1.

Daylight prediction has traditionally been based on the convention of a Standard Overcast Sky. It was conventionally simulated by Daylight Factor method, which was quite simple in nature. The penalty of simplicity however, is a considerable loss in realism. With the daylight factor approach it is impossible to reproduce the naturally occurring variation in the quantity, character and distribution of internal daylight levels. A true measure of the long-term daylighting performance of a building must account for the illumination that results from a wide range of sky and sun conditions. Daylight Coefficients can be used to predict hourly values of internal illuminance accurately and efficiently for a period of a full year. [6]

Daylight coefficients are normalized contributions from discretized sky or ground segments, or preset solar positions, to solar quantities calculated at various building sensor points. Once generated, daylight coefficients can be folded against luminance efficacy and distribution models to calculate, for instance, time series of illuminances i.e. Dynamic Daylighting Simulations (DSS). [7]

2.3 Daylight Prediction Tool

Although using daylight is extremely economic and energy efficient, it should be well designed and controlled in order to maximize these traits. One of the solutions to overcome such problems is the use of daylight prediction methods.

Types of users who apply daylight prediction methods are Architect, Lighting Designer, Interior Designer, Energy Consultant, Engineer, Researcher, Manufacturer etc. [8]

From the decade of 1970s use of daylight prediction becomes popular. However, in 1973 various design tools have been developed. By mid 1980"s, only a handful of daylight prediction software was able to predict illumination levels in day lighted spaces. Between 1988 and 1998, several major methods were introduced. [8]

Some of the popular day lighting software is Desktop Radiance, Rayfront, Relux 2004 Vision, Lightscape etc. From the previous research it can be concluded that each of them has their own advantage and limitations also. Among the softwares analyzed, RELUX PRO 2004 + VISION is the most adequate for architect's use; RAYFRONT and DESKTOP RADIANCE presents more difficulties to be used in the design process. DESKTOP RADIANCE has the advantage to be enclosed in AUTOCAD, a graphical interface, very known by the architects. Moreover, it uses dialogue boxes to materials and glass selection and visualization with synthetic cameras. LIGHTSCAPE has a user-friendly interface, but not as intuitive as RELUX. [9]

This clearly reveals the fact, that still the ideal software of simulation does not exist. But, there is a great potential to use of simulation softwares in the architecture design. [9]

The Perez´s (1991) model was based on the scan measured luminance data at Berkeley but it has been applied in simulation programs using routine irradiance measurements in e.g. RADIANCE or GENELUX. Japanese authors Nakamura et al. (1985) have classified sky conditions into three groups i.e. overcast, clear and intermediate trying to define the luminance distribution of the intermediate sky. Later Igawa (1997) suggested twenty patterns of luminance distributions based on scan measured luminance data at Tokyo and derived by a statistical method to fill the relative sky luminance distribution gap between two extreme CIE standard skies. [10]

Fifteen sky types of relative luminance distributions in the SSLD model by Kittler et al. (1998) are based on scan measured luminance data at Tokyo, Berkeley and Sydney and were proposed at the same time. Five overcast, five clear and five transitional skies are modelled by the combination of gradation and indicatrix functions. This solution is proposed as a CIE code draft CIE (2001). In this process, the determination of daylighting conditions is in more details and covers the whole occurrence spectrum considering different diffuse scattering by the atmosphere and effects of direct sunlight. Applying additional parametrisation it is possible to calculate illuminance and luminance levels not only in relative but also in absolute physical units. [10]

Different Sky models are described in CIE (International Commission on Illumination) model. Five types of each of Clear Sky, Intermediate or Mixed sky and Overcast or Cloudy sky are specified by the essential coefficients. To compute the Zenith luminance value of any sky type, many more constants and coefficients are also required, which are also presented in this work. The mechanism of computation of Zenith luminance and even relative luminance of any sky vault are described in details in this model. Actually this process has been followed to develop a daylight prediction tool in this project.

Earlier work was already done to find out representative CIE (International Commission on Illumination) Standard Clear Sky model(s) for three different seasons - winter solstice, equinox, and summer solstice applicable for prevailing clear sky climatic conditions in India [Roorkee].

Indian measured sky luminance distribution database is available only for Roorkee [29°51′ N; 77°53′ E]. To find out the best match between Indian measured sky luminance distribution and each of five CIE Standard Clear sky models, sky component of spatial illuminance distribution over the working plane of a room was simulated by MATLAB for three different seasons. Analysis revealed that CIE Standard General Clear sky type 15 described as "White-blue sky, turbid with a wide solar corona effect" is the best-fit clear sky model for both summer and equinox seasons and sky type 11 described as "White blue sky with a clear solar corona" is the best-fit clear sky model for winter season at Roorkee. [11, 12]

The same data and daylight simulation is also used for dimming control of luminaires in another research work. The adequacy of daylight availability is judged on the basis of desired average illuminance level on working plane. Here simulation is done using MATLAB coding. This paper provides information on daylight availability and the dimming levels of all artificial light sources which are set accordingly so that contribution from artificial lighting system together with available daylight meets the desired lighting level and uniformity. [13]

Chapter 3

Development of Daylight Prediction Model

3.1 Introduction

`Daylight is the light which is available in nature during daytime. So it is a very useful natural resource of light. By the proper utilisation of this energy the dependency on artificial electrical light source can be reduced to a considerable extent. At large, it helps in energy savings and thereby promotes a sustainable development strategy.

Daylight varies in intensity as well as in colour appearance throughout the day which helps in maintaining the circadian rhythm or body clock of the occupant. It also helps to avoid depression and maintains psychological health of the people. Thereby daylight integration within the interior of the room improves the production or work efficiency in commercial or office building.

Daylight has mainly two components – (a) direct sunlight coming from the Sun and (b) the sunlight scattered by the atmospheric particles, which is commonly known as skylight. The former one having the extremely high intensity or luminance value may cause direct and disability glare to the viewer's eye. In order to avoid this problem, in case of indoor lighting window or other opening in the building envelope are so designed that, the Sun generally will not appear within the field of vision of the occupants. Therefore, whenever we are talking about the use of daylight, we actually want to mean here the utilisation of the latter component i.e. the skylight. Every energy efficient lighting design must be aimed at the wise and optimized utilisation of the skylight. Hence, in this thesis also, the process of development of the daylight prediction tool actually ignores the direct sunlight and is basically based on the skylight component of the available daylight.

But due to widely varying response and behaviour of daylight any daylight based building design needs a reliable daylight prediction tool. In the next part of this chapter we will try to develop such a prediction model based on CIE General Standard Sky defining Luminance Distribution (SSLD).

3.2 Room Dimension and Window Specification

At the initial stage of developing the tool, a cuboidal room having single window has been considered.

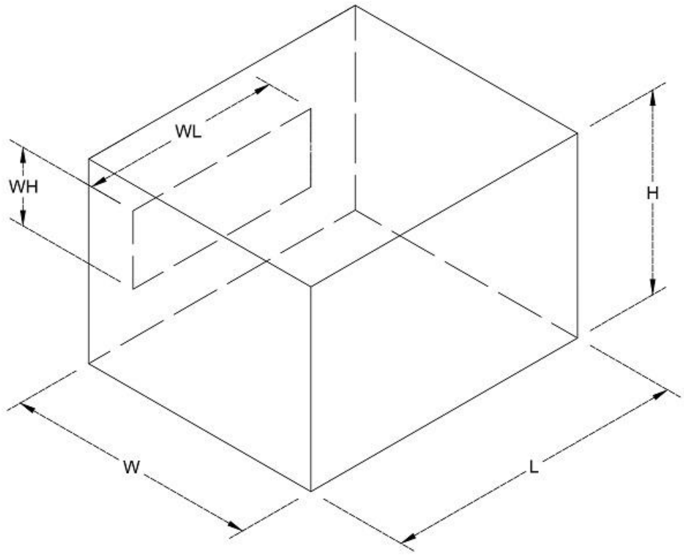


Figure 3.1: Diagram illustrating the Room Dimension

Length of the room = L

Width of the room = W

Height of the room = H

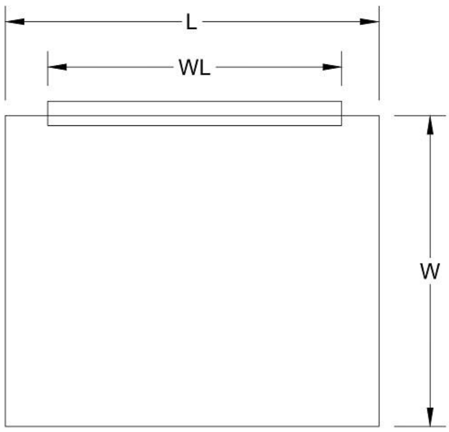


Figure 3.2: Plan view of the Room

A room of 6 metre length, 5 metre width and 4 metre height is considered. Therefore, in the sample model, L = 6, W = 5 & H = 4. (As shown in Fig. 3.1 and Fig.3.2)

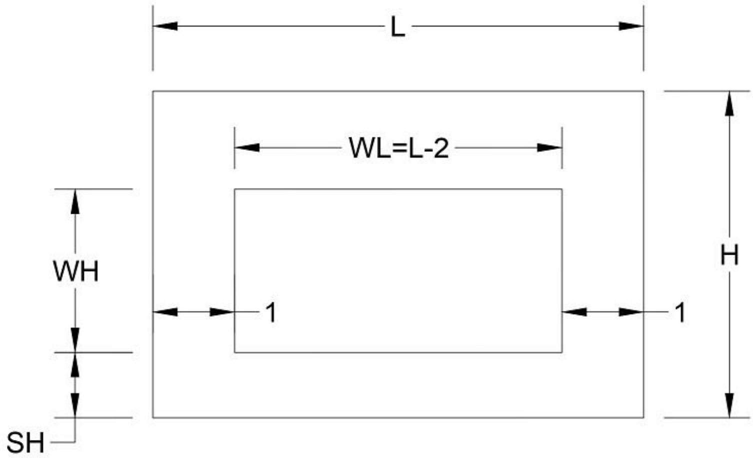


Figure 3.3: Elevation of Window Wall

A rectangular window has been considered at the central location on the longer wall of the room i.e. on the length wise wall. (As shown in Fig. 3.3)

Window Wall Area = WWA = L * H

Window Area = WA

Window Wall Ratio = WWR = Window Area / Window Wall Area i.e.

WWR = WA / WWA

Or, WA = WWR * WWA

Window Length = WL and Window Height = WH

So, WA = WL * WH

Window is located on the wall lengthwise centrally leaving 1 metre on both ends of the wall.

So, WL = (L – 2) and WH = WA / WL

In our sample case, WWR is taken as 0.33 or 1/3.

Therefore, WWA = L * H = 6m * 4m = 24 m^2

$WA = WWR * WWA = 1/3 * 24 = 8\ m^2$

$WL = L – 2 = 6 – 2 = 4$ m.

$WH = WA / WL = 8 / 4 = 2$ m.

SH = Height of Window Sill from the floor on metre.

Ʈ = Transmittance = Visible Light Transmittance of the Window Glazing material.

MF = Maintenance Factor or Light Loss Factor

In the sample study,

SH = 0.8 m, MF = 0.75 i.e. 75 % and Transmittance of glazing material of the window is 0.5 i.e. 50 %.

θ is angular orientation in degrees of the window. (Due north line is considered as 0°).

3.3 Relative Luminance of Sky Element based on CIE SSLD model

Fifteen sky types of relative luminance distribution in the Sky Standard Luminance Distribution (SSLD) are based on scan measured luminance data at Tokyo, Berkley and Sydney. Here, five overcast, five clear and five transitional skies are modelled on by the combination of gradation and indicatrix functions. The determination process of daylighting conditions in this model is more detailed. By the application of additional parametrisation it is possible to calculate luminance and illuminance levels not only in relative but also in absolute physical units. [10]

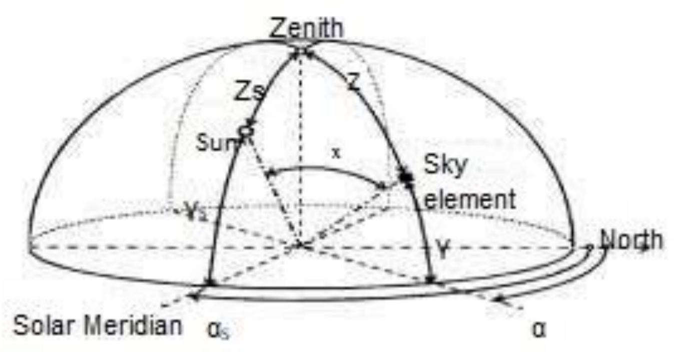


Figure 3.4: Diagram illustrating Zenith angle, altitude angle and azimuth angle of the Sun and sky element

Zenith is the point in the sky or celestial sphere directly above an observer. (As shown in Fig. 3.4)

Meridian is the vertical plane containing the zenith and the meridian containing the Sun is called Solar Meridian.

Z is the zenith angle of the sky element and Z_S is the Zenith angle of the Sun.

γ is the altitude angle of the sky element and γ_S is Solar altitude angle.

Hence, $Z + \gamma = 90°$ or $\pi/2$

And $Z_S + \gamma_S = 90°$ or $\pi/2$

α is the surface Azimuth angle of the sky element and α_S is the Azimuth angle of the solar meridian.

A_Z is the Azimuth difference between the sky element and the Sun.

χ is the angular distance of the sky element from the Sun (As shown in Fig. 3.4)

χ = arc cos (cos Z_S * cos Z + sinZ_S * sinZ * cos A_Z)

or, $\chi = \cos^{-1} \cos Z_s * \cos Z + \sin Z_s * \sin z * \cos A_Z$.......................(3.1) [10]

$L_{\gamma\alpha}$ = Luminance of an arbitrary sky element

L_Z = Luminance of the Zenith

Then, $\frac{L_{\gamma\alpha}}{L_z} = \frac{[f(\chi) * \varphi(Z)]}{[f(Z_S) * \varphi(0°)]}$...(3.2) [10]

Where, φ is luminance gradation function and it relates the luminance of a sky element to its zenith angle and f is the scattering indicatrix function which relates the relative luminance of a sky element to its angular distance from the sun i.e. χ.[10]

$$\varphi\ (Z)\ =\ 1\ +\ a\ \exp\frac{b}{\cos Z}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.2a)$$

$$\varphi(0^{\circ}) = 1 + a\exp\frac{b}{\cos(0^{\circ})} = 1 + a\exp(b)\ldots\ldots\ldots\ldots\ldots\ldots(3.2b)$$

$$f\ (\chi)\ =\ 1\ +\ c\ (\exp(d * \chi) - \exp\left(d * \frac{\pi}{2}\right)\ + e\cos^{2}\chi\ldots\ldots\ldots(3.2c)$$

$$f(Z_s) = 1 + c(\exp(d * Z_s) - \exp\left(d * \frac{\pi}{2}\right) + e\cos^{2}Z_s\ldots\ldots\ldots(3.2d)$$

Where, a,b.c.d and e all are constants. They are given in SSLD model. A and b are useful for gradation function and c,d,e are useful for scattering indicatrix function.

The values of the constants for 15 different standard skies as per CIE SSLD model are given in the following table. [10]

Type	**Gradation**	**Indicatrix**	**a**	**b**	**c**	**d**	**E**	**Description of Luminance Distribution**
1	I	1	4.0	-0.70	0	-1.0	0.00	Overcast Sky with steep luminance gradation towards zenith, azimuthal uniformity
2	I	2	4.0	-0.70	2	-1.5	0.15	Overcast with steep luminance gradation and slight brightening towards the Sun
3	II	1	1.1	-0.80	0	-1.0	0.00	Overcast moderately graded with azimuthal uniformity
4	II	2	1.1	-0.80	2	-1.5	0.15	Overcast moderately graded and slightly brightening towards the Sun
5	III	1	0.0	-1.00	0	-1.0	0.00	Sky of uniform Luminance

6	III	2	0.0	-1.00	2	-1.5	0.15	Partly cloudy sky, no gradation towards zenith, slight brightening towards the Sun
7	III	3	0.0	-1.00	5	-2.5	0.30	Partly cloudy sky, no gradation towards zenith, brighter circumsolar region
8	III	4	0.0	-1.00	10	-3.0	0.45	Partly cloudy sky, no gradation towards zenith, distinct solar corona
9	IV	2	-1.0	-0.55	2	-1.5	0.15	Partly cloudy with the obstructed Sun
10	IV	3	-1.0	-0.55	5	-2.5	0.30	Partly cloudy, with brighter circumsolar region
11	IV	4	-1.0	-0.55	10	-3.0	0.45	White-Blue sky with distinct solar corona
12	V	4	-1.0	-0.32	10	-3.0	0.45	Clear sky low luminance turbidity
13	V	5	-1.0	-0.32	16	-3.0	0.30	Clear sky, polluted atmosphere
14	VI	5	-1.0	-0.15	16	-3.0	0.30	Cloudless turbid sky with broad solar corona
15	VI	6	-1.0	-0.15	24	-2.8	0.15	White –Blue turbid sky with broad solar corona

Table 3.1: Standard Parameters of CIE Sky Models

3.4 Solar Geometry

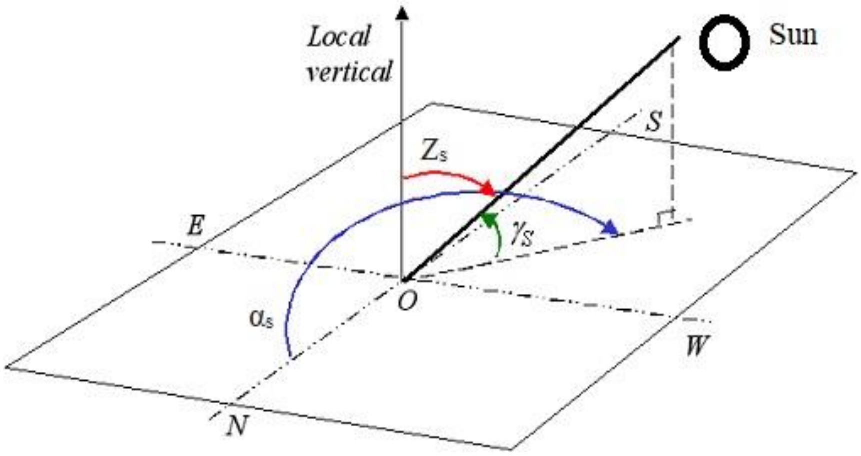


Fig 3.5: Diagram illustrating zenith angle, solar altitude angle, surface and solar azimuth angle.

- $\cos(\chi) = \text{Cos}(Z_s)\cos(90°- \gamma) + \sin(Z_s)\sin(90°- \gamma)\cos(A_z)$
- $A_z = (\alpha - \alpha_s)$ = azimuth difference between the sky element & Zenith and χ = angular distance of sky element from the Sun. (As shown in Fig. 3.5)

- Φ = Latitude of the place, λ = Longitude of the place (positive for Western Hemisphere and negative for Eastern Hemisphere) and λ_s = Longitude of standard meridian.
- n = Julian Day (1 for 1st January & 365 for 31st December)
- δ = Declination angle = 23.45sin[360/365(284+n)] in degree........(3.3) [14]
- x = Hour (1 for 1 am, 12 for 12 noon & 23 for 11 pm)
- ω = Hour angle = [x +/- $(\lambda_s - \lambda)/15$] in degree ....(3.4) [14]

  - sign for Eastern Hemisphere and + sign for Western Hemisphere.
- $\gamma_s = 90° - Z_s = 90° - \cos^{-1}[\sin(\Phi)\sin(\delta) - \cos(\Phi)\cos(\delta)\cos(\omega)]$.(3.5) [14]
- α_s = Solar Azimuth angle = $cos^{-1} \frac{[\sin(\delta)-\cos(Z_s)\sin(\Phi)]}{[\sin(Z_s)\cos(\Phi)]}$

  For 0°< ω<180°..(3.6a) [14]
- or $\alpha_s = 360° - cos^{-1} \frac{[\sin(\delta)-\cos(Z_s)\sin(\Phi)]}{[\sin(Z_s)\cos(\Phi)]}$ For 180°< ω ≤360°..(3.6b) [14]

Therefore, it is obvious from the above mathematical relationships that Solar Zenith angle Zs and hence Solar Altitude angle γ_s depends on latitude, longitude, Declination angle and hour angle i.e. in other words on location, date and time.

Again, it is also quite clear that Solar Azimuth angle α_s directly depends on zenith angle of the Sun, Declination, latitude and hour angle i.e. in other words on location, date and time.

3.5 Computation of Zenith Luminance

Zenith Luminance L_Z is given as -

$L_Z = \frac{D_V}{E_V} * [\frac{B(sin\gamma_S)^C}{(cos\gamma_S)^D} + E(sin\gamma_S)]$ in Kcad/m^2 for sky type 1 to 6..(3.7a) [10]

or

$L_Z = [A(sin\gamma_s) + 0.7(T_V + 1)\frac{(sin\gamma_S)^C}{(cos\gamma_S)^D} + 0.04T_V]$ for sky type 7 to 15

(when $T_v \leq 12$).....(3.7b) [10]

Where A, B, C, D, E, (D_v / E_v) and T_v all are given constants for different sky types. They are also called sky descriptors.

D_v = Diffuse horizontal illuminance, P_v = Direct solar horizontal exterior illuminance and G_v = measured Global illuminance. $G_v = D_v + P_v$.

E_v = Extraterrestrial horizontal illuminance

T_v = luminous turbidity factor.

The values of the above mentioned constants for 15 different standard skies as per CIE SSLD model are given in the following table. [10]

Sky Type	Sky Code	A	B	C	D	E	Tv	Dv /Ev
1	I.1	Eqn. 3.7.b is not valid.	54.63	1.00	0.00	0.00	Over 45	0.10
2	I.2		12.35	3.68	0.59	50.47	Over 20	0.18
3	II.1		48.30	1.00	0.00	0.00	Over 45	0.15
4	II.2		12.23	3.57	0.57	44.27	Over 20	0.22
5	III.1		42.59	1.00	0.00	0.00	Over 45	0.20
6	III.2		11.84	3.53	0.55	38.78	Over 20	0.38
7	III.3	13.27	21.72	4.52	0.63	34.56	12.0	0.42
8	III.4	10.33	29.35	4.94	0.70	30.41	10.0	0.41
9	IV.2	8.70	10.34	3.45	0.50	27.47	12.0	0.40
10	IV.3	8.28	18.41	4.27	0.63	24.04	10.0	0.36
11	IV.4	5.01	24.41	4.60	0.72	20.76	4.0	0.23
12	V.4	3.30	23.00	4.43	0.74	18.52	2.5	0.10
13	V.5	4.76	27.45	4.61	0.76	16.59	4.5	0.28
14	VI.5	4.86	25.54	4.40	0.79	14.56	5.0	0.28
15	VI.6	3.62	28.08	4.13	0.79	13.00	4.0	0.30

Table 3.2: Typical values of parameters and sky descriptors linked with various sky types.

3.6 Computation of Sky Element Luminance

Now for a particular location and for given date and time Z_S and α_s are solved. Hence, φ (0°) and f (Z_S) are also solved.

L_Z is also solved from the relationships (3.7.a) or (3.7.b) depending on the sky type using the values of parameters from Table 3.2.

Luminance of Particular Sky element specified by altitude angle γ and azimuth angle α, $L_{\gamma\alpha}$ is given by

$$L_{\gamma\alpha} = L_z * \frac{[f(\chi) * \varphi(Z)]}{[f(Z_S) * \varphi(0°)]} \text{.....................................(from equation 3.2)}$$

Now, f (χ) and φ (Z) are function of γ and α.

Therefore, $L_{\gamma\alpha}$ can be computed as a function of γ and α i.e. can be expressed in terms of γ and α.

3.7 Grid Specifications

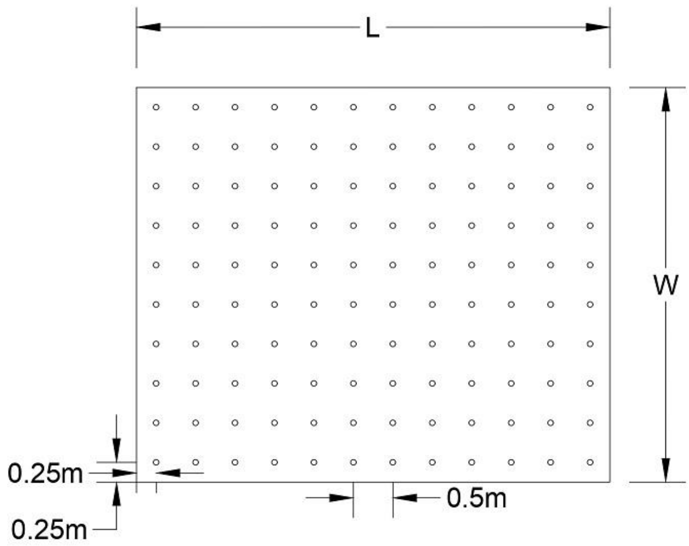


Figure 3.6: Diagram illustrating the grid points on Work Plane.

The imaginary grid points are considered on the work plane at regular interval of 0.5 m distance both length wise and width wise. (As shown in the Fig. 3.6) So the end grids points on every side are 0.25 m apart from the adjacent wall. Thus, a rectangular grid is formed, where horizontal illuminances are to be computed on every grid points.

First grid point is at uppermost left corner i.e. first row and first column point.

Last grid point is at lowermost right corner i.e. last row and last column point.

The first row is located in front of the wall containing the window which means the uppermost row is the nearest to the window wall.

An arbitrary point 'P' is specified by co-ordinate values (xg,yg). In our MATLAB program xg starts from 0.25, increases with an increment 0.5 and ends at (L-0.25) whereas, yg starts from (W-0.25) decreases with an decrement 0.5 and finally ends at 0.25.

	Start Point	Interval	End Point
xg :	0.25	0.5	(L – 0.25)
yg :	(W – 0.25)	- 0.5	0.25

Therefore, the point 'P' (xg,yg) is at a distance of 'xg' from the left wall of the point and 'W - yg' from the window wall.

In this sample case study total no of grid points are 12 x 10 = 120.

3.8 Computation of point specific Illuminance within a room having single window

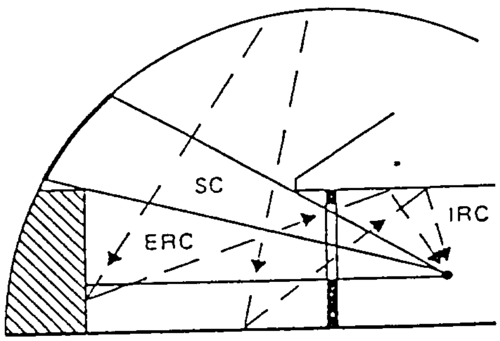


Figure 3.7: Diagram illustrating SC, ERC and IRC

The illuminance at the point has 3 components – Sky Component (SC), External Reflection Component (ERC) and Internal Reflection Component (IRC) (As shown in Fig. 3.7). The computational method has been discussed in Section 1.5. We will consider only SC and IRC in our design. It is practically difficult to consider ERC, because distance, dimension, surface reflection property and other essential information about external surfaces are not generally available. As per national Building code, (page 114, Sec. 4.4.3) also the window is suggested to consider unobstructed if S/H ratio is greater than 3, where S is the separation of the building from the external obstruction and H is the Building Height. [15]

3.9 Computation of point specific Horizontal Illuminance on Work Plane due to sky luminanace

The point P receives light from the window.

The horizontal acceptance angle for the point varies from α_1 to α_2 and vertical acceptance angle varies from γ_1 to γ_2. This means, the surface azimuth angle of the sky patch responsible for the illumination at the point P varies from α_1 to α_2 and altitude angle for the same varies from γ_1 to γ_2.

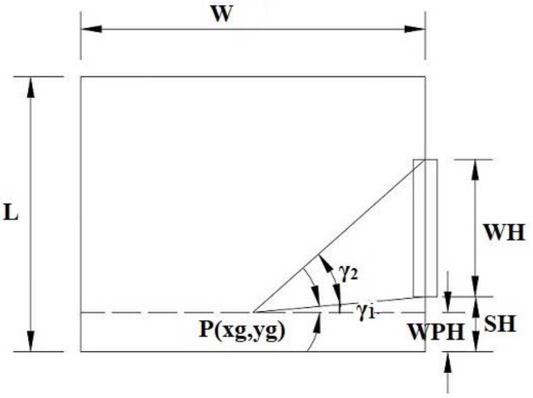


Figure 3.8(a): Diagram illustrating γ_1 and γ_2

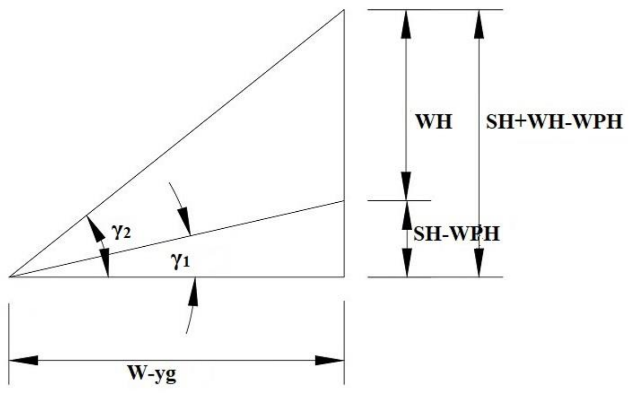


Figure 3.8(b): Diagram illustrating γ_1 and γ_2

From the above figure 3.8(a) and 3.8(b)

$$tan\,\gamma_1 = \frac{(SH - WPH)}{(W - yg)} \quad \text{and} \quad tan\,\gamma_2 = \frac{(SH + WH - WPH)}{(W - yg)}$$

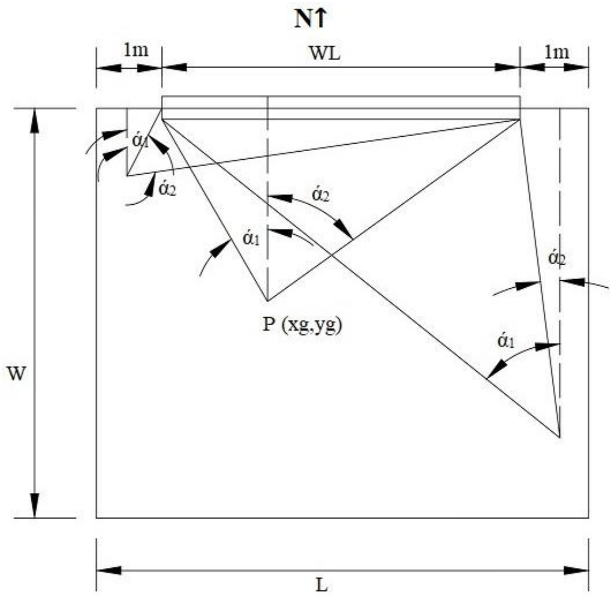


Figure 3.9(a): Diagram illustrating $\acute{\alpha}_2$ & $\acute{\alpha}_2$ at different points with North Facing Window

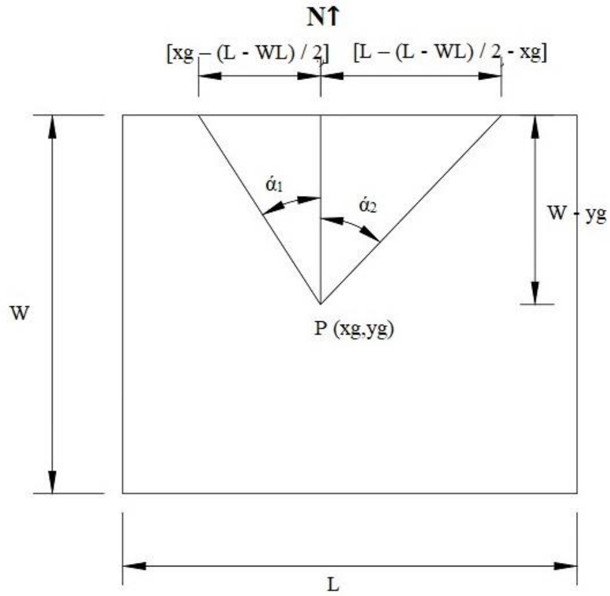


Figure 3.9(b): Diagram illustrating $\acute{\alpha}_1$ & $\acute{\alpha}_2$ with North Facing Window

From the above figure 3.9(a) and3.9(b)

$$tan\ \acute{\alpha}_1 = \frac{[xg - (L - WL)\ /\ 2]}{(W - yg)}$$

and $$tan\ \acute{\alpha}_2 = \frac{[L - (L - WL)\ /\ 2 - xg]}{(W - yg)}$$

$\alpha_1 = \theta - \acute{\alpha}_1$ and $\alpha_2 = \theta + \acute{\alpha}_2$

For North facing window θ = 0°,

For South facing window θ = 180°

For East facing window θ° = 90 and

For West facing window θ = 270°.

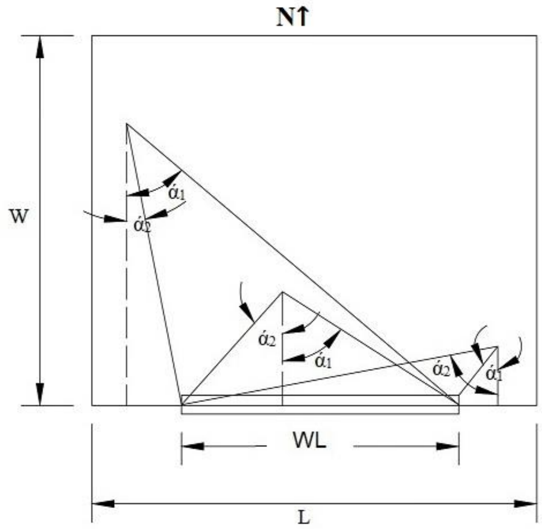


Figure 3.10 (a): Diagram illustrating $\acute{\alpha}_1$ & $\acute{\alpha}_2$ at different points with South Facing Window

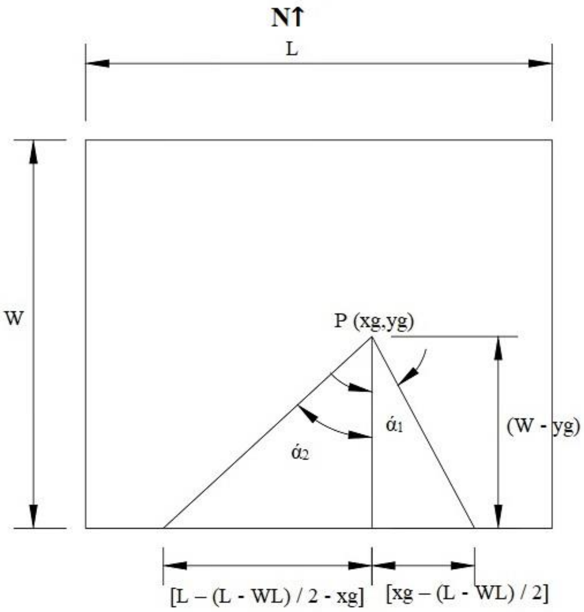


Figure 3.10 (b): Diagram illustrating $\acute{\alpha}_1$ & $\acute{\alpha}_2$ with South Facing Window

Now, using equation (1.14), horizontal illuminance at point P is given by

$E = \int_{\gamma 1}^{\gamma 2} \int_{\alpha 1}^{\alpha 2} L_{\gamma\alpha} * \sin\gamma\cos\gamma \, d\gamma d\alpha$ ....From equation (1.14)

Or, $E = \int_{\gamma 1}^{\gamma 2} \int_{\alpha 1}^{\alpha 2} Lz * \frac{[f(\chi) * \varphi(Z)]}{[f(Z_S) * \varphi(0°)]} * \sin\gamma\cos\gamma \, d\gamma d\alpha$...From equation (3.2)

Or, $E = \frac{L_Z}{[f(Z_S) * \varphi(0°)]} \int_{\gamma 1}^{\gamma 2} \int_{\alpha 1}^{\alpha 2} [f(\chi) * \varphi(Z)] * \sin\gamma\cos\gamma \, d\gamma d\alpha$

Therefore, point specific horizontal illuminance E_p is given by

$E_p = Ʈ * MF * E$

Esum = Algebric summation of illuminance of all grid points.

Esum = ΣE_p

N = total no of grid points.

Therefore, Average illuminance Eavg = Esum / N...............(3.8)

Emin and Emax are the minimum and maximum value of E_p .

Overall Uniformity U_O is given by U_O = Emin / Eavg.........(3.9)

3.10 Computation of Vertical Illumination on the room walls due to sky luminance

The sky element is also responsible for the vertical illumination on the lower part of the walls of the room except the wall containing the window. But, here for mathematic operation the upper limit of this lower part is considered to be the near sill height (SH+0.2m) of the window.

Starting from the window wall, if we move in clock wise direction the consecutive walls are considered as 1st, 2nd and 3rd wall respectively. For example if the window is located on North wall, then 1st, 2nd and 3rd vertical plane will be East, South and West walls respectively.

An imaginary grid is also developed just like the earlier case. So the point specific vertical illuminance is to be computed on the three walls analytically using the MATLAB coding.

The computation method is based on the same Daylight Coefficient (DC) approach and CIE SSLD model. But, in case vertical illumination DC is equal to $\cos\gamma\cos\beta$ instead of $\sin\gamma$, as it is in case of horizontal illumination computation process. Here, β is the angle between the normal at the point on the surface and the direction of incoming beam both projected on the horizontal surface or in other words angular orientation of vertical plane w.r.t incoming light beam. (as earlier discussed in 1.5.2)

Therefore, the point specific vertical illuminance E_{pV} is given by -

$E_{pV} = \int_{\gamma 1}^{\gamma 2} \int_{\alpha 1}^{\alpha 2} L_{\gamma\alpha} * \cos\gamma\cos\gamma\cos\beta \, d\gamma d\alpha$ [from equation (1.15)]

3.10.1 Point Specific Vertical Illuminance on the lower part of 1st wall

P is an arbitrary point on grid of the lower part of the 1st wall. P is specified by the coordinate (xg_{V1L}, yg_{V1L})

xg_{V1L} starts from (W – 0.25), changes with a decrement of 0.5 and ends at 0.25.Again, yg_{V1L} starts at 0.25 changes with an increment 0.5 and ends at (SH + 0.2 - 0.25).

	Start Point	Interval	End Point
xg_{V1L} :	(W – 0.25)	- 0.5	0.25
yg_{V1L} :	0.25	0.5	(SH + 0.2 - 0.25)

The horizontal acceptance angle for the point varies from α_{V1L1} to α_{V1L2} and vertical acceptance angle varies from γ_{V1L1} to γ_{V1L2}. This means, the surface azimuth angle of the sky patch responsible for the illumination at the point P varies from α_{V1L1} to α_{V1L2} and altitude angle for the same varies from γ_{V1L1} to γ_{V1L2}.

β_{V1L} is the orientation angle of the vertical plane.

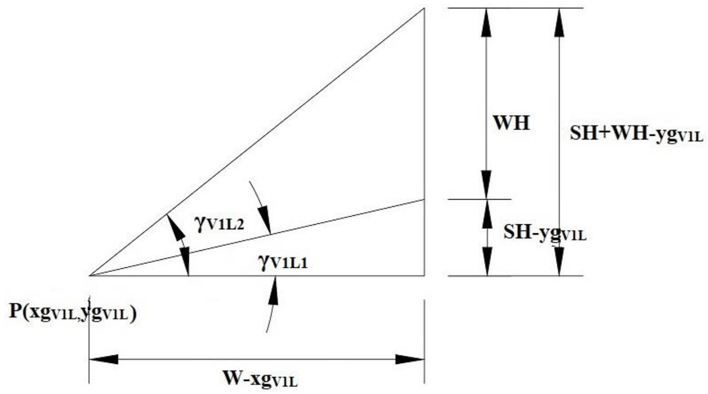


Figure 3.11: Diagram illustrating γ_{V1L1} and γ_{V1L2}

From the above figure 3.11

$tan\,\gamma_{V1L1} = \frac{(SH - yg_{V1L})}{(W - xg_{V1L})}$ and $tan\,\gamma_{V1L2} = \frac{(SH + WH - yg_{V1L})}{(W - xg_{V1L})}$

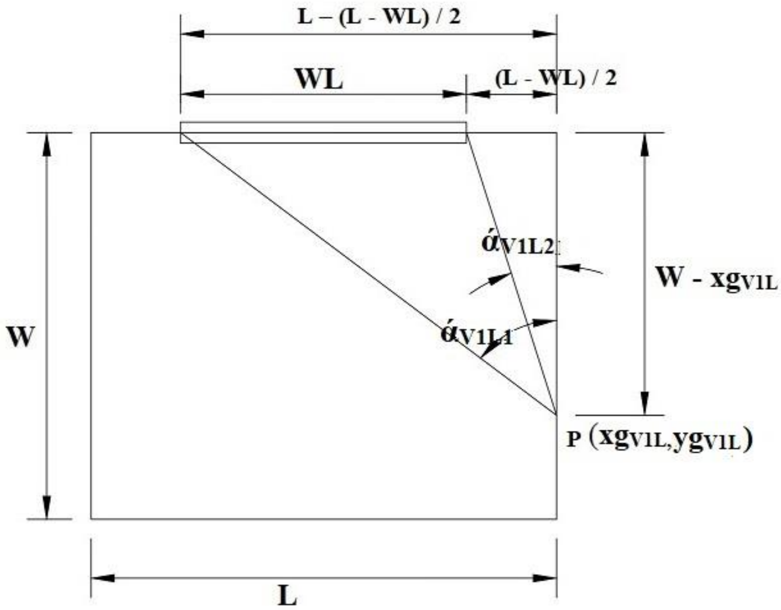


Figure 3.12: Diagram illustrating $ά_{V1L1}$ and $ά_{V1L2}$

From the above figure 3.12

$tan\,ά_{V1L1} = \frac{[(L - (L - WL) / 2]}{(W - xg_{V1L})}$

and $tan\,ά_{V1L2} = \frac{[(L - WL) / 2]}{(W - xg_{V1L})}$

$\alpha_{V1L1} = \theta - ά_{V1L1}$ and $\alpha_{V1L2} = \theta - ά_{V1L2}$

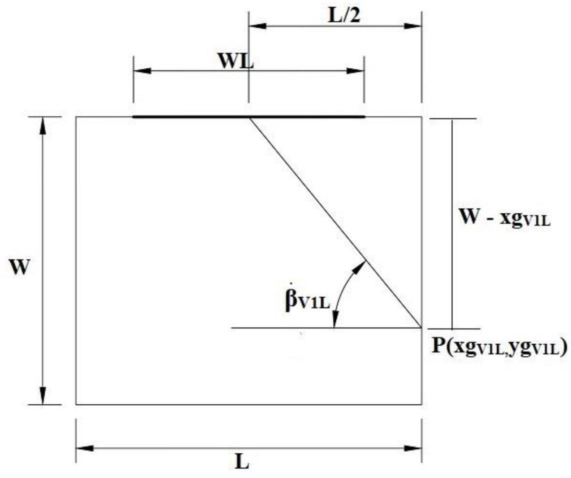


Figure 3.13: Diagram illustrating β_{V1L}

From the above figure 3.13

$\beta_{V1L} = 90° - \tan^{-1} \left[\frac{(L/2)}{(W - xg_{V1L})}\right]$

$E_{V1L} = \int_{\gamma_{V1L1}}^{\gamma_{V1L2}} \int_{\alpha_{V1L1}}^{\alpha_{V1L2}} L_{\gamma\alpha} * \cos\gamma\cos\gamma \cos\beta_{V1L}\, d\gamma d\alpha$..........from eqn. (1.15)

Or, $E_{V1L} = \int_{\gamma_{V1L1}}^{\gamma_{V1L2}} \int_{\alpha_{V1L1}}^{\alpha_{V1L2}} L_Z * \frac{[f(\chi)*\varphi(Z)]}{[f(Z_S)\ \varphi(0°)]} \cos\gamma\cos\gamma\cos\beta_{V1L}\ d\gamma d\alpha$

Or, $E_{V1L} = \frac{L_Z * \cos\beta_{V1L}}{[f(Z_S * \varphi(0°)]} \int_{\gamma_{V1L1}}^{\gamma_{V1L2}} \int_{\alpha_{V1L1}}^{\alpha_{V1L2}} [f(\chi) * \varphi(Z)] \cos\gamma\cos\gamma\cos\beta_{V1L}\ d\gamma d\alpha$

Therefore, $E_{pV1L} = τ * MF * E_{V1L}$

$Esum_{V1L}$ = Algebric summation of illuminance of all grid points.

$Esum_{V1L} = \Sigma\ E_{pV1L}$

N_{V1L} = total no of grid points.

Therefore, Average illuminance $Eavg_{V1L} = Esum_{V1L} / N_{V1L}$

$Emin_{V1L}$ and $Emax_{V1L}$ are the minimum and maximum value of E_{pV1L} .

Overall Uniformity U_{OV1L} is given by $U_{OV1L} = Emin_{V1L} / Eavg_{V1L}$.

Grid area $Area_{V1L} = W * (SH + 0.2)$..(3.10a)

Total Luminous Flux reached $Flux_{V1L} = Eavg_{V1L} * Area_{V1L}$.........(3.11a)

3.10.2 Point Specific Vertical Illuminance on the lower part of 2nd wall

P is an arbitrary point on grid of the lower part of the 2nd wall. P is specified by the coordinate (xg_{V2L}, yg_{V2L})

xg_{V2L} starts from 0.25, changes with a increment of 0.5 and ends at (L - 0.25). Again, yg_{V2L} starts at 0.25 changes with an increment 0.5 and ends at (SH + 0.2 - 0.25).

	Start Point	Interval	End Point
xg_{V2L} :	0.25	0.5	(L – 0.25)
yg_{V2L} :	0.25	0.5	(SH + 0.2 - 0.25)

The horizontal acceptance angle for the point varies from α_{V2L1} to α_{V2L2} and vertical acceptance angle varies from γ_{V2L1} to γ_{V2L2}. This means, the surface azimuth angle of the sky patch responsible for the illumination at the point P varies from α_{V2L1} to α_{V2L2} and altitude angle for the same varies from γ_{V2L1} to γ_{V2L2}.

β_{V2L} is the orientation angle of the vertical plane.

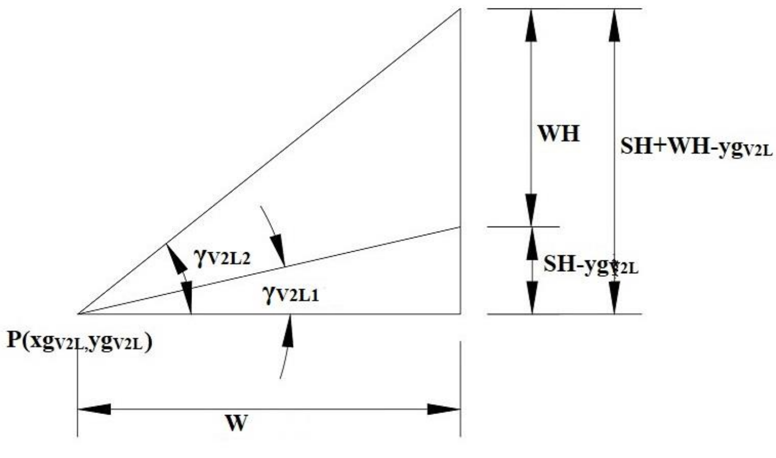


Figure 3.14: Diagram illustrating γ_{V2L1} and γ_{V2L2}

From the above figure 3.14

$$tan\,\gamma_{V2L1} = \frac{(SH - yg_{V2L})}{W} \text{ and } tan\,\gamma_{V2L2} = \frac{(SH + WH - yg_{V2L})}{W}$$

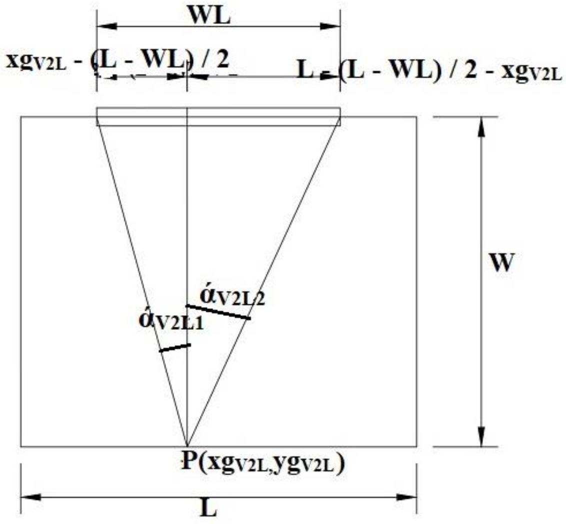


Figure 3.15: Diagram illustrating $\acute{\alpha}_{V2L1}$ and $\acute{\alpha}_{V2L2}$

From the above figure 3.15

$$\tan \acute{\alpha}_{V2L1} = \frac{[xg_{V2L} - (L - WL) / 2]}{W}$$

$$\tan \acute{\alpha}_{V2L2} = \frac{[L - (L - WL) / 2 - xg_{V2L}]}{W}$$

$$\alpha_{V2L1} = \theta - \acute{\alpha}_{V2L1}$$

$$\alpha_{V2L2} = \theta + \acute{\alpha}_{V2L2}$$

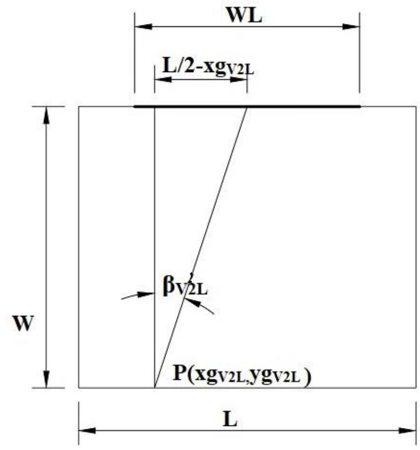


Figure 3.16: Diagram illustrating β_{V2L}

From the above figure 3.16

$$\beta_{V2L} = \tan^{-1} \left[\frac{\frac{L}{2} - xg_{V2L}}{W}\right]$$

$E_{V2L} = \int_{\gamma_{V2L1}}^{\gamma_{V2L2}} \int_{\alpha_{V2L1}}^{\alpha_{V2L2}} L_{\gamma\alpha} * \cos\gamma\cos\gamma \cos\beta_{V2L}\, d\gamma d\alpha$.......From eqn. (1.15)

Or, $E_{V2L} = \int_{\gamma_{V2L1}}^{\gamma_{V2L2}} \int_{\alpha_{V2L1}}^{\alpha_{V2L2}} L_Z * \frac{[f(\chi)*\varphi(Z)]}{[f(Z_S)*\varphi(0°)]} \cos\gamma\cos\gamma \cos\beta_{V2L}\, d\gamma d\alpha$

Or, $E_{V2L} = \frac{L_Z * \cos\beta_{V2L}}{[f(Z_S)*\varphi(0°)]} \int_{\gamma_{V2L1}}^{\gamma_{V2L2}} \int_{\alpha_{V2L1}}^{\alpha_{V2L2}} [f(\chi) * \varphi(Z)] \cos\gamma\cos\gamma\, d\gamma d\alpha$

Therefore, $E_{pV2L} = Ʈ * MF * E_{V2L}$

$Esum_{V2L}$ = Algebraic summation of illuminance of all grid points.

$Esum_{V2L} = \Sigma\ E_{pV2L}$

N_{V2L} = total no of grid points.

Therefore, Average illuminance $Eavg_{V2L} = Esum_{V2L} / N_{V2L}$

$Emin_{V2L}$ and $Emax_{V2L}$ are the minimum and maximum value of E_{pV2L} .

Overall Uniformity U_{OV2L} is given by $U_{OV2L} = Emin_{V2L} / Eavg_{V2L}$.

Grid area $Area_{V2L} = L* (SH + 0.2)$...(3.10b)

Total Luminous Flux reached $Flux_{V2L} = Eavg_{V2L} * Area_{V2L}$.........(3.11b)

3.10.3 Point Specific Vertical Illuminance on the lower part of 3rd wall

P is an arbitrary point on grid of the lower part of the 3rd wall. P is specified by the coordinate (xg_{V3L}, yg_{V3L})

xg_{V3L} starts from(W – 0.25), changes with a decrement of 0.5 and ends at 0.25. Again, yg_{V3L} starts at 0.25 changes with an increment 0.5 and ends at (SH + 0.2 - 0.25).

	Start Point	Interval	End Point
xg_{V3L} :	(W - 0.25)	- 0.5	0.25
yg_{V3L} :	0.25	0.5	(SH + 0.2 - 0.25)

The horizontal acceptance angle for the point varies from α_{V3L1} to α_{V3L2} and vertical acceptance angle varies from γ_{V3L1} to γ_{V3L2}. This means, the surface azimuth angle of the sky patch responsible for the illumination at the point P varies from α_{V3L1} to α_{V3L2} and altitude angle for the same varies from γ_{V3L1} to γ_{V3L2}.

β_{V3L} is the orientation angle of the vertical plane.

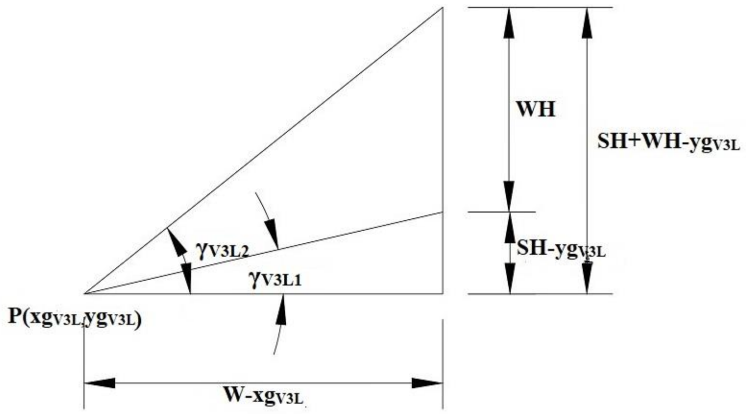


Figure 3.17: Diagram illustrating γ_{V3L1} and γ_{V3L2}

From the above figure 3.17

$\tan\gamma_{V3L1} = \frac{(SH - yg_{V3L})}{(W - xg_{V3L})}$ and $\tan\gamma_{V3L2} = \frac{(SH + WH - yg_{V3L})}{(W - xg_{V3L})}$

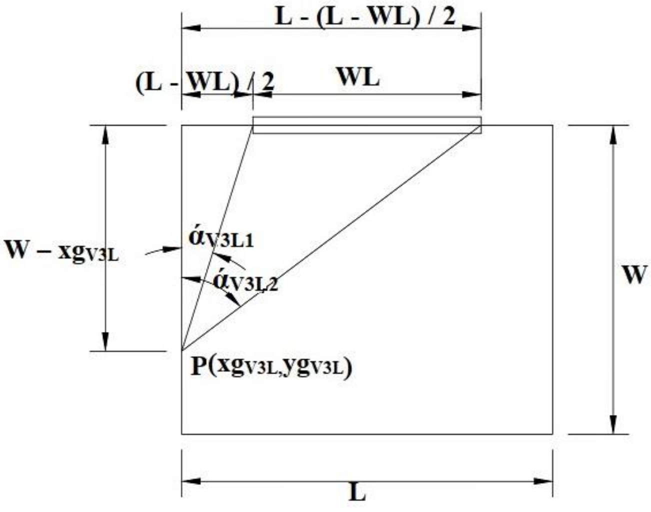


Figure 3.18: Diagram illustrating $ά_{V3L1}$ and $ά_{V3L2}$

From the above figure 3.18

$\tan ά_{V3L1} = \frac{[(L - WL) / 2]}{(W - xg_{V3L})}$ and $\alpha_{V3L1} = \theta + ά_{V3L1}$

$\tan ά_{V3L2} = \frac{[L - (L - WL) / 2]}{(W - xg_{V3L})}$ and $\alpha_{V3L2} = \theta + ά_{V3L2}$

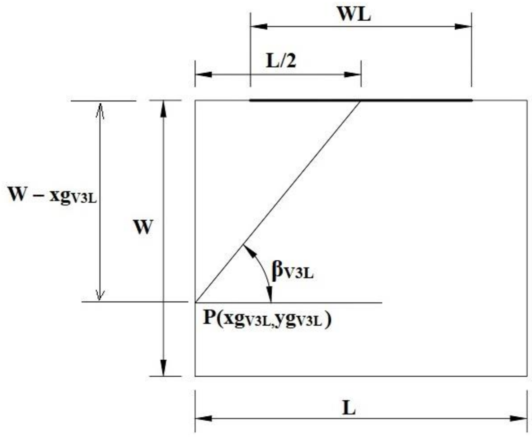


Figure 3.19: Diagram illustrating β_{V3L}

From the above figure 3.19

$\beta_{V3L} = 90° - \tan^{-1} \frac{L/2}{(W - xg_{V3L})}$

$E_{V3L} = \int_{\gamma_{32L1}}^{\gamma_{V3L2}} \int_{\alpha_{V3L1}}^{\alpha_{V3L2}} L_{\gamma\alpha} * \cos\gamma\cos\gamma \cos\beta_{V3L} \, d\gamma d\alpha$...........from eqn. (1.15)

Or, $E_{V3L} = \int_{\gamma_{V3L1}}^{\gamma_{V3L2}} \int_{\alpha_{V3L1}}^{\alpha_{V3L2}} L_Z * \frac{[f(\chi) * \varphi(Z)]}{[f(Z_S) * \varphi(0°)]} \cos\gamma\cos\gamma \cos\beta_{V3L} \, d\gamma d\alpha$

Or, $E_{V3L} = \frac{L_Z * \cos\beta_{V3L}}{[f(Z_S) * \varphi(0°)]} \int_{\gamma_{V3L1}}^{\gamma_{V3L2}} \int_{\alpha_{V3L1}}^{\alpha_{V3L2}} [f(\chi) * \varphi(Z)] \cos\gamma\cos\gamma \, d\gamma d\alpha$

Therefore, $E_{pV3L} = \tau * MF * E_{V3L}$

$Esum_{V3L}$ = Algebraic summation of illuminance of all grid points.

$Esum_{V3L} = \Sigma \, E_{pV3L}$

N_{V3L} = total no of grid points.

Therefore, Average illuminance $Eavg_{V3L} = Esum_{V3L} / N_{V3L}$

$Emin_{V3L}$ and $Emax_{V3L}$ are the minimum and maximum value of E_{pV3L} .

Overall Uniformity U_{OV3L} is given by $U_{OV3L} = Emin_{V3L} / Eavg_{V3L}$.

Grid area $Area_{V3L} = W * (SH + 0.2)$..(3.10c)

Total Luminous Flux reached $Flux_{V3L} = Eavg_{V3L} * Area_{V3L}$.........(3.11c)

3.11 Computation of point specific Horizontal Illuminance on the Floor due to sky luminanace

The sky element also illuminates the floor of the room, which in turn, contributes to the overall illumination of the work plane. An imaginary grid is also developed on the floor just like that on the work plane. Horizontal illuminances on all grid points are computed by using the process, which is already been adopted for the work plane.

The point P receives light through the window.

The horizontal acceptance angle for the point varies from α_{F1} to α_{F2} and vertical acceptance angle varies from γ_{F1} to γ_{F2}. This means, the surface azimuth angle of the sky patch responsible for the illumination at the point P varies from α_F1 to α_{F2} and altitude angle for the same varies from γ_{F1} to γ_{F2}.

An arbitrary point 'P' is specified by co-ordinate values (xg_F,yg_F). In our MATLAB program xg_F starts from 0.25, increases with an increment 0.5 and ends at (L-0.25) whereas, yg_F starts from (W-0.25) decreases with an decrement 0.5 and finally ends at 0.25.

	Start Point	Interval	End Point
xg_F :	0.25	0.5	(L – 0.25)
yg_F :	(W – 0.25)	- 0.5	0.25

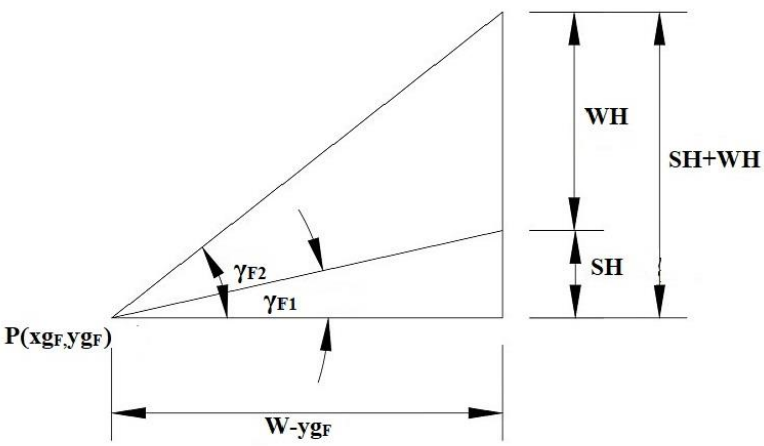


Figure 3.20: Diagram illustrating γ_{F1} and γ_{F2}

From the above figure 3.20

$$\tan \gamma_{F1} = \frac{SH}{(W - yg_F)} \text{ and } \tan \gamma_{F2} = \frac{(SH+WH)}{(W - yg_F)}$$

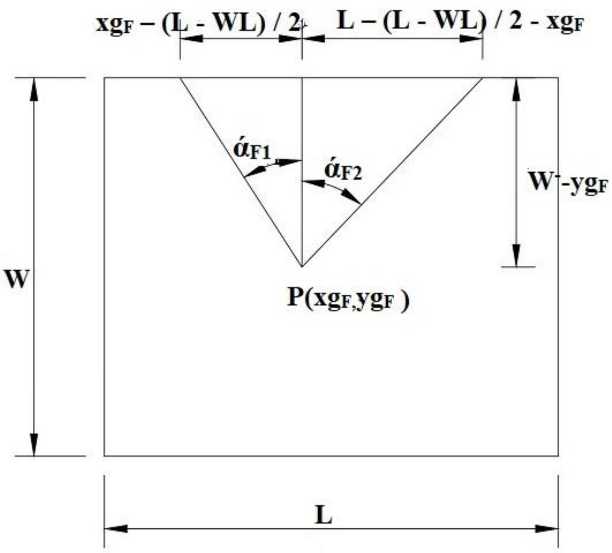


Figure 3.21: Diagram illustrating $ά_{F1}$ and $ά_{F2}$

From the above figure 3.21

$$\tan ά_{F1} = \frac{[(xg_F - (L - WL) / 2]}{(W - yg_F)}$$

$$\text{and } \tan ά_{F2} = \frac{[L - (L - WL) / 2 - xg_F]}{(W - yg_F)}$$

$α_{F1} = θ - ά_{F1}$

$α_{F2} = θ + ά_{F2}$

Now, using equation (1.14), horizontal illuminance at point P is given by

$E_F = \int_{\gamma_{F1}}^{\gamma_{F2}} \int_{\alpha_{F1}}^{\alpha_{F2}} L_{\gamma\alpha} * \sin\gamma\cos\gamma \, d\gamma d\alpha$.......................from eqn. (1.14)

Or, $E_F = \int_{\gamma_{F1}}^{\gamma_{F2}} \int_{\alpha_{F1}}^{\alpha_{F2}} L_Z * \frac{[f(\chi) * \varphi(Z)]}{[f(Z_S) * \varphi(0°)]} \sin\gamma\cos\gamma \, d\gamma d\alpha$

Or, $E_F = \frac{L_Z}{[f(Z_S) * \varphi(0°)]} \int_{\gamma_{F1}}^{\gamma_{F2}} \int_{\alpha_{F1}}^{\alpha_{F2}} [f(\chi) * \varphi(Z)] \sin\gamma\cos\gamma \, d\gamma d\alpha$

Therefore, point specific horizontal illuminance E_{pF} is given by

$E_{pF} = \tau * MF * E_F$

$Esum_F$ = Algebraic summation of illuminance of all grid points.

$Esum_F = \Sigma E_{pF}$

N_F = total no of grid points.

Therefore, Average illuminance $Eavg_F = Esum_F / N_F$

$Emin_F$ and $Emax_F$ are the minimum and maximum value of E_{pF}.

Overall Uniformity U_{OF} is given by $U_{OF} = Emin_F / Eavg_F$

Grid area $Area_F = L*W$..(3.12)

Total Luminous Flux reached $Flux_F = Eavg_F * Area_F$.........(3.13)

3.12 Computation of Ground Luminance

External ground surface is also illuminated by the sky luminance. The point on the ground receives light from the entire sky vault. So, the horizontal acceptance angle i.e. surface azimuth angle varies from 0 to 2π (360°) and vertical acceptance angle i.e. altitude angle varies from 0 to π/2 (90°).

$E_G = \int_{\gamma=0}^{\pi/2} \int_{\alpha=0}^{2\pi} L_{\gamma\alpha} \sin\gamma \cos\gamma \, d\gamma d\alpha$..................from eqn. (1.14)

Or, $E_G = \int_{\gamma=0}^{\pi/2} \int_{\alpha=0}^{2\pi} L_Z * \frac{[f(\chi) * \varphi(Z)]}{[f(Z_S) * \varphi(0°)]} \sin\gamma \cos\gamma \, d\gamma d\alpha$

Or, $E_G = \frac{L_Z}{[f(Z_S) * \varphi(0°)]} \int_{\gamma=0}^{\pi/2} \int_{\alpha=0}^{2\pi} [f(\chi) * \varphi(Z)] \sin\gamma \cos\gamma \, d\gamma d\alpha$

Therefore, point specific horizontal illuminance E_{pG} is given by

$E_{pG} = LLF * E_G$ where, LLF stands for Light Loss Factor. (LLF = MF)

ρ_{Gavg} = Average Ground Surface Reflectance

In our case study it is taken as 0.2 i.e. 20%.

Therefore, Average Ground Luminance L_{gavg} is given by

$L_{gavg} = (E_{pG} * \rho_{Gavg}) / \pi$ ....[From Equation 1.7]

So, in this case, luminance is of constant value i.e. $L_{\gamma\alpha} = L_{gavg}$

3.13 Computation of Vertical Illumination on the room walls due to Ground luminance

The average ground luminance illuminates the upper part of the three walls (except the window wall) and also the ceiling of the room. The lower boundary of the imaginary grid area coincides with the upper boundary of the area illuminated directly by sky luminance. Following the earlier process as discussed in Section 3.10 the vertical illumination distribution on the upper portion of the three walls can also be computed.

3.13.1 Point Specific Vertical Illuminance on the upper part of 1st wall

P is an arbitrary point on grid of the upper part of the 1st wall. P is specified by the coordinate (xg_{V1U}, yg_{V1U}).

xg_{V1U} starts from (W – 0.25), changes with a decrement of 0.5 and ends at 0.25.Again, yg_{V1U} starts at (H - 0.25) changes with an decrement 0.5 and ends at (SH + 0.2 + 0.25).

	Start Point	Interval	End Point
xg_{V1U} :	(W – 0.25)	- 0.5	0.25
yg_{V1U} :	(H - 0.25)	- 0.5	(SH + 0.2 + 0.25)

The horizontal acceptance angle for the point varies from α_{V1U1} to α_{V1U2} and vertical acceptance angle varies from γ_{V1U1} to γ_{V1U2}. This means, the surface azimuth angle of the sky patch responsible for the illumination at the point P varies from α_{V1U1} to α_{V1U2} and altitude angle for the same varies from γ_{V1U1} to γ_{V1U2}.

β_{V1U} is the orientation angle of the vertical plane.

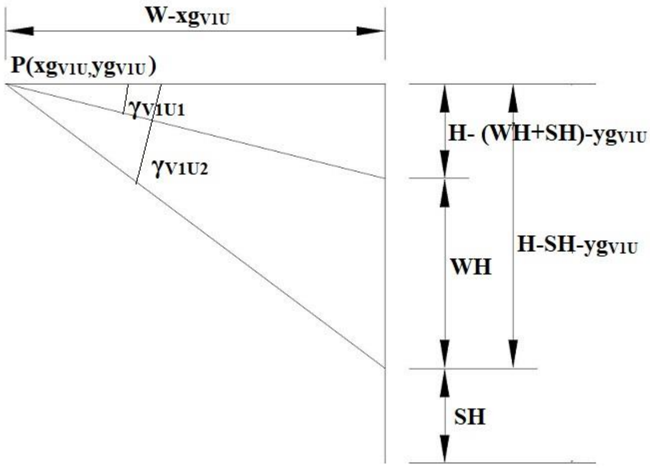


Figure 3.22: Diagram illustrating γ_{V1U1} and γ_{V1U2}

From the above figure 3.22

$$\tan \gamma_{V1U1} = \frac{[H-(WH+SH)-yg_{V1U}]}{(W-xg_{V1U})} \quad \text{and} \quad \tan \gamma_{V1U2} = \frac{[H-SH-yg_{V1U}]}{(W-xg_{V1U})}$$

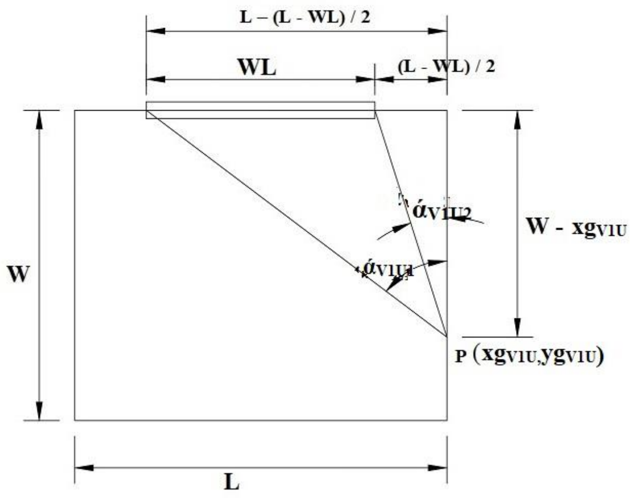


Figure 3.23: Diagram illustrating $ά_{V1U1}$ and $ά_{V1U2}$

From the above figure 3.23

tan $ά_{V1U1} = \frac{[L-((L-WL)/2]}{(W-xg_{V1U})}$

tan $ά_{V1U2} = \frac{[(L-WL)/2]}{(W-xg_{V1U})}$

$α_{V1U1} = θ – ά_{V1U1}$

$α_{V1U2} = θ - ά_{V1U2}$

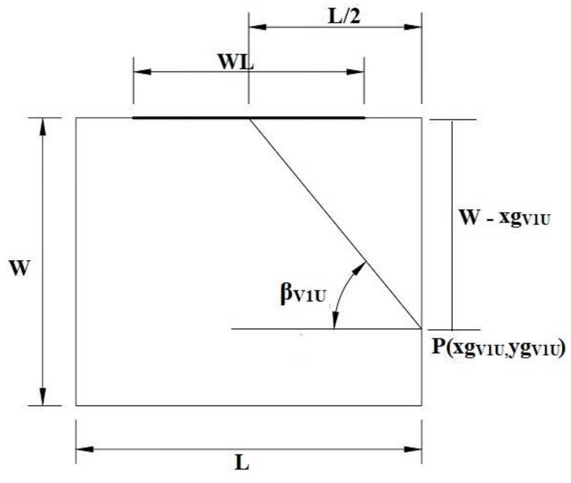


Figure 3.24: Diagram illustrating $β_{V1U}$

From the above figure 3.24

$β_{V1U} = 90° - \tan^{-1} \frac{(L/2)}{(W-xg_{V1U})}$

$E_{V1U} = \int_{\gamma_{V1U1}}^{\gamma_{V1U2}} \int_{\alpha_{V1U1}}^{\alpha_{V1U2}} L_{\gamma\alpha} * \cos\gamma\cos\gamma \cos\beta_{V1U}\, d\gamma d\alpha$........from eqn. (1.15)

Or, $E_{V1U} = \int_{\gamma_{V1U1}}^{\gamma_{V1U2}} \int_{\alpha_{V1U1}}^{\alpha_{V1U2}} L_{gavg} \cos\gamma\cos\gamma \cos\beta_{V1U}\, d\gamma d\alpha$ [since, $L\gamma\alpha = L_{gavg}$]

Or, $E_{V1U} = L_{gavg} * \cos\beta_{V1U} \int_{\gamma_{V1U1}}^{\gamma_{V1U2}} \int_{\alpha_{V1U1}}^{\alpha_{V1U2}} \cos\gamma\cos\gamma\, d\gamma d\alpha$

Therefore, $E_{pV1U} = \tau * MF * E_{V1U}$

$Esum_{V1U}$ = Algebraic summation of illuminance of all grid points.

$Esum_{V1U} = \Sigma\ E_{pV1U}$

N_{V1U} = total no of grid points.

Therefore, Average illuminance $Eavg_{V1U} = Esum_{V1U} / N_{V1U}$

$Emin_{V1U}$ and $Emax_{V1U}$ are the minimum and maximum value of E_{pV1U}.

Overall Uniformity U_{OV1U} is given by $U_{OV1U} = Emin_{V1U} / Eavg_{V1U}$.

Grid area $Area_{V1U} = W * [H – (SH + 0.2)]$..................................(3.14a)

Total Luminous Flux reached $Flux_{V1U} = Eavg_{V1U} * Area_{V1U}$.........(3.15a)

3.13.2 Point Specific Vertical Illuminance on the upper part of 2nd wall

P is an arbitrary point on grid of the upper part of the 2nd wall. P is specified by the coordinate (xg_{V2U}, yg_{V2U}).

xg_{V2U} starts from 0.25 changes with an increment of 0.5 and ends at (L - 0.25). Again, yg_{V2U} starts at (H - 0.25) changes with a decrement 0.5 and ends at (SH + 0.2 + 0.25).

	Start Point	Interval	End Point
xg_{V2U} :	0.25	0.5	(L - 0.25)
yg_{V2U} :	(H - 0.25)	- 0.5	(SH + 0.2 + 0.25)

The horizontal acceptance angle for the point varies from α_{V2U1} to α_{V2U2} and vertical acceptance angle varies from γ_{V2U1} to γ_{V2U2}. This means, the surface azimuth angle of the sky patch responsible for the illumination at the point P varies from α_{V2U1} to α_{V2U2} and altitude angle for the same varies from γ_{V2U1} to γ_{V2U2}.

β_{V2U} is the orientation angle of the vertical plane.

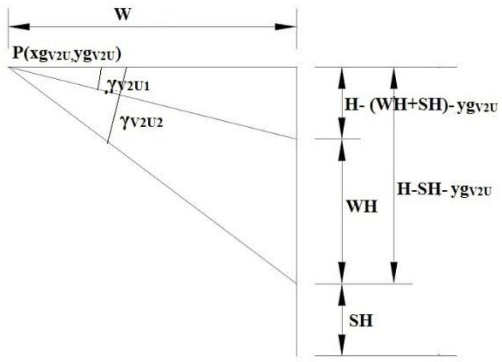


Figure 3.25: Diagram illustrating γ_{V2U1} and γ_{V2U2}

From the above figure 3.25

$\tan\gamma_{\,V2U1} = \frac{[H-(WH+SH)-yg_{V2U}]}{W}$ and $tan\,\gamma_{\,V2U2} = \frac{[H-SH-yg_{V2U}]}{W}$

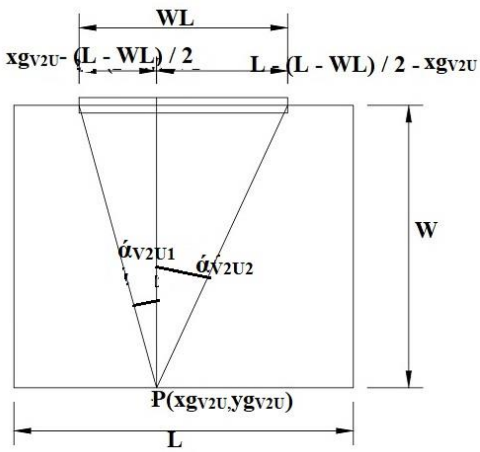


Figure 3.26: Diagram illustrating $ά_{V2U1}$ and $ά_{V2U2}$

From the above figure 3.26

$tan\, ά_{V2U1} = \frac{[xg_{V2U} - (L-WL)/2]}{W}$ and $\alpha_{V2U1} = \theta - ά_{V2U1}$

$tan\, ά_{V2U2} = \frac{[\,L-\frac{(L-WL)}{2}-xg_{V2U}]}{W}$ and $\alpha_{V2U2} = \theta + ά_{V2U2}$

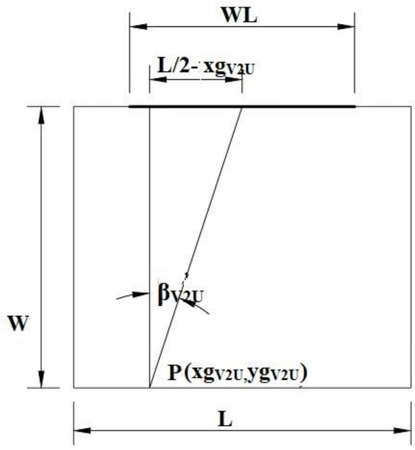


Figure 3.27: Diagram illustrating β_{V2U}

From the above figure 3.27

$\beta_{V2U} = \tan^{-1} \frac{(L/2 - xgV2U)}{W}$

$E_{V2U} = \int_{\gamma_{V2U1}}^{\gamma_{V2U2}} \int_{\alpha_{V2U1}}^{\alpha_{V2U2}} L_{\gamma\alpha} * \cos\gamma\cos\gamma \cos\beta_{V2U} \, d\gamma d\alpha$........from eqn. (1.15)

Or, $E_{V2U} = \int_{\gamma_{V2U1}}^{\gamma_{V2U2}} \int_{\alpha_{V2U1}}^{\alpha_{V2U2}} L_{gavg}\cos\gamma\cos\gamma \cos\beta_{V2U} \, d\gamma d\alpha$

Or, $E_{V2U} = L_{gavg} * \cos\beta_{V2U} \int_{\gamma_{V2U1}}^{\gamma_{V2U2}} \int_{\alpha_{V2U1}}^{\alpha_{V2U2}} \cos\gamma\cos\gamma \, d\gamma d\alpha$

Therefore, $E_{pV2U} = \tau * MF * E_{V2U}$

$Esum_{V2U}$ = Algebraic summation of illuminance of all grid points.

$Esum_{V2U} = \Sigma E_{pV2U}$

N_{V2U} = total no of grid points.

Therefore, Average illuminance $Eavg_{V2U} = Esum_{V2U} / N_{V2U}$

$Emin_{V2U}$ and $Emax_{V2U}$ are the minimum and maximum value of E_{pV2U} .

Overall Uniformity U_{OV2U} is given by $U_{OV2U} = Emin_{V2U} / Eavg_{V2U}$.

Grid area $Area_{V2U} = L*[H - (SH+0.2)]$.......................................(3.14b)

Total Luminous Flux reached $Flux_{V2U} = Eavg_{V2U} * Area_{V2U}$.........(3.15b)

3.13.3 Point Specific Vertical Illuminance on the upper part of 3rd wall

P is an arbitrary point on grid of the upper part of the 3rd wall. P is specified by the coordinate (xg_{V3U}, yg_{V3U})

xg_{V3U} starts from(W – 0.25), changes with a decrement of 0.5 and ends at 0.25. Again, yg_{V3U} starts at (H - 0.25) changes with a decrement 0.5 and ends at (SH + 0.2 + 0.25).

	Start Point	Interval	End Point
xg_{V3U} :	(W - 0.25)	- 0.5	0.25
yg_{V3U} :	(H - 0.25)	-0.5	(SH + 0.2 + 0.25)

The horizontal acceptance angle for the point varies from α_{V3U1} to α_{V3U2} and vertical acceptance angle varies from γ_{V3U1} to γ_{V3U2}. This means, the surface azimuth angle of the sky patch responsible for the illumination at the point P varies from α_{V3U1} to α_{V3U2} and altitude angle for the same varies from γ_{V3U1} to γ_{V3U2}.

β_{V3U} is the orientation angle of the vertical plane.

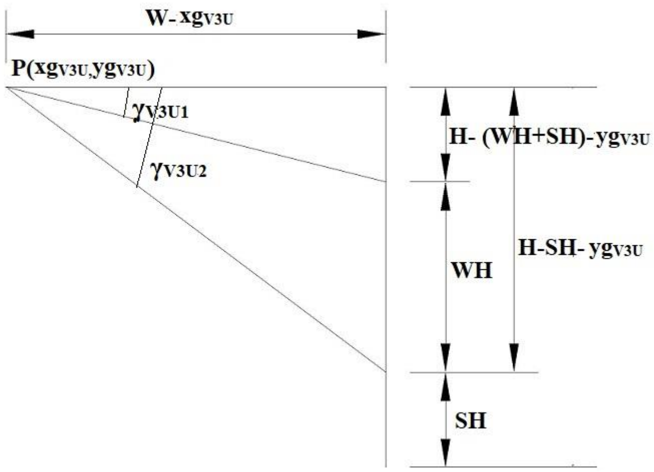


Figure 3.28: Diagram illustrating γ_{V3U1} and γ_{V3U2}

From the above figure 3.28

$$\tan\gamma_{V3U1} = \frac{[H-(WH+SH)-yg_{V3U}]}{(W-xg_{V3U})} \quad \text{and} \quad \tan\gamma_{V3U2} = \frac{[H-SH-yg_{V3U}]}{(W-xg_{V3U})}$$

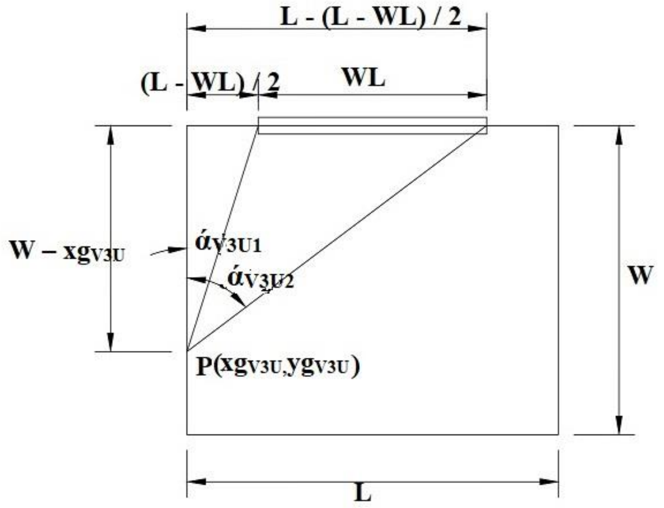


Figure 3.29: Diagram illustrating $ά_{V3U1}$ and $ά_{V3U2}$

From the above figure 3.29

tan $ά_{V3U1} = \frac{[(L-WL)/2]}{(W-xg_{V3U})}$ and tan $ά_{V3U2} = \frac{[L-((L-WL)/2]}{(W-xg_{V3U})}$

$α_{V3U1} = θ + ά_{V3U1}$

$α_{V3U2} = θ + ά_{V3U2}$

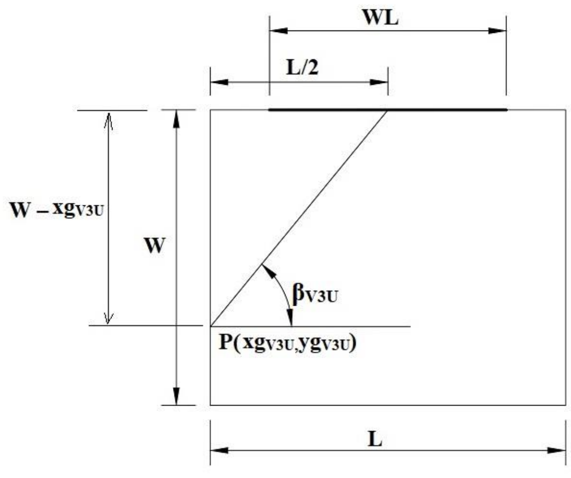


Figure 3.30: Diagram illustrating $β_{V3U}$

From the above figure 3.30

$β_{V3U} = 90° - \tan^{-1} \frac{(\frac{L}{2})}{(W-xg_{V3U})}$

$E_{V3U} = \int_{\gamma_{V3U1}}^{\gamma_{V3U2}} \int_{\alpha_{V3U1}}^{\alpha_{V3U2}} L_{\gamma\alpha} * \cos\gamma\cos\gamma \cos\beta_{V3U}\, d\gamma d\alpha$...........from eqn. (1.15)

Or, $E_{V3U} = \int_{\gamma_{V3U1}}^{\gamma_{V3U2}} \int_{\alpha_{V3U1}}^{\alpha_{V3U2}} L_{gavg} \cos\gamma\cos\gamma \cos\beta_{V3U}\, d\gamma d\alpha$

Or, $E_{V3U} = L_{gavg} * \cos\beta_{V3U} \int_{\gamma_{V3U1}}^{\gamma_{V3U2}} \int_{\alpha_{V3U1}}^{\alpha_{V3U2}} \cos\gamma\cos\gamma\, d\gamma d\alpha$

Therefore, $E_{pV3\backslash U} = \tau * MF * E_{V3U}$

$Esum_{V3U}$ = Algebraic summation of illuminance of all grid points.

$Esum_{V3U} = \Sigma\, E_{pV3U}$

N_{V3U} = total no of grid points.

Therefore, Average illuminance $Eavg_{V3U} = Esum_{V3U} / N_{V3U}$

$Emin_{V3U}$ and $Emax_{V3U}$ are the minimum and maximum value of E_{pV3U}.

Overall Uniformity U_{OV3U} is given by $U_{OV3U} = Emin_{V3U} / Eavg_{V3U}$.

Grid area $Area_{V3U} = W * [H – (SH + 0.2)]$.................................(3.14c)

Total Luminous Flux reached $Flux_{V3U} = Eavg_{V3U} * Area_{V3U}$.........(3.15c)

3.14 Computation of point specific Horizontal Illuminance on the Ceiling due to Ground luminanace

The average ground luminance also illuminates the ceiling of the room, which in turn, contributes to the overall illumination of the work plane. An imaginary grid is also developed on the ceiling just like that on the work plane. Horizontal illuminances on all grid points are computed by using the process, which is already been adopted for the work plane.

The point P receives light through the window.

The horizontal acceptance angle for the point varies from α_{C1} to α_{C2} and vertical acceptance angle varies from γ_{C1} to γ_{C2}. This means, the surface azimuth angle responsible for the illumination at the point P varies from α_C1 to α_{C2} and altitude angle for the same varies from γ_{C1} to γ_{C2}.

An arbitrary point 'P' is specified by co-ordinate values (xg_C,yg_C). In our MATLAB program xg_C starts from 0.25, increases with an increment 0.5 and ends at (L-0.25) whereas, yg_C starts from (W-0.25) decreases with an decrement 0.5 and finally ends at 0.25.

	Start Point	Interval	End Point
xg_C :	0.25	0.5	(L – 0.25)
yg_C :	(W – 0.25)	- 0.5	0.25

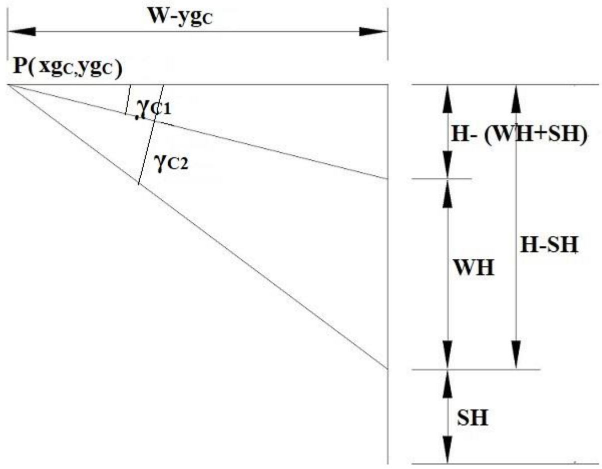


Figure 3.31: Diagram illustrating γ_{C1} and γ_{C2}

From the above figure 3.31

$$\tan\gamma_{C1} = \frac{[H - (WH + SH)]}{(W - yg_C)}$$

and $$tan\,\gamma_{C2} = \frac{(H - SH)}{(W - yg_C)}$$

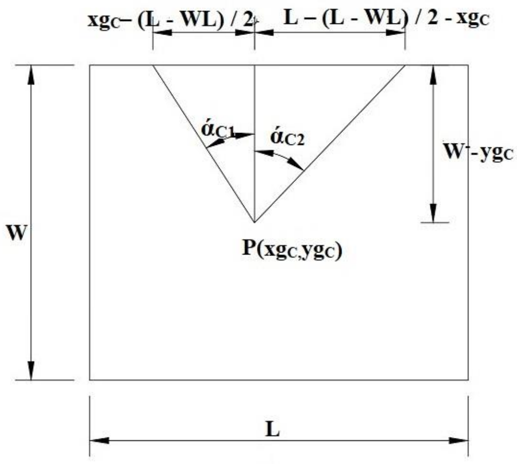


Figure 3.32: Diagram illustrating $ά_{C1}$ and $ά_{C2}$

From the above figure 3.32

$\tan ά_{C1} = \frac{[(xg_C - (L - WL) / 2]}{(W - yg_C)}$ and $α_{C1} = θ - ά_{C1}$

$\tan ά_{C2} = \frac{[L - (L - WL) / 2 - xg_C]}{(W - yg_C)}$ and $α_{C2} = θ + ά_{C2}$

Now, using equation (1.14), horizontal illuminance at point P is given by

$E_C = \int_{γ_{C1}}^{γ_{C2}} \int_{α_{C1}}^{α_{C2}} L_{γα} * \sin γ \cos γ \, dγ dα$............from eqn. (1.14)

Or, $E_C = \int_{γ_{C1}}^{γ_{C2}} \int_{α_{C1}}^{α_{C2}} L_{gavg} * \sin γ \cos γ \, dγ dα$

Or, $E_C = L_{gavg} \int_{γ_{C1}}^{γ_{C2}} \int_{α_{C1}}^{α_{C2}} \sin γ \cos γ \, dγ dα$

Therefore, point specific horizontal illuminance E_{pC} is given by

$E_{pC} = τ * MF * E_C$

$Esum_C$ = Algebraic summation of illuminance of all grid points.

$Esum_C = \Sigma E_{pC}$

N_C = total no of grid points.

Therefore, Average illuminance $Eavg_C = Esum_C / N_C$

$Emin_C$ and $Emax_C$ are the minimum and maximum value of E_{pC}.

Overall Uniformity U_{OC} is given by $U_{OC} = Emin_C / Eavg_C$

Grid area $Area_C$ = L*W..(3.16)

Total Luminous Flux reached $Flux_C$ = $Eavg_C$ * $Area_C$.............(3.17)

3.15 Computation of Average Inter reflected Illuminance (IRC)

Areas of the 1st, 2nd and 3rd wall are expressed as $Area_{V1}$, $Area_{V2}$ and $Area_{V3}$ respectively.

Therefore, $Area_{V1} = Area_{V1L} + Area_{V1U}$

= W*(SH + 0.2) + W*[H – (SH + 0.2)].....[from Eqn. 3.10a and 3.14a]

= W*H

Similarly, $Area_{V2} = Area_{V2L} + Area_{V2U}$

= L*(SH + 0.2) + L*[H – (SH + 0.2)]........[from Eqn. 3.10b and 3.14b]

= L*H

Similarly, $Area_{V3} = Area_{V3L} + Area_{V3U}$

= W*(SH + 0.2) + W*[H – (SH + 0.2)].....[from Eqn. 3.10c and 3.14c]

= W*H

Therefore, total Wall area $Area_W$ is given by

$Area_W = Area_{V1} + Area_{V2} + Area_{V3}$

Total areas of the floor and ceiling have already been computed and are denoted by $Area_F$ and $Area_C$ respectively..........[Eqn. 3.12 and 3.16]

Fluxes reached on the 1st, 2nd and 3rd wall are expressed as $Flux_{V1}$, $Flux_{V2}$ and $Flux_{V3}$ respectively.

Therefore, $Flux_{V1} = Flux_{V1L} + Flux_{V1U}$ [from Eqn. 3.11a and 3.15a]

Similarly, $Flux_{V2} = Flux_{V2L} + Flux_{V2U}$ [from Eqn. 3.11b and 3.15b]

Similarly, $Flux_{V3} = Flux_{V3L} + Flux_{V3U}$ [from Eqn. 3.11b and 3.15b]

Total Flux on three walls is $Flux_W$ is given by

$Flux_W = Flux_{V1} + Flux_{V2} + Flux_{V3}$

Total fluxes reached on the floor and ceiling have already been computed and are denoted by $Flux_F$ and $Flux_C$ respectively........[Eqn. 3.13 and 3.17]

The reflection coefficient of the floor, wall and ceiling are ρ_F, ρ_W and ρ_C respectively.

In our sample case study, $\rho_F = 0.2$ (20%)

$\rho_W = 0.5$ (50%)

$\rho_C = 0.8$ (80%)

First Reflectant Flux = FRF

$$FRF = \rho_F * Flux_F + \rho_W * Flux_W + \rho_C * Flux_C \quad \text{.........................(3.18)}$$

Area weighted average reflectance coefficient ρ_{avg} is given as

$$\rho_{avg} = \frac{(Area_F * \rho_F + Area_W * \rho_W + Area_C * \rho_C)}{(Area_F + Area_W + Area_C)}$$

Internal Reflected Flux $Flux_{IR}$ is given as

$$Flux_{IR} = \frac{FRF}{(1 - \rho_{avg})} \quad \text{...(3.19)}$$

Average point specific horizontal Internal Reflected Illuminance E_{InR} can be derived from Eqn. 1.7

$$E_{InR} = \frac{Flux_{IR}}{Total\ Area} = \frac{FRF}{[(1 - \rho_{avg}) * (Area_F + Area_W + Area_C)]} \quad \text{.........(3.20)}$$

3.16 Computation of point specific total Horizontal Illuminance on the Work Plane.

The work plane was already formed on the work plane in Section 3.7.

An arbitrary point 'P' is specified by co-ordinate values (xg,yg). In our MATLAB program xg starts from 0.25, increases with an increment 0.5 and ends at (L-0.25) whereas, yg starts from (W-0.25) decreases with an decrement 0.5 and finally ends at 0.25.

	Start Point	Interval	End Point
xg :	0.25	0.5	(L – 0.25)
yg :	(W – 0.25)	- 0.5	0.25

Therefore, the point specific horizontal illuminance on the work plane is E_{WP} and it is given as –

$E_{WP} = E_P + E_{InR}$

$Esum_{WP}$ = Algebraic summation of illuminance of all grid points.

$Esum_{WP} = \Sigma E_{WP}$

N = total no of grid points.

Therefore, Average illuminance $Eavg_{WP} = Esum_{WP} / N$................. (3.21)

$Emin_{WP}$ and $Emax_{WP}$ are the minimum and maximum value of E_{WP} .

Overall Uniformity U_{OWP} is given by $U_{OWP} = Emin_{WP} / Eavg_{WP}$......(3.22)

Accordingly, ISO LUX Plot is developed for the work plane by using MATLAB programming code. The plots for 90%, 80%, 70%, 60%, 50%, 40%, 30%, 20% and 10% of $Emax_{WP}$ are formed and produced with the title 'IsoLux Plot on the Work plane'.

<u>Chapter – 4</u>

Model Validation through Case Study

4.1 Case Study 1: Design Considerations

A sample model room with the following dimension along with a single window having following specification and other physical conditions are considered for the purpose of result analysis and validation of the proposed daylight simulation model.

Room Dimension

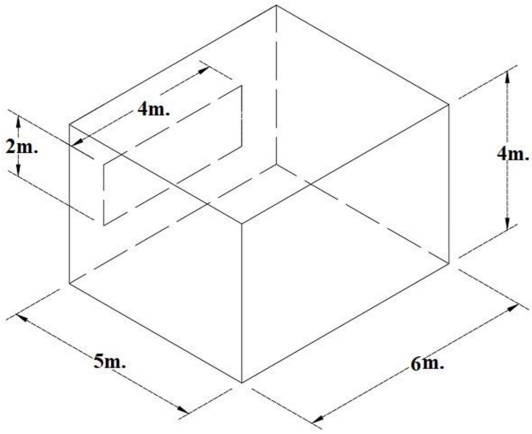
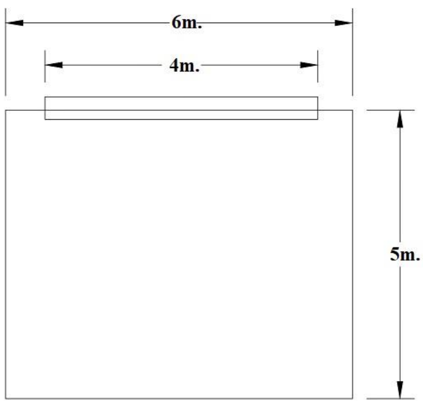


Figure 4.1: Diagram illustrating the Room Dimension

Length L = 6 m. Width W = 5 m. and Height H = 4 m. (As shown in Fig.4.1)

Window Dimension



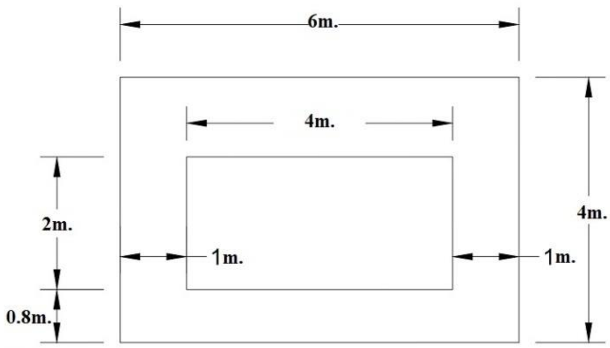


Figure 4.2: Plan View

Figure 4.3: Window Wall Elevation

Window Wall Area = 6x4 = 24m^2 Window Wall Ratio = 0.33

Therefore, Window Area = 0.33 x 24 = 8 m^2

Window Length WL = 6 – (2 x 1) = 4m. (As shown in Fig.4.2 & Fig.4.3)

So, Window Height WH = 8/4 = 2 m.

Sill Height of Window SH = 0.8 m.

Other Design Considerations

Work Plane Height WPH = 0.75 m.

Transmittance of Window Glazing Material Ʈ = 0.5 i.e. 50 %

Maintenance Factor MF = 0.75 i.e. 75 %

Average Outdoor Ground Surface Reflectance ρ_{Gavg} = 0.2 i.e. 20 %

Average Room Floor Reflectance ρ_F = 0.2 (20%)

Average Room Wall Reflectance ρ_W = 0.5 (50%)

Average Room Ceiling Reflectance ρ_C = 0.8 (80%)

Grid Formation

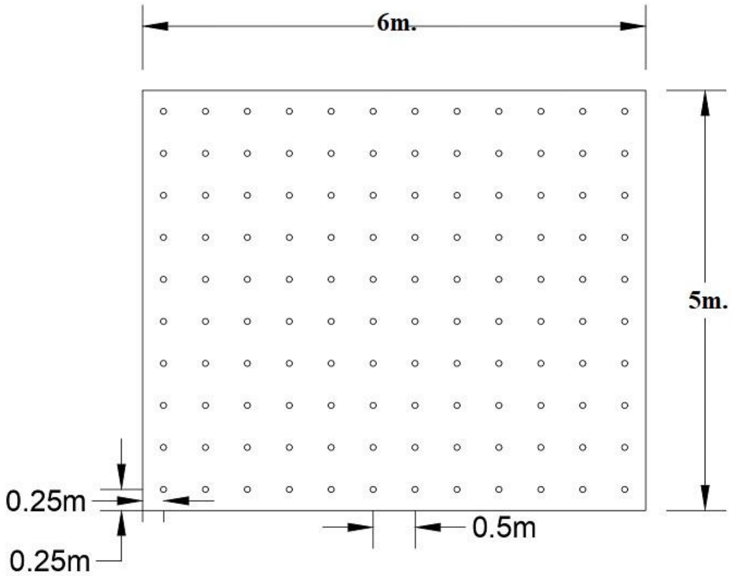


Fig. 4.4: Diagram illustrating the grid points on Work Plane.

Total no of grid points are (12 x 10) = 120

Design Variables

- Date i.e. Julian Day n (1 for 1st January & 365 for 31st December).
- Time i.e. Hour x (1 for 1 am, 12 for 12 noon & 23 for 11 pm).
- Location i.e. Latitude (Φ) and Longitude (λ).
- Sky Type ST (1 to 15 as per SSLD model).
- Window Orientation θ (0° for North Facing Window).

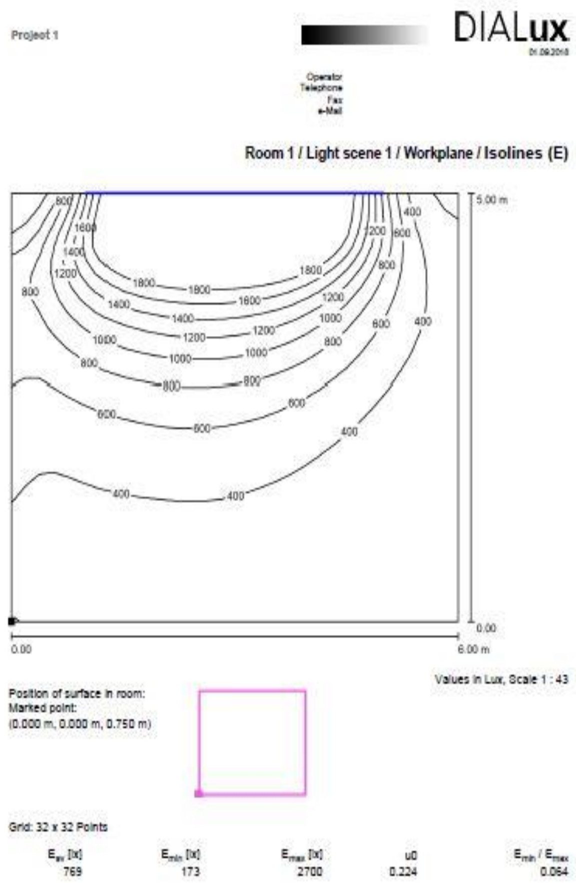
Design Output

- ❖ Average Illuminance on the Work Plane (Eavg).
- ❖ Overall Uniformity (U_O).
- ❖ Iso Lux Plot on the Work Plane.

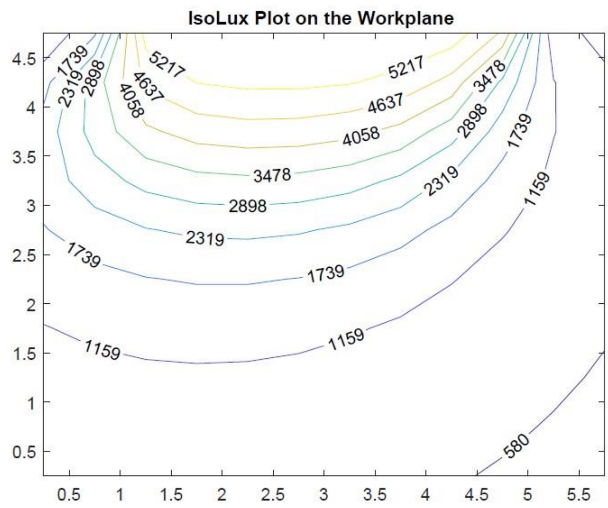
4.2 Comparison of Light Distribution Pattern with Output of the DIALux Software for the same design.

4.2.1 Iso Lux Plot for East facing window at 9 am on 23rd September at Kolkata

<table>
<tr><th>Through DIALux for Clear Sky</th><th>Through proposed Model for Sky Type 15 (pure clear sky)</th></tr>
<tr><td>



</td><td>



Eavg = 1969 Lux

U_O = 0.2246

</td></tr>
</table>

Figure 4.5: Iso Lux Plot for East facing window at 9 am on 23rd September at Kolkata

4.2.2 Iso Lux Plot for West facing window at 3 pm on 22nd December at Kolkata

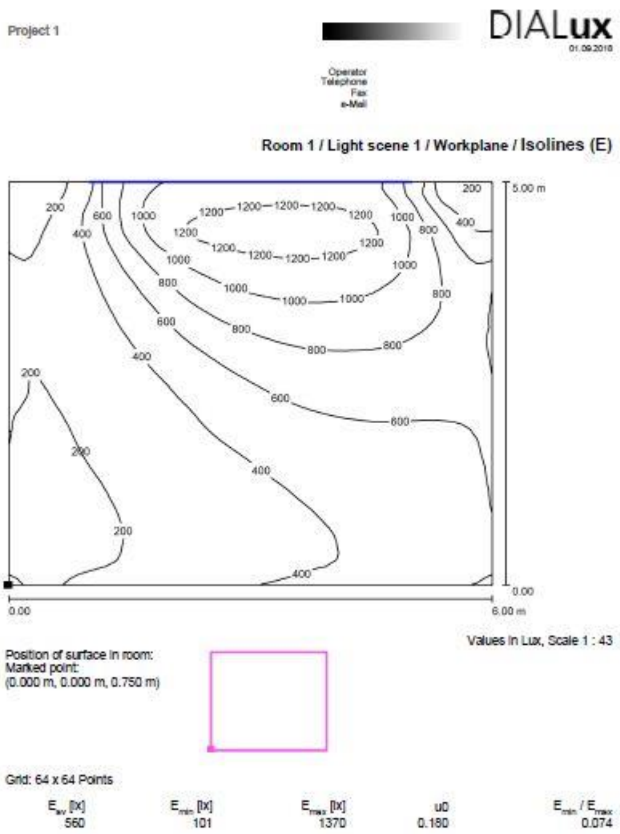
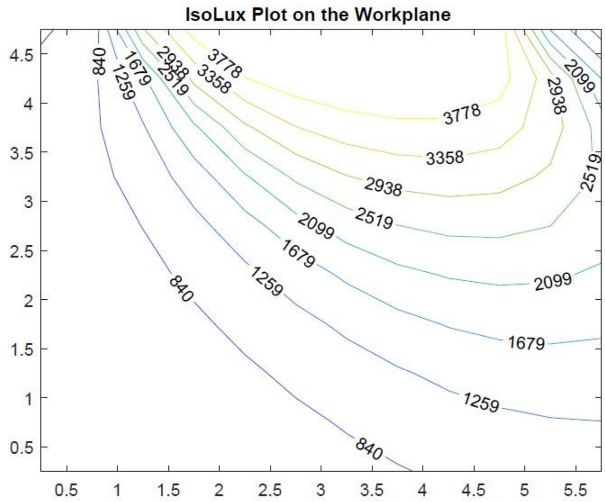
Through DIALux for Clear Sky	Through proposed Model for Sky Type 15 (pure clear sky)
	 Eavg = 1744 Lux U_O = 0.2194

Figure 4.6: Iso Lux Plot for West facing window at 3 pm on 22nd December at Kolkata

4.2.3 Iso Lux Plot for North facing window at 8 am on 21st March at Kolkata

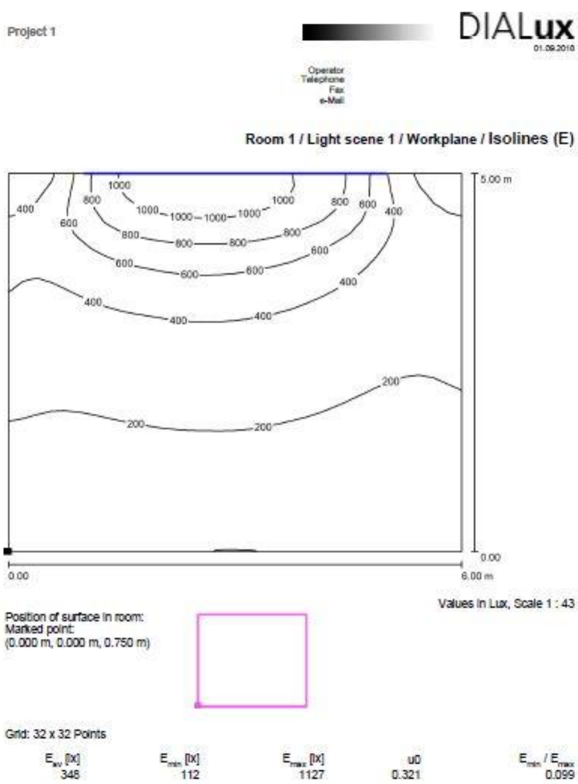
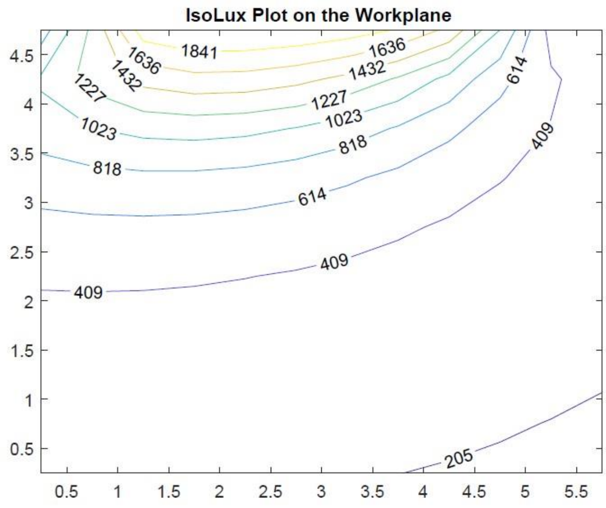
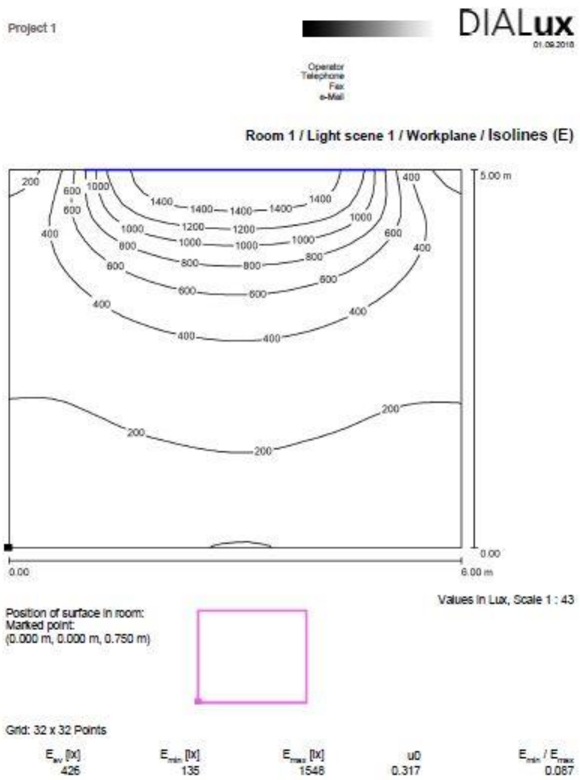
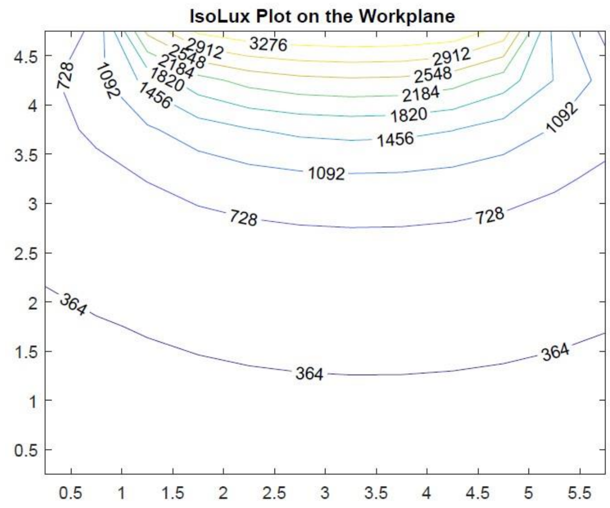
Through DIALux for Clear Sky	Through proposed Model for Sky Type 15 (pure clear sky)
	 Eavg = 573 Lux U_O = 0.3226

Figure 4.7: Iso Lux Plot for North facing window at 8 am on 21st March at Kolkata

4.2.4 Iso Lux Plot for South facing window at 11 am on 21st June at Kolkata

<table>
<tr><th>Through DIALux for Clear Sky</th><th>Through proposed Model for Sky Type 15 (pure clear sky)</th></tr>
<tr><td>


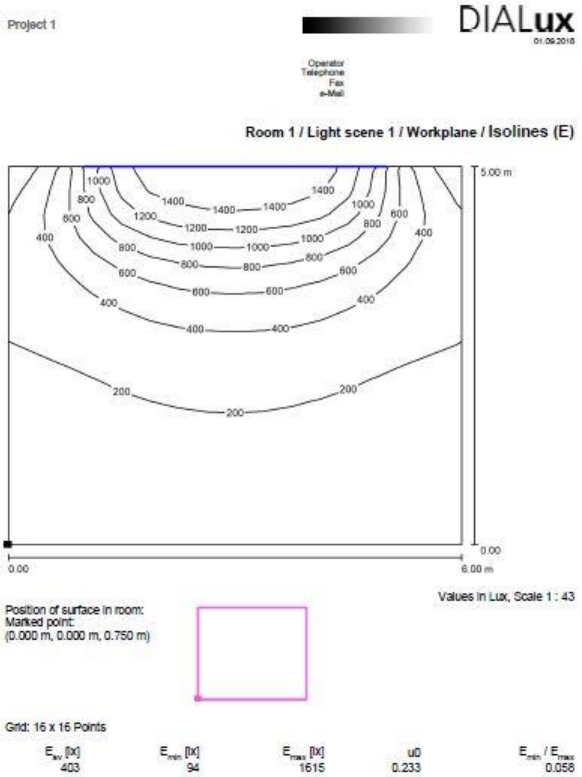
</td><td>


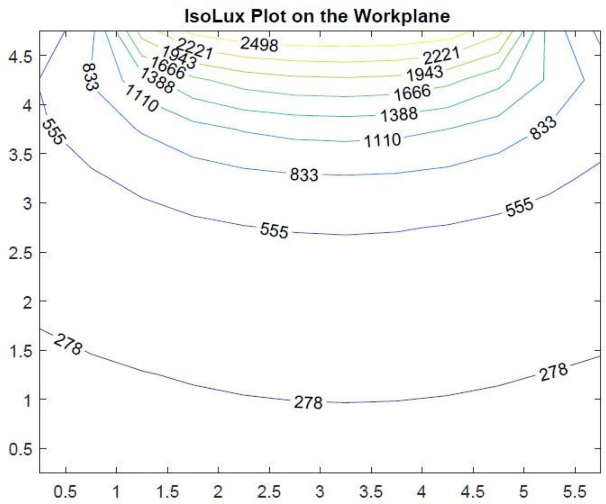
Eavg = 870 Lux

U_O = 0.2883
</td></tr>
</table>

Figure 4.8: Iso Lux Plot for South facing window at 11 am on 21st June at Kolkata

4.2.5 Iso Lux Plot for North facing window at 12 noon on 15th August at Kolkata

<table>
<tr><th>Through DIALux for Clear Sky</th><th>Through proposed Model for Sky Type 15 (pure clear sky)</th></tr>
<tr><td>


</td><td>


Eavg = 685 Lux

U_O = 0.3125
</td></tr>
</table>

Figure 4.9: Iso Lux Plot for North facing window at 12 noon on 15th August at Kolkata

4.2.6 Iso Lux Plot for West facing window at 2 pm on 15th August at Kolkata

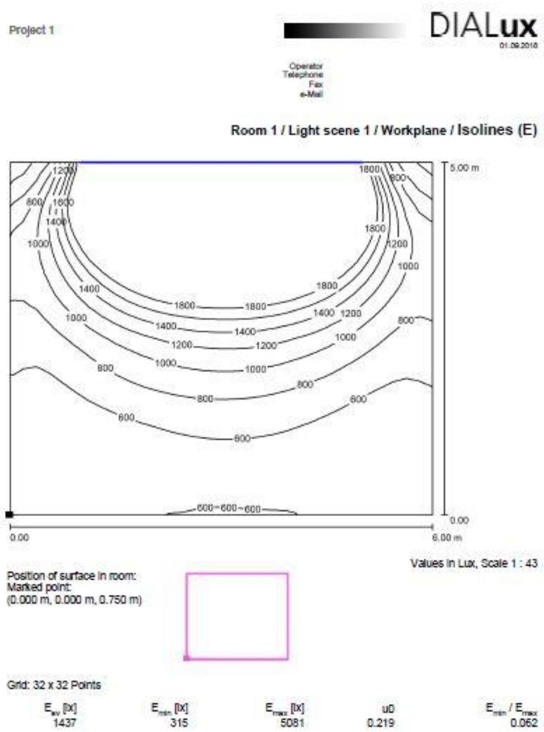
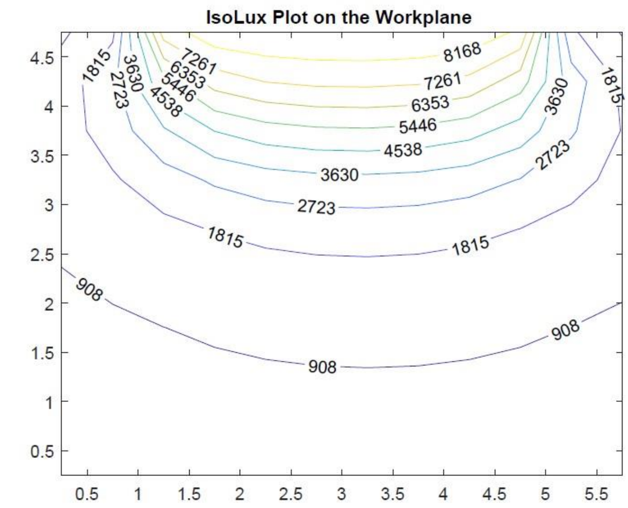
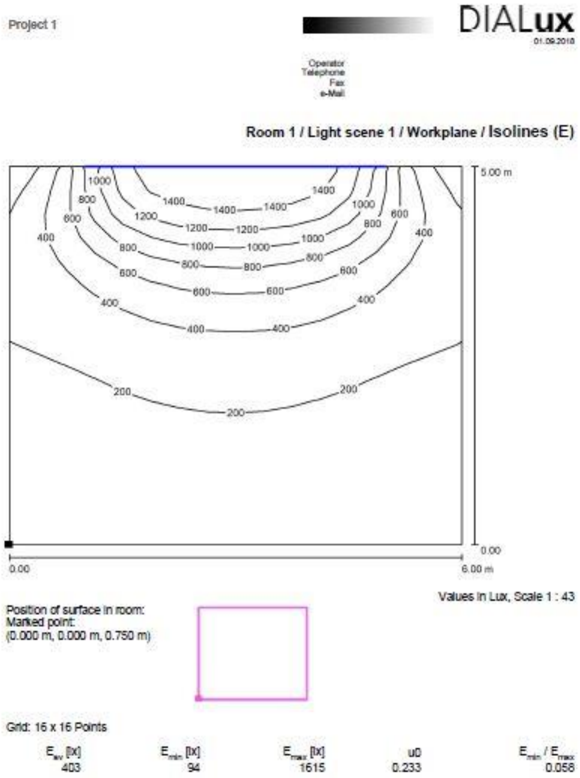
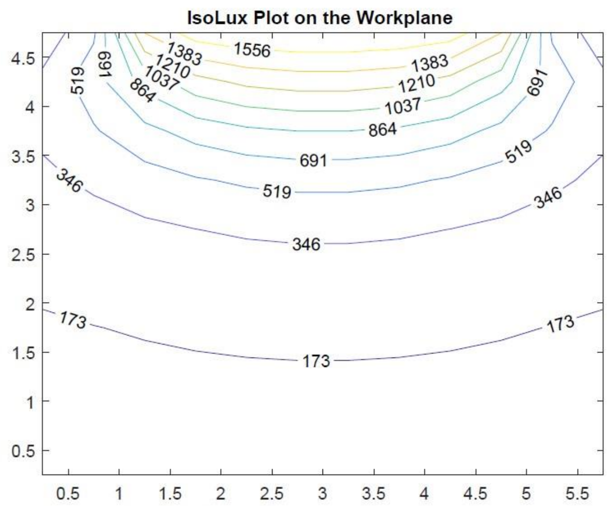
Through DIALux for Mixed Sky	Through proposed Model for Sky Type 8 (Intermediate sky)
	 Eavg = 2369 Lux U_O = 0.2213

Figure 4.10: Iso Lux Plot for West facing window at 2 pm on 15th August at Kolkata

4.2.7 Iso Lux Plot for East facing window at 12 noon on 26th January at Kolkata

<table>
<tr><th>Through DIALux for Overcast Sky</th><th>Through proposed Model for Sky Type 2 (Overcast Sky)</th></tr>
<tr><td>


</td><td>


Eavg = 435 Lux

U_O = 0.2506
</td></tr>
</table>

Figure 4.11: Iso Lux Plot for East facing window at 12 noon on 26th January at Kolkata

4.2.8 Result Analysis

- Light Distribution Pattern i.e. Iso Lux plot matches to a satisfactorily good extent with that of DIALux output.
- The difference in Overall Uniformity U_O with that of DIALux output is within acceptable limit in almost all of the above seven cases.
- But, illuminance value and hence Average illuminance on the work plane Eavg in Lux varies considerably from that of DIALux result, which is based on Perez's model for all weather condition.

4.3 Variation of Daylight distribution for different sky condition and different window orientation throughout the day on different dates at Kolkata

Both the parameters Average Illuminance Eavg and Overall Uniformity U_O are computed at the interval of 1 hour starting from 7 am up to 5 pm at Kolkata for four calendar days –

(a) 21st March (Spring Equinox),

(b) 21st June (Summer Solstice),

(c) 23rd September (Autumn Equinox) and

(d) 22nd December (Winter Solstice).

Different Window Orientations are considered.

(a) North Facing Window ($\theta = 0°$)

(b) East Facing Window ($\theta = 90°$)

(c) South Facing Window ($\theta = 180°$)

(d) West Facing Window ($\theta = 270°$)

(e) South-East Facing Window ($\theta = 135°$)

Different sky types are also considered in order to verify the result under different circumstances.

(a) Pure Clear Sky (Sky Type 15)

(b) Overcast Sky (Sky Type 1)

(c) Mixed Sky (Sky Type 8)

Location: Kolkata			Sky Type : Pure Clear Sky 15					
	NORTH FACING WINDOW							
	Average Illuminance				Overall Uniformity			
Time	Eavg21/03	Eavg21/06	Eavg23/09	Eavg22/12	$U_0$21/03	$U_0$21/06	$U_0$23/09	$U_0$22/12
7am	488	1024	478	211	0.3170	0.2478	0.3191	0.3879
8am	574	1060	565	340	0.3226	0.2469	0.3249	0.3991
9am	563	971	557	386	0.3324	0.2536	0.3347	0.4093
10am	520	856	516	393	0.3444	0.2662	0.3466	0.4179
11am	487	919	483	389	0.3562	0.2827	0.3582	0.4239
12noon	484	1081	480	388	0.3585	0.2864	0.3605	0.4249
01pm	511	840	507	392	0.3471	0.2696	0.3493	0.4195
02pm	555	945	549	389	0.3350	0.2558	0.3372	0.4114
03pm	577	1048	569	355	0.3245	0.2477	0.3267	0.4014
04pm	519	1049	510	249	0.3178	0.2468	0.3199	0.3904
05pm	299	826	289		0.3168	0.2557	0.3186	

Table4.1

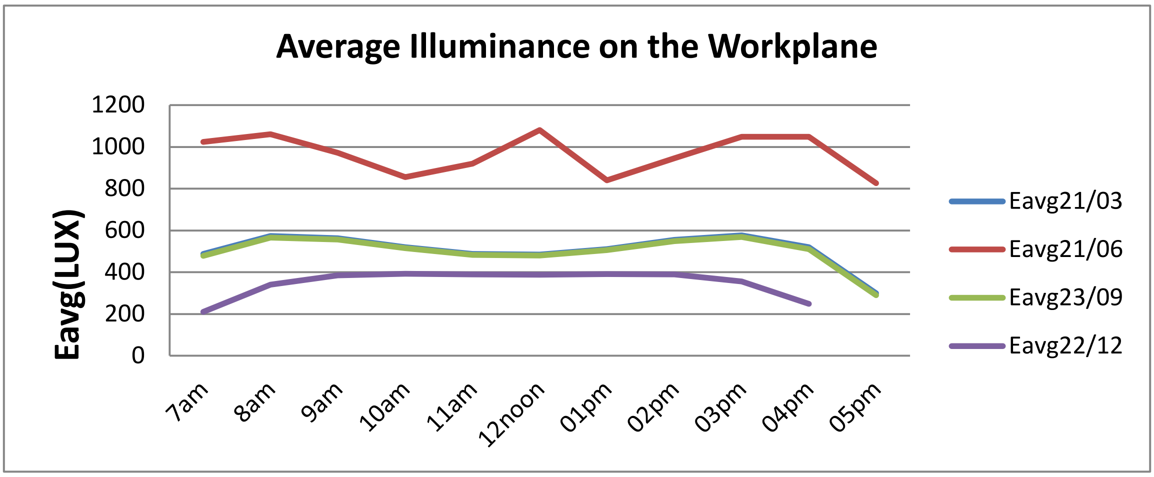


Figure 4.12: Plot showing hourly variation of Eavg for North window and Sky Type 15

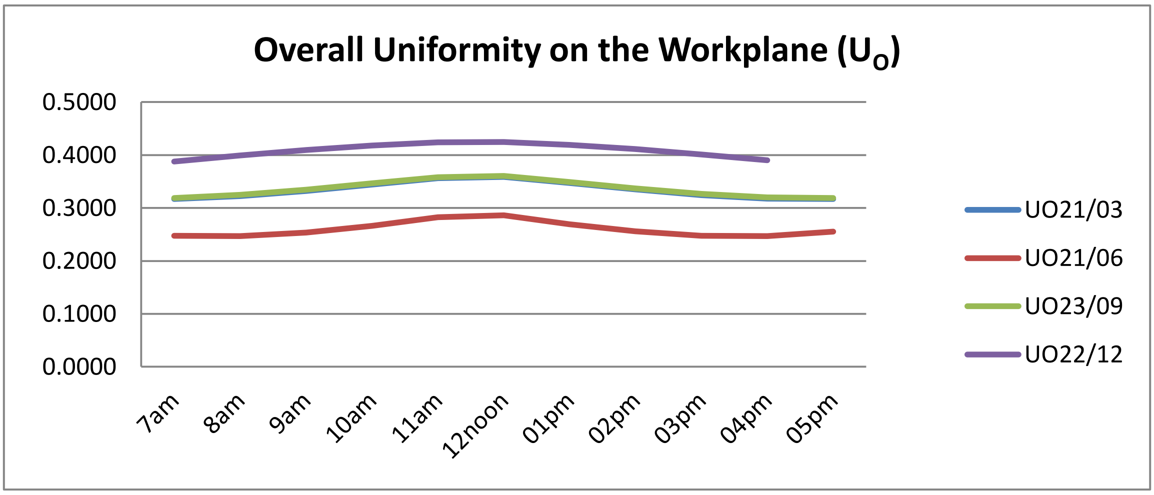


Figure 4.13: Plot showing hourly variation of U_O for North Window and Sky Type 15

Location: Kolkata				Sky Type : Pure Clear Sky 15				
	SOUTH FACING WINDOW							
	Average Illuminance				Overall Uniformity			
Time	Eavg21/03	Eavg21/06	Eavg23/09	Eavg22/12	$U_0$21/03	$U_0$21/06	$U_0$23/09	$U_0$22/12
7am	713	527	717	627	0.2698	0.3289	0.2689	0.2557
8am	1101	663	1114	1358	0.2437	0.3030	0.2429	0.2289
9am	1332	735	1350	1869	0.2323	0.2861	0.2317	0.2158
10am	1381	749	1401	2092	0.2360	0.2812	0.2357	0.2158
11am	1347	870	1366	2143	0.2536	0.2883	0.2535	0.2292
12noon	1342	1032	1361	2145	0.2589	0.2911	0.2589	0.2343
01pm	1375	752	1395	2112	0.2388	0.2818	0.2385	0.2171
02pm	1357	742	1375	1940	0.2318	0.2839	0.2313	0.2146
03pm	1167	685	1181	1495	0.2399	0.2984	0.2392	0.2249
04pm	808	562	814	794	0.2629	0.3228	0.2620	0.2487
05pm	350	377	347		0.2971	0.3511	0.2962	

Table4.2

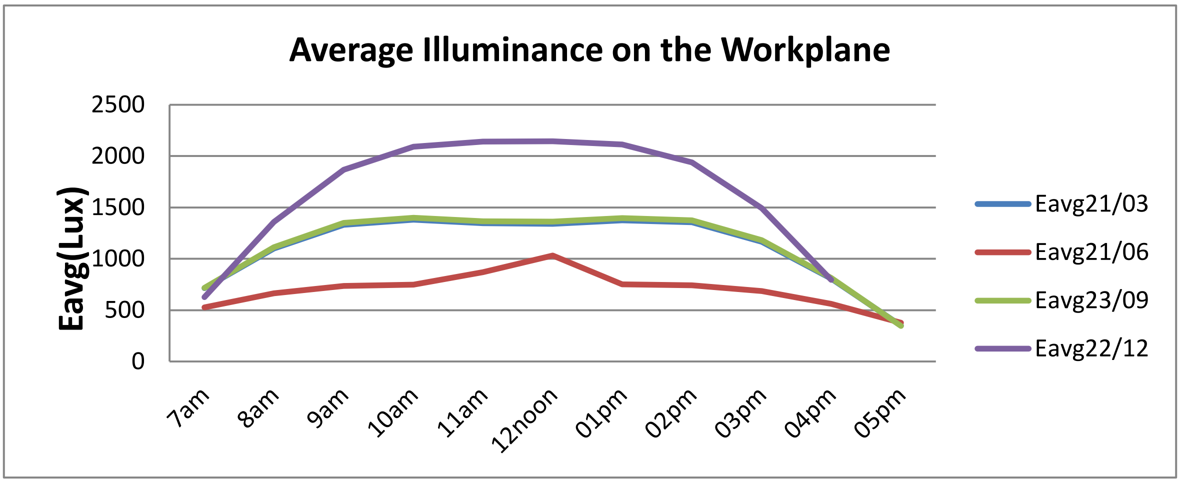


Figure 4.14: Plot showing hourly variation of Eavg for South window and Sky type 15

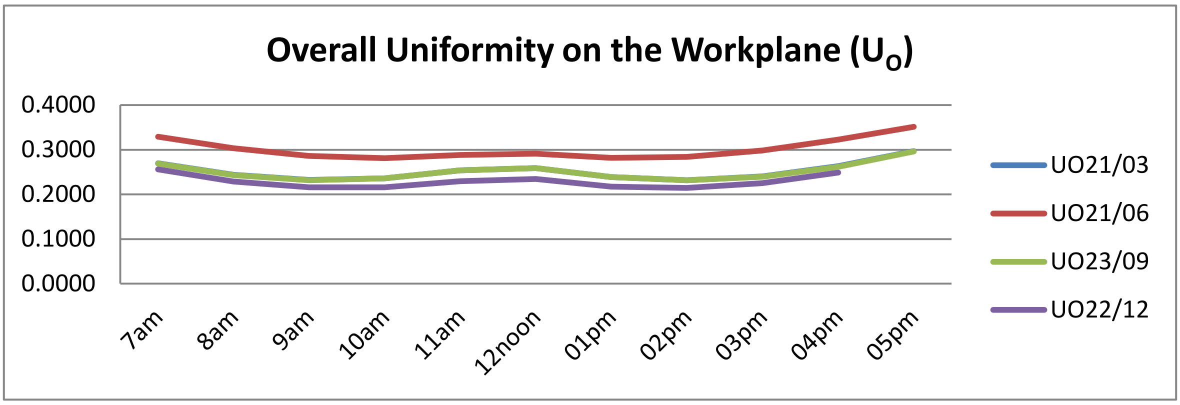


Figure 4.15: Plot showing hourly variation of U_O for south window and Sky type 15

Location: Kolkata Sky Type : Pure Clear Sky 15								
	EAST FACING WINDOW							
	Average Illuminance				Overall Uniformity			
Time	Eavg21 / 03	Eavg21/ 06	Eavg23/ 09	Eavg22/ 12	$U_0$21/ 03	$U_0$21/ 06	$U_0$23/ 09	$U_0$22/ 12
7am	1994	2254	1977	989	0.2235	0.2150	0.2235	0.2377
8am	2292	2207	2287	1685	0.2149	0.2241	0.2145	0.2213
9am	1967	1786	1969	1733	0.2254	0.2633	0.2246	0.2187
10am	1467	1309	1471	1432	0.2376	0.2645	0.2370	0.2300
11am	1018	1090	1021	1048	0.2511	0.2770	0.2507	0.2477
12noon	695	927	696	735	0.2911	0.3071	0.2908	0.2880
01pm	517	514	518	541	0.3448	0.3481	0.3447	0.3393
02pm	426	434	427	423	0.3967	0.3899	0.3967	0.3882
03pm	369	390	368	331	0.4336	0.4233	0.4336	0.4226
04pm	301	345	299	213	0.4479	0.4425	0.4477	0.4347
05pm	169	264	166		0.4433	0.4435	0.4429	

Table 4.3

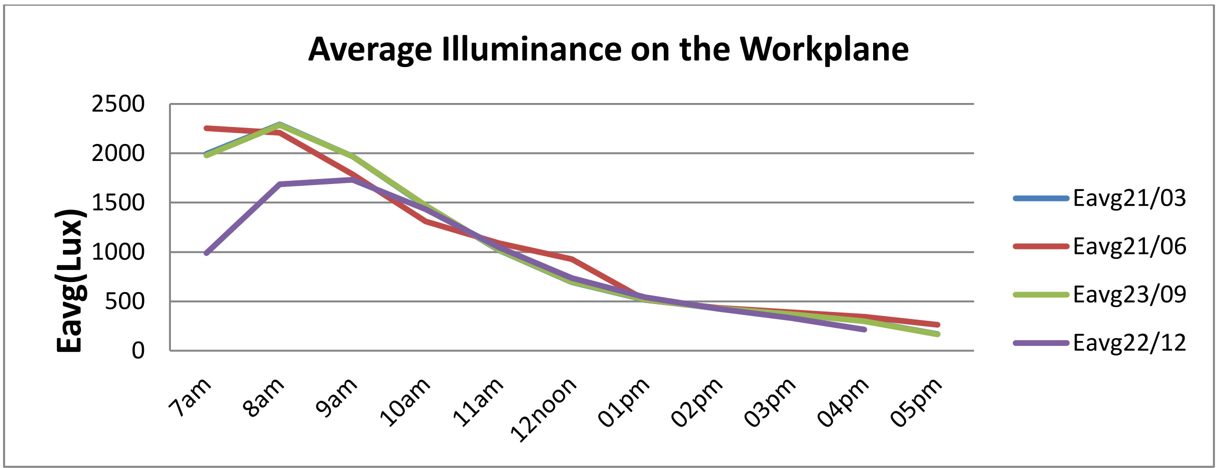


Figure 4.16: Plot showing hourly variation of Eavg for East window and Sky type 15

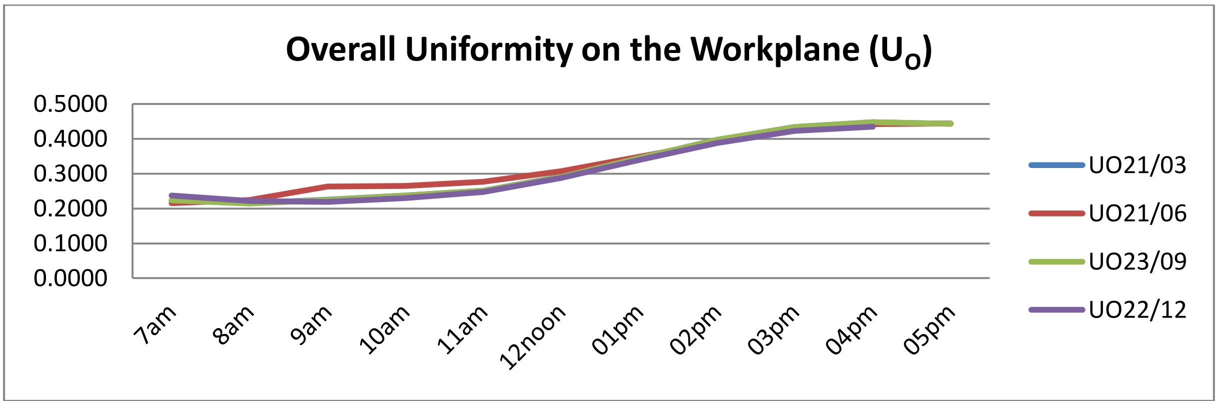


Figure 4.17: Plot showing hourly variation of U_O for East window and Sky Type 15

Location: Kolkata Sky Type : Pure Clear Sky 15								
	WEST FACING WINDOW							
	Average Illuminance				Overall Uniformity			
Time	Eavg21/03	Eavg21/06	Eavg23/09	Eavg22/12	$U_0$21/03	$U_0$21/06	$U_0$23/09	$U_0$22/12
7am	279	332	277	179	0.4481	0.4446	0.4479	0.4334
8am	356	381	356	309	0.4389	0.4288	0.4389	0.4275
9am	413	423	413	403	0.4064	0.3982	0.4064	0.3973
10am	492	489	493	511	0.3569	0.3575	0.3567	0.3507
11am	645	731	646	683	0.3022	0.3155	0.3019	0.2987
12noon	935	1201	937	970	0.2577	0.2822	0.2572	0.2548
01pm	1360	1223	1364	1349	0.2385	0.2658	0.2379	0.2320
02pm	1862	1678	1864	1685	0.2303	0.2655	0.2293	0.2203
03pm	2255	2133	2252	1744	0.2156	0.2298	0.2152	0.2194
04pm	2141	2297	2126	1198	0.2200	0.2148	0.2199	0.2332
05pm	1099	1772	1074		0.2417	0.2239	0.2417	

Table4.4

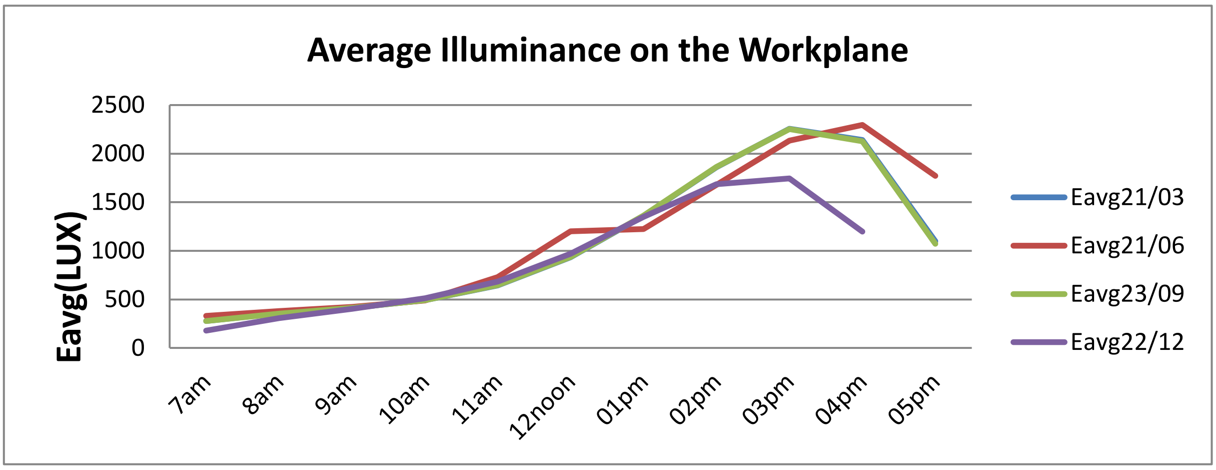


Figure 4.18: Plot showing hourly variation of Eavg for West window and Sky type 15

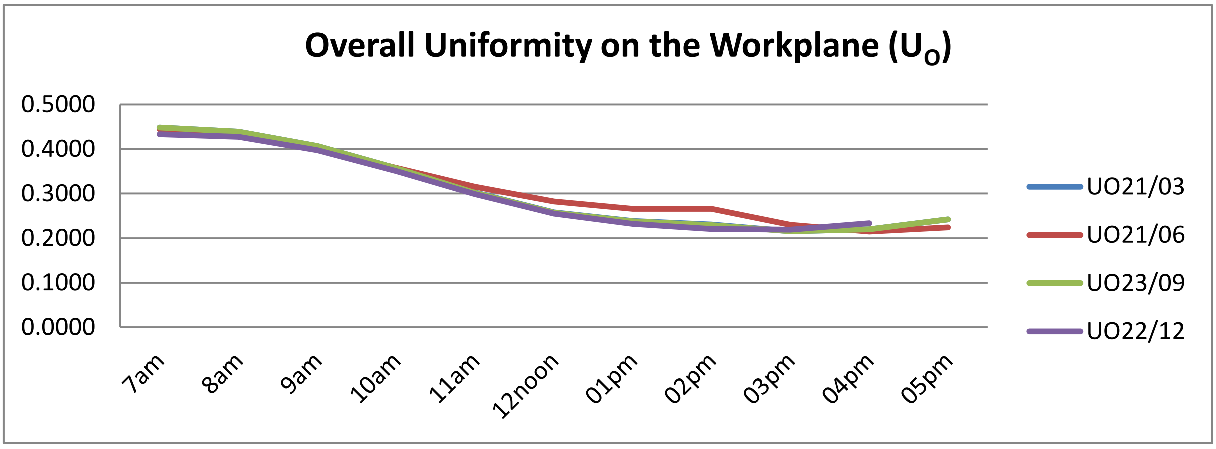


Figure 4.19: Plot showing hourly variation of U_O for West window and Sky Type 15

Location: Kolkata Sky Type : Pure Overcast Sky 1								
	WINDOW FACING ANY DIRECTION							
	Average Illuminance				Overall Uniformity			
Time	Eavg21/03	Eavg21/06	Eavg23/09	Eavg22/12	$U_0$21/03	$U_0$21/06	$U_0$23/09	$U_0$22/12
7am	191	266	189	87	0.2506	0.2506	0.2506	0.2506
8am	315	380	313	201	0.2506	0.2506	0.2506	0.2506
9am	418	474	416	295	0.2506	0.2506	0.2506	0.2506
10am	492	542	490	363	0.2506	0.2506	0.2506	0.2506
11am	532	580	530	400	0.2506	0.2506	0.2506	0.2506
12noon	536	583	534	404	0.2506	0.2506	0.2506	0.2506
01pm	504	553	501	374	0.2506	0.2506	0.2506	0.2506
02pm	437	492	434	313	0.2506	0.2506	0.2506	0.2506
03pm	340	403	337	224	0.2506	0.2506	0.2506	0.2506
04pm	220	293	217	113	0.2506	0.2506	0.2506	0.2506
05pm	84	168	82		0.2506	0.2506	0.2506	

Table 4.5

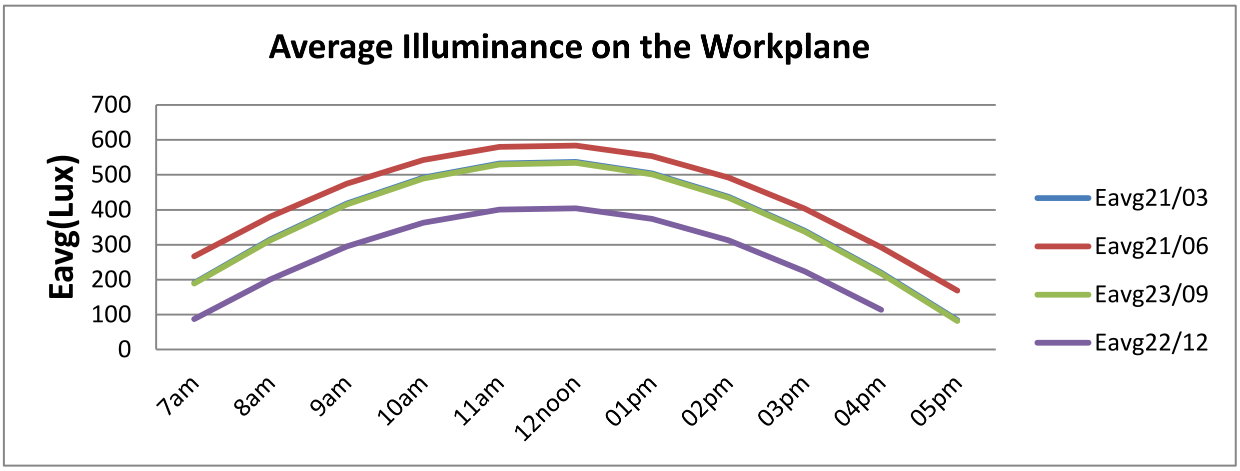


Figure 4.20: Plot showing hourly variation of Eavg for any direction of window & Sky Type 1

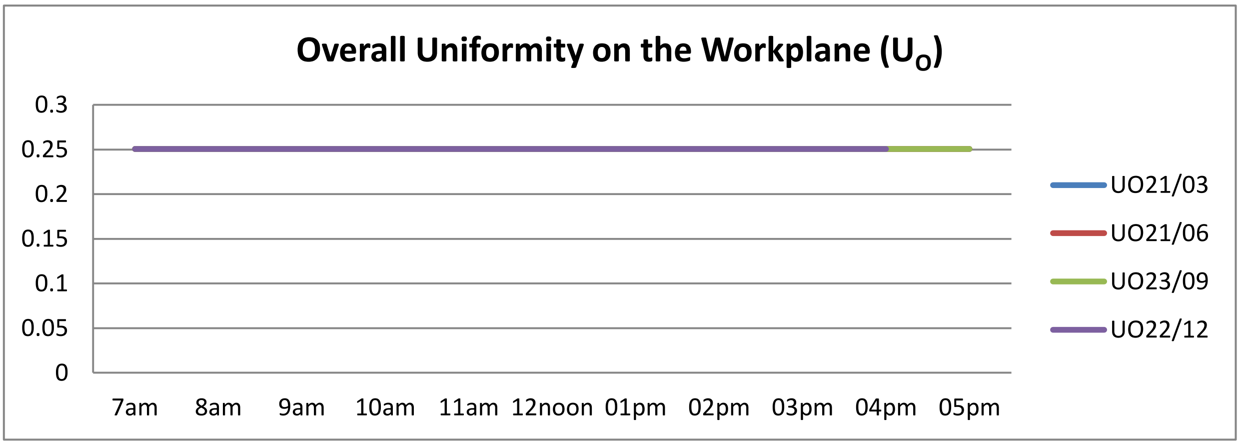


Figure 4.21: Plot showing hourly variation of U_O for any direction of window & Sky Type 1

Location: Kolkata Sky Type : Mixed Sky 8								
	SOUTH EAST FACING WINDOW							
	Average Illuminance				Overall Uniformity			
Time	Eavg21/03	Eavg21/06	Eavg23/09	Eavg22/12	$U_0$21/03	$U_0$21/06	$U_0$23/09	$U_0$22/12
7am	1365	1394	1356	741	0.2296	0.2216	0.2303	0.2805
8am	2113	1836	2111	1630	0.2180	0.2124	0.2187	0.2717
9am	2407	1961	2412	2191	0.2170	0.2129	0.2177	0.2642
10am	2333	1796	2343	2365	0.2233	0.2229	0.2239	0.2247
11am	2063	1677	2077	2263	0.2187	0.2420	0.2182	0.2101
12noon	1745	1594	1757	1971	0.2242	0.2634	0.2235	0.2100
01pm	1398	1093	1406	1554	0.2451	0.2851	0.2442	0.2226
02pm	1092	953	1096	1128	0.2753	0.3089	0.2744	0.2469
03pm	851	827	850	765	0.3034	0.3231	0.3026	0.2747
04pm	618	692	615	419	0.3109	0.3257	0.3106	0.2963
05pm	308	495	301		0.3045	0.3206	0.3042	

Table4.6

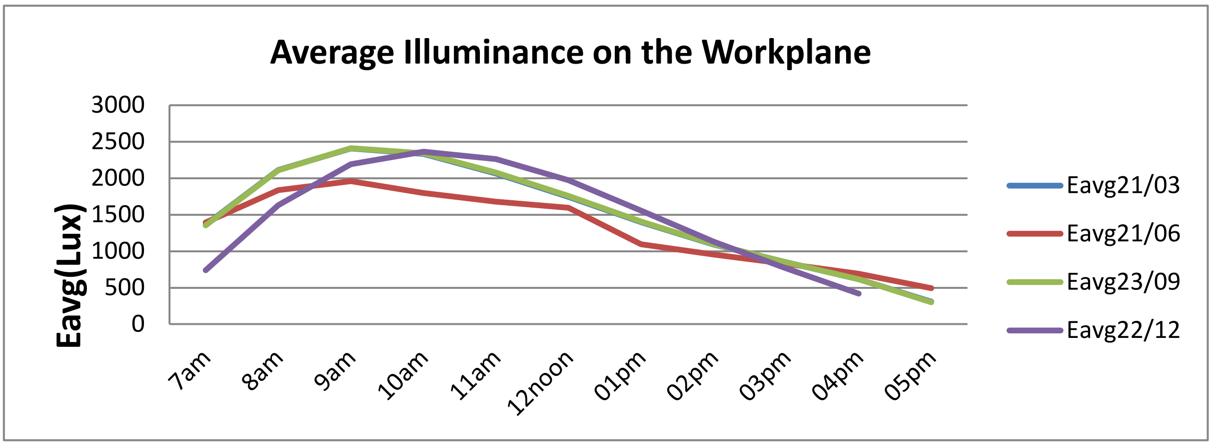


Figure 4.22: Plot showing hourly variation of Eavg for South-East window & Sky Type 8

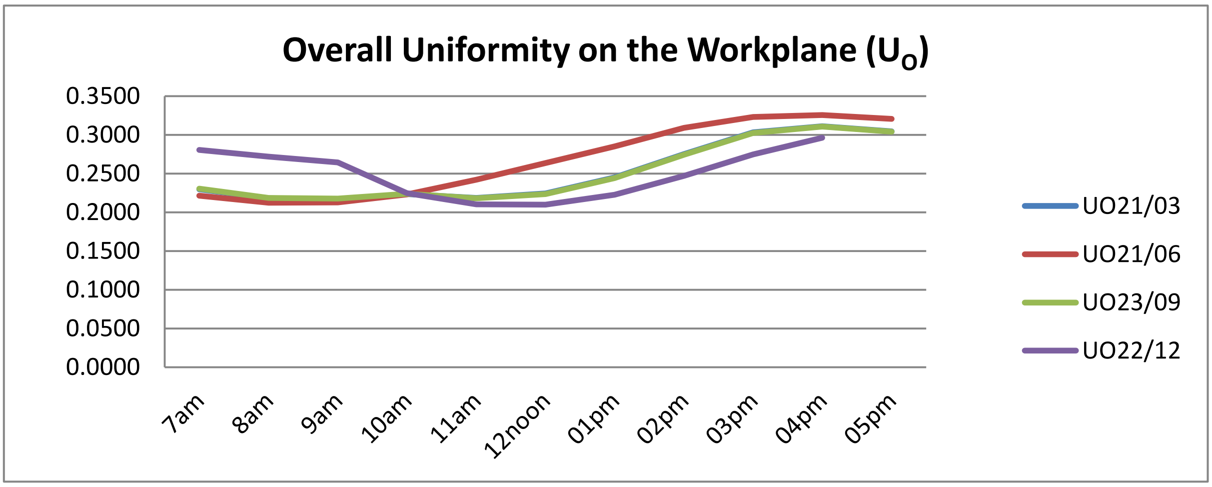


Figure 4.23: Plot showing hourly variation of U_O for South-East window & Sky Type 8

4.3.7 Result Analysis

- In all of the Figures from 4.12 to 4.23, the plots showing both Eavg (Lux) and U_O for two equinox dates (21st March and 23rd September) coincide with each other which clearly indicates about the almost identical daylight distribution on these two dates.
- No real value is available for Eavg and U_O from the proposed model (MATLAB program) at 5 pm on 22nd December (As shown in Tables 4.1 to 4.6 and Figures 4.12 to 4.23). The Sunset time on this date at Kolkata is earlier than 5 pm (4:57 pm in 2019), which logically supports the output result.
- Table 4.1 and Figure 4.12 show that for North facing window and for purely clear sky Eavg is the highest on Summer solstice (21st June) and the lowest on Winter solstice (22nd December) throughout the day.
- Table 4.2 and Figure 4.14 show that for South facing window and for purely clear sky Eavg is the highest on Winter solstice and the lowest on Summer solstice throughout the day.
- Figure 4.12 and 4.14 show for the clear sky, Eavg is the highest during noon period of the day and quite low in the morning and afternoon period of the day.
- Table 4.3 and Figure 4.16 show for East facing window and pure clear sky, Eavg has high value during morning period and quite low value in the afternoon session.
- Table 4.4 and Figure 4.18 show for West facing window and pure clear sky, Eavg has low value during morning period and quite high value in the afternoon session.
- Table 4.5 and Figure 4.20 indicate that for purely overcast sky, Eavg is the highest on summer solstice and the lowest on winter solstice throughout the day.
- Table 4.5 and Figure 4.20 also show that Eavg for all of the dates in case of overcast sky gradually increases from lower value at morning to its peak value during the 12 noon and then again gradually decreases to the lower value at afternoon period of the day and this dynamic nature of Eavg is true for all the dates.
- Table 4.5 and Figure 4.21 also show that uniformity U_O is completely independent of date and time for purely overcast sky and hence throughput the day and for all of the dates the value of U_O is unaltered.

- Table 4.6 and Figure 4.22 show that for mixed sky (sky type 8) Eavg for all dates increases from morning and attains its highest value within 9 am to 11 am and then goes on decreasing gradually.
- Table 4.6 and Figure 4.22 also indicate that from 7 am to 10 am Eavg is higher on equinox dates than other days and from 11 am to 3 pm it is higher on 22nd December. Finally, from 3 pm to 5 pm Eavg attains comparatively higher value on 21st June.

Almost all of the above observations are quite equipoise to the physical perception about daylight distribution.

4.4 Variation of Daylight distribution for particular window orientation and particular Sky type on particular date but for different location.

Now, Average Illuminance Eavg and U_O are computed for South facing window and pure Clear Sky (type 15) for four different Metro Cities of India on a particular date 15th August. The names, geographical location of the cities and Sunrise and Sunset Time on 15th August of them are as follows –

Name	Latitude	Longitude	Sunrise time	Sunset Time
New Delhi	28.61°N	77.21°E	5:50 am	7:01pm
Mumbai	19.07°N	72.88°E	6:19 am	7:07 pm
Kolkata	22.57°N	88.36°E	5:13 am	6:09 pm
Chennai	13.08°N	80.27°E	5:57 am	6:30 pm

Table 4.7: Latitude, Longitude, Sunrise and Sunset time of Four Metro Cities

The output result data (Eavg and U_O) and graphical presentation has been produced the following table and plots.

Location: Four Metro Cities Date : 15th August Sky Type : Pure Clear Sky 15								
	SOUTH FACING WINDOW							
	Average Illuminance				Overall Uniformity			
Time	**New Delhi**	**Mumbai**	**Kolkata**	**Chennai**	**New Delhi**	**Mumbai**	**Kolkata**	**Chennai**
7am	423	287	602	404	0.3193	0.3365	0.3009	0.3285
8am	715	571	817	628	0.2838	0.3069	0.2733	0.3040
9am	952	769	940	748	0.2567	0.2809	0.2570	0.2856
10am	1089	872	964	777	0.2441	0.2651	0.2550	0.2774
11am	1110	886	1004	770	0.2475	0.2623	0.2669	0.2810
12noon	1120	952	1040	1677	0.2640	0.2727	0.2706	0.2938
01pm	1113	1060	963	797	0.2583	0.2773	0.2565	0.2841
02pm	1112	885	953	773	0.2449	0.2640	0.2553	0.2772
03pm	1062	883	853	765	0.2462	0.2629	0.2686	0.2820
04pm	890	808	656	674	0.2633	0.2752	0.2942	0.2976
05pm	633	636	382	482	0.2938	0.2988	0.3262	0.3209

Table4.8

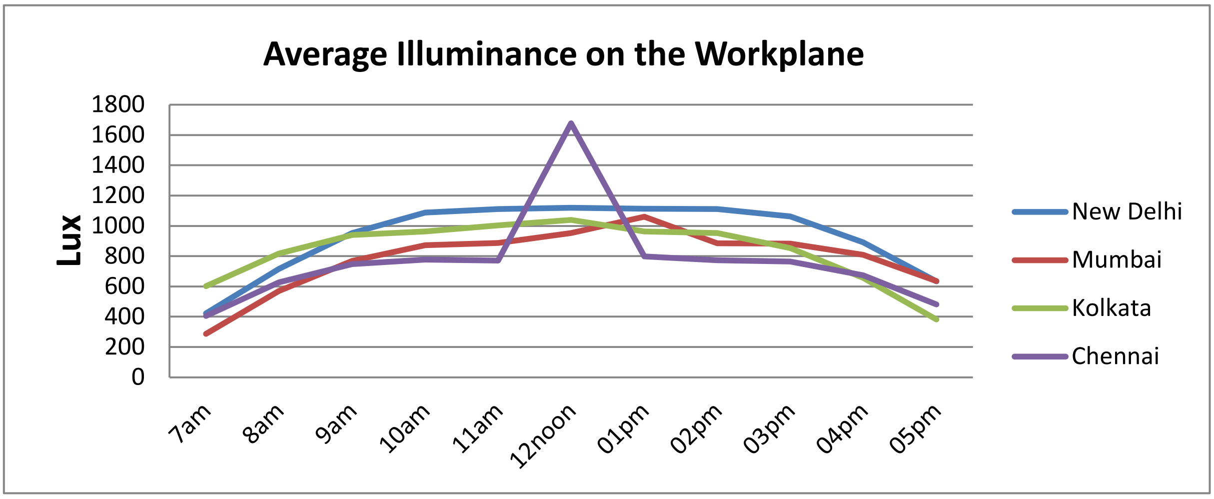


Figure 4.24: Plot showing hourly variation of Eavg for four Metro Cities

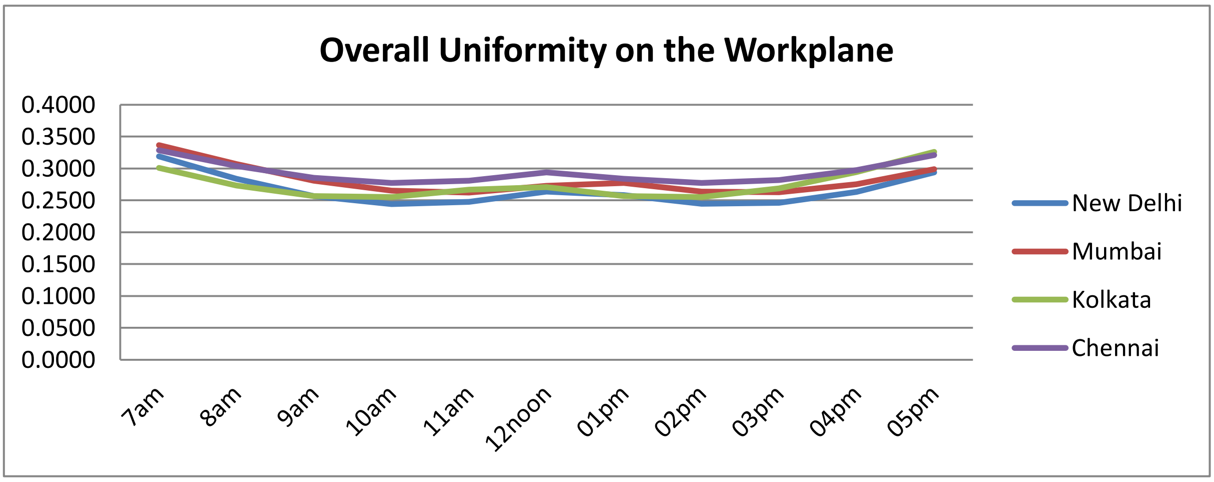


Figure 4.25 Plot showing hourly variation of U_O for four Metro Cities

4.4.2 Result Analysis

- In all four cities Eavg increases from lower value and gradually reaches its peak value at noon and finally goes on decreasing up to the evening period.
- Latitude of Chennai is much lower i.e. it is closer to the Equator than other three cities. The result shows that Eavg at Chennai is much higher at 12 noon than other three cities.
- Sunrise time of Kolkata is much earlier than other three cities and the result also indicates that Eavg is much higher in the morning section at Kolkata than other cities.
- Sunset time of Kolakta is much earlier and the result also confirms that showing the lowest Evening (5pm) Eavg value at this city.
- Sunset time of New Delhi and Mumbai are quite later (even after 7 pm) than other two cities. The result also shows that at 5 pm the value of Eavg is much higher at Mumbai and the New Delhi than Chennai and Kolkata.

Therefore, the outcomes of this section are also quite compatible with the general ideas about daylight nature.

4.5 Comparison of Hourly Daylight Variation obtained from proposed Model with DIALux output

The Average Illuminance Eavg and Overall Uniformity are computed for North facing window and pure Clear Sky (type 15) at Kolkata on four dates – Summer Solstice (21st June), Equinox dates (21st March and 23rd September) and Winter Solstice (22nd December) by DIALux lighting design software. The result is compared with the output under the identical condition obtained from the proposed daylight prediction model computed in the MATLAB environment.

4.5.1 Result from DIALux

Location: Kolkata Sky Type : Pure Clear Sky 15								
	NORTH FACING WINDOW							
	Average Illuminance				Overall Uniformity			
Time	Eavg21/03	Eavg21/06	Eavg23/09	Eavg22/12	$U_0$21/03	$U_0$21/06	$U_0$23/09	$U_0$22/12
7am	298	495	318	181	0.3470	0.2600	0.3430	0.3670
8am	348	507	353	262	0.3210	0.2650	0.3190	0.3760
9am	351	481	349	295	0.3190	0.2570	0.3200	0.3510
10am	339	454	337	303	0.3290	0.2740	0.3330	0.3520
11am	332	441	332	304	0.3530	0.3230	0.3620	0.3610
12noon	335	450	338	304	0.3450	0.2830	0.3390	0.3660
01pm	346	474	350	302	0.3290	0.2620	0.3260	0.3570
02pm	353	503	353	286	0.3250	0.2530	0.3250	0.3810
03pm	329	505	316	236	0.3480	0.2640	0.3490	0.3820
04pm	239	430	206	131	0.3390	0.2630	0.3420	0.3760
05pm	71	242			0.3530	0.2730		

Table 4.9

4.5.2 Graphical Presentation

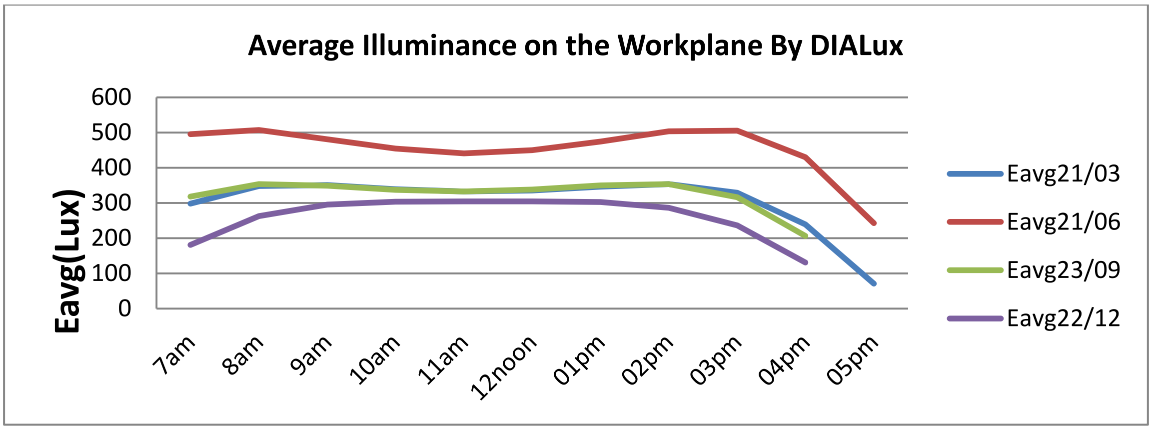


Figure 4.26: Plot showing hourly variation of Eavg derived from DIALux software

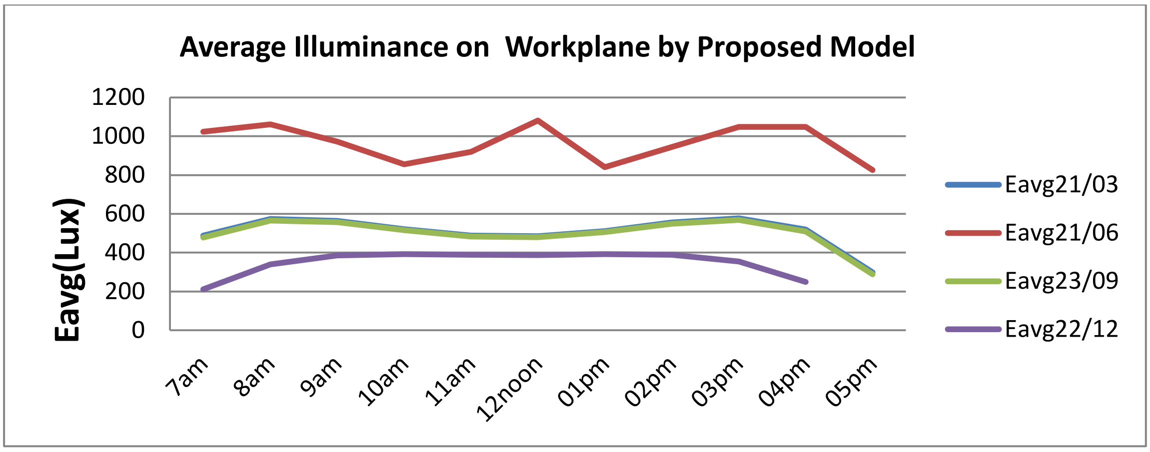


Figure 4.27: Plot showing hourly variation of Eavg derived from proposed model

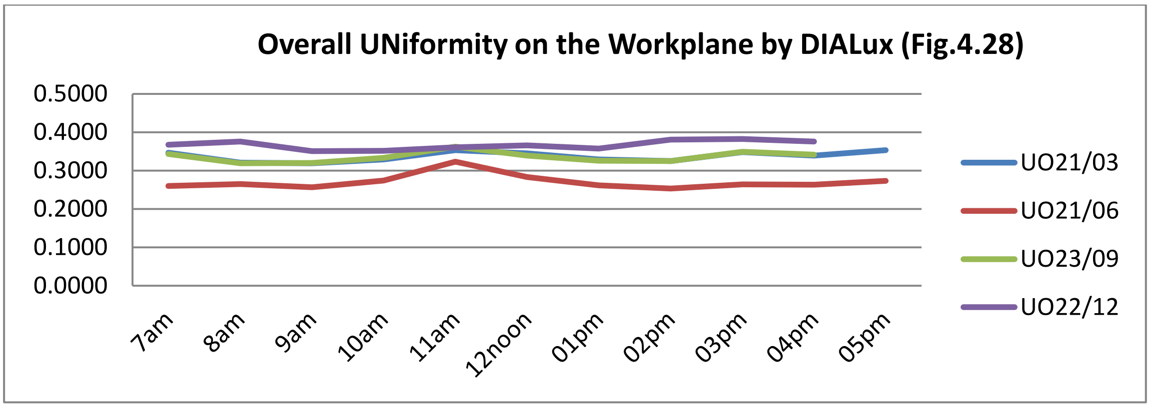


Figure 4.28: Plot showing hourly variation of U_O derived from DIALux software

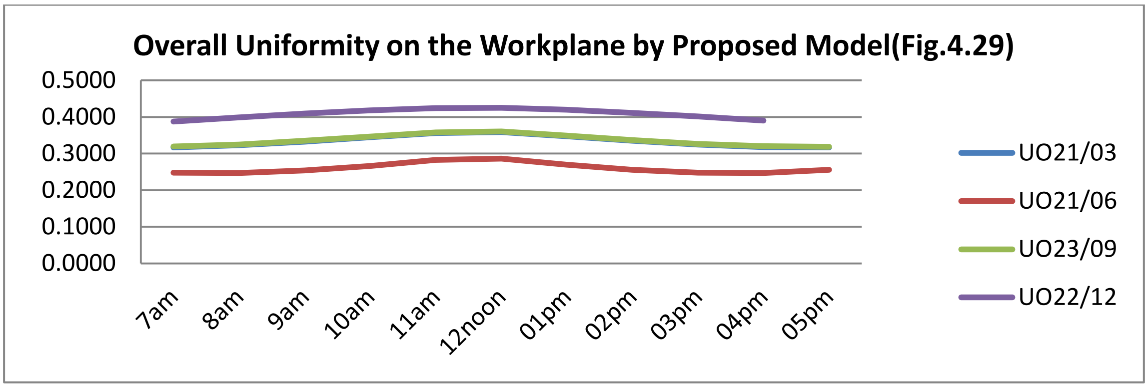


Figure 4.29: Plot showing hourly variation of U_O derived from proposed model

4.5.3 Result Analysis

- The variation of uniformity throughout the day, both in nature and absolute value are almost identical in both of the cases – DIALux software and proposed model.
- The variation of Eavg is also of the same nature in both cases except at 12 noon.
- The absolute value of Eavg, obtained from proposed tool is quite high in comparison to the DIALux output. This is because of higher sky luminance value computed by the proposed model in comparision to DIALux value based on Perez's model for all weather condition.

Chapter – 5

Application of the Proposed Model to Window Design

Although the proposed daylight prediction model developed in this project, needs further introspection and necessary improvement based on verification with real time data, still it can be concluded that outcome of the tool shows reliability to a good extent. Therefore, an optimistic and sincere effort is taken to utilise the model in the field of building architecture, more specifically in designing an energy efficient window. For the purpose of designing, the National Building Code'2016 of India has been followed.

5.1 Relevant Recommendations from National Building Code'2016

The following features regarding the good practice of window designing are noted from the various part and sections of both volume 1 and volume 2 of the National Building Code'2016 of our country (India). [15]

1. **Vol.1, part 6, section 8, page no. 29**
   6.1.2: design Considerations –
   (a) Maximum area of glass panel is restricted to 15 m^2.
   (b) Maximum span of window (window length) is restricted to 4m.
   (c) Aspect ratio (window Length / Window Height) of the glass panel should be greater than 1.5.

2**. Vol.1, part 6, section 8, page nos. 53, 54: table 30**

H_s correspond to sill height and for glass window $H_s \geq 0.75$ m.

3. Vol.1 part 6, section 8, page no. 62

The Window wall Ratio (WWR) which is the ratio of Window Area to Window Wall Area is limited to 70 %.

4. Vol.2, part 8 section 1, page no.28

Unilateral lighting side opening will be, in general, unsatisfactory, if the effective width is more than 2 to 1.5 times the distance from the floor to the top of the opening. (4.2.8.4)

Opening on two opposite sides will give greater uniformity of internal daylight illumination (4.2.8.5)

Cross lighting with openings on adjacent walls tends to increase the diffused lighting within a room. (4.2.8.6)

5. Vol.2, part 8, section 1, page no. 31

The obstructions at a distance of 3 times their height or more from a window facade are not significant and the window may be regarded as unobstructed window. (4.4.3)

6. Vol.2, part 8, section 1, page no. 33

In office building window height should be more than or equal to 1.2 m. and sill height ranges from 1.0 m to 1.2 m. above floor i.e. $WH \geq 1.2$ m. and 1.0 m. $\leq SH \leq$ 1.2 m.

In residential building window height should vary from 1.0 m. to 1.1 m. with sill height ranging from 0.7 m. to 0.9 m.

If the room depth (width W) is more than 10 m. windows on opposite walls are recommended.

6. Vol.2, part 8, section 1, page no. 41

For critical air movement sill height should be at 85 % of the critical height (such as head level).

Sill height for occupants sitting on the chair should be 0.75 m. (4.4.8)

6. Vol.2, part 8, section 1, page no. 43

In case of industrial building, window height should be about 1.6 m. and width about two-third of wall width. Sill height should be at 1.1 m. above the floor.

5.2 <u>Case Study 2: Window Optimisation with Two variables</u>

A sample model room with the following dimension along with a single window having following specification and other physical conditions are considered for the purpose of optimizing the window dimensions to ensure energy efficient building design.

Room Dimension

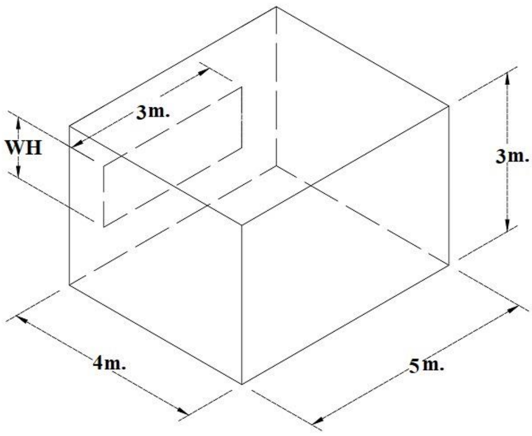
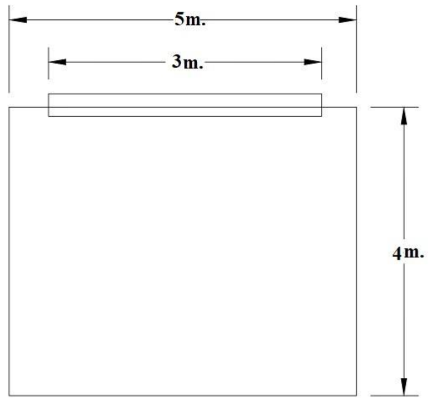


Figure 5.1: Diagram illustrating the Room Dimension

Length L = 5 m. Width W = 4 m. and Height H = 3 m.

Window Dimension



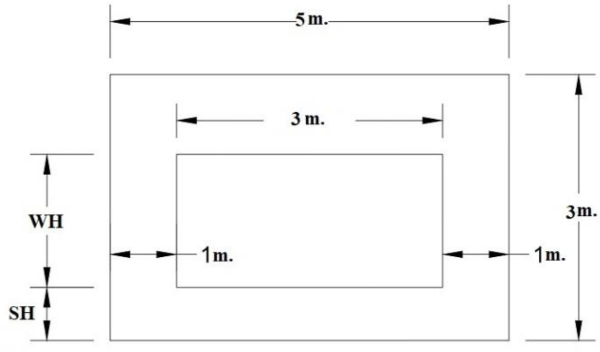


Figure 5.2: Plan View *Figure 5.3: Window Wall Elevation*

Window span = 3 m. and Window Wall Area = 5x3 = 15m^2

The design computation is carried out for different combination of Window Wall Ratio (WWR) and Sill Height (SH) or in other words **optimizing variables are WWR and SH.**

Window Wall Ratio (WWR) varies from 0.24 (24%) to 0.30 (30%) in step of 0.01 (7 possible combinations)

Therefore, Minimum Window Area = 0.24 x 15 = 3.6 m^2 and Maximum Window Area = 0.30 x 15 = 4.50 m^2

Window Length WL = L – (2x1) = 3m.

So, Minimum Window Height = 3.6 / 3 = 1. 2 m. and Maximum Window Height = 4.50 / 3 = 1.50 m.

Aspect Ratio AR = Window Length / Window Height = WL / WH

Therefore, Minimum AR = 3 / 1.2 = 2.5 and Maximum AR = 3 / 1.5 = 2.0

Sill Height SH (in m.) varies from 0.80 to 1.20 in step of 0.05 (9 possible combinations).

All the values (WWR, SH, AR etc.) of the abovementioned parameters are within the range recommended in National Building Code’2016.

Grid Formation of the Work plane

In all 4 sides of the room 1m is eliminated i.e. not utilised in actual work plane for the visual task.

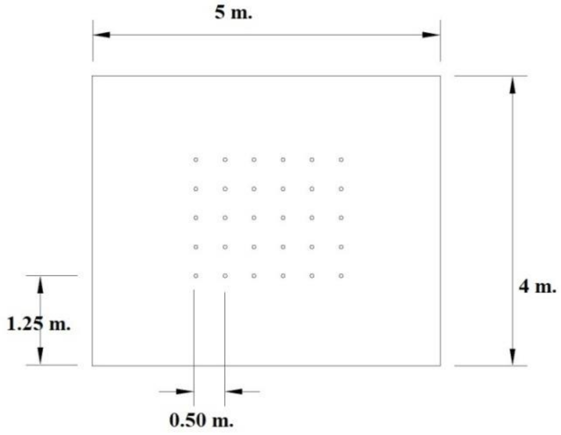


Fig. 5.4: Diagram illustrating the grid points on Work Plane.

Total no of grid points are 6x4 = 24

Design Considerations

a. Date: 15th August (Julian Day no. n = 227)
b. time: 07 am (x = 7) to 5 pm (x=17) at the interval of 1 hour.
c. Location: Kolkata (latitude i.e. Φ = 22.5° and longitude i.e. λ = 88.36°)
d. Pure clear sky (Sky Type =15)
e. Window Orientation: South Facing (θ = 180°)

Other Design Considerations

- Work Plane Height WPH = 0.75 m.
- Transmittance of Window Glazing Material τ = 0.5 i.e. 50 %
- Maintenance Factor MF = 0.75 i.e. 75 %
- Average Outdoor Ground Surface Reflectance ρ_{Gavg} = 0.2 i.e. 20 %
- Average Room Floor Reflectance ρ_F = 0.2 (20%)
- Average Room Wall Reflectance ρ_W = 0.5 (50%)
- Average Room Ceiling Reflectance ρ_C = 0.8 (80%)

Optimizing Design Variables or Decision Variables

1. Window Wall Ratio (WWR)
2. Sill Height of Window (SH)

Design Output

- Optimized window dimensions –
- Average Illuminance on work plane (Eavg) at optimized condition.
- Overall Uniformity (U_O) at optimized condition.
- Value of Minimized Objective Function (F) at optimized condition.

5.2.1 Window Optimisation

Grid Search Optimisation technique is applied in MATLAB Environment to maximise the combination of two output design parameters - Average illuminance (Eavg) and Overall Uniformity (U_O) to get the optimized dimensions – Window Wall ratio (WWR) and Sill Height (SH) from total (7 x 9) or 63 different combinations of input variables.

Grid Search Method [16]

- Methodology involves setting up grids in the decision space.
- Objective function values are evaluated at the grid points.
- The point corresponding to the best objective function value considered as optimum solution.
- Major Drawback: number of grid points increases exponentially with the number of decision variables.

Optimisation Protocol

Optimized dimensions are derived to achieve the best result i.e. highest combination of Eavg and U_O, ensuring Eavg is not more than 3000 Lux but not less than 500 Lux and U_O is not less than 0.2. Eavg more than 3000 Lux may create visual discomfort and less than 500 lux is not sufficient for visual task in an office building. For proper indoor design U_O should be more than 0.5, but it is hard to achieve the value with single window. So, minimum value of U_O is considered here as 0.2. Therefore, the necessary conditions are as follows.

i. Maximisation of Eavg and U_O
ii. Elimination of the case when Eavg > 3000 Lux
iii. Elimination of the case when Eavg < 500 Lux
iv. Elimination of the case when U < 0.2

$F_1(x)$ = Eavg , $F_2(x)$ = Overall Uniformity U_O

Penalty Factor 1 for condition (ii), $PF_1 = 100$

Penalty Factor 1 for condition (iii), $PF_2 = 100$

Penalty Factor 1 for condition (iii), $PF_3 = 100$

The objective function F is developed as –

$$Minimise\ F = \frac{1}{F_1(\mathrm{x})} + \frac{1}{F_2(\mathrm{x})} + PF_1 + PF_2 + PF_3$$

The initial value of F is taken as 100.This Function is to be minimised by using grid search optimisation technique to fulfil the conditions and hence we get the optimized window dimensions (WWR and SH).

5.2.2. Dynamic Window

Since, the daylight varies over a wide range with date and time, the optimized window dimension is expected to vary with date and time, even for a fixed location and fixed window direction. But, window in general, is a static device. Therefore, it is essential to introduce a dynamic nature in window in order to achieve the best energy efficient design. For this purpose, an automatically movable opaque screen i.e. motorised shading device should be placed on the window opening or the window glass panel.

SH varies from 0.8 m. to 1.2 m. and WH varies from 1.2 m. to 1.5 m.

Floor clearance (FC) = Sill Height (SH)

Ceiling Clearance (CC) = Room Height – (Window Height + Sill Height)

= H – (WH + SH)

Therefore, FC varies from 0.8 m to 1.2 m. in the steps of 0.05m.

Minimum value of CC = H – (WHmax + SHmax)

= 3 – (1.2 +1.5) = 0.3 m. i.e. 30 cm.

Maximum value of CC = H – (WHmin + SHmin)

= 3 – (0.8 + 1.2) = 1.0 m. i.e. 100 cm.

Therefore, CC varies from 0.3 m. to 1.0 m.

The best suitable dimension of the window is selected from the result derived from the proposed model for different time throughout the daytime on 15th August at Kolkata with South facing window for Pure Clear Sky (Sky Type 15).

The following table (Table 5.3) shows the hourly variation of required optimum dimension (SH, WWR, WH, FC, CC etc.) along with the relevant design outputs (Eavg, U_O) and Minimised objective function value F on **15th August at Kolkata with South facing window for Pure Clear Sky (Sky Type 15).**

Date: 15th August	Optimizing Design Variables or Decision Variables					Design Outputs		
TIME	**SH (m.)**	**WWR**	**WH (m.)**	**FC (m.)**	**CC (m.)**	**Eavg (Lux)**	**U_O**	**Minimised F**
7 am	0.90	0.30	1.50	0.90	0.60	545	0.2800	3.5732
8 am	1.15	0.30	1.50	1.15	0.35	528	0.2904	3.4456
9 am	1.20	0.30	1.50	1.20	0.30	657	0.2642	3.7861
10 am	0.80	0.24	1.20	0.80	1.00	1094	0.2333	4.2881
11 am	0.80	0.25	1.25	0.80	0.95	1244	0.2580	3.7511
12 noon	0.80	0.30	1.50	0.80	0.70	1608	0.3306	3.0250
01 pm	0.90	0.30	1.50	0.90	0.60	1523	0.4250	2.3536
02 pm	0.95	0.30	1.50	0.95	0.55	1457	0.4792	2.0875
03 pm	0.95	0.30	1.50	0.95	0.55	1220	0.4999	2.0012
04 pm	0.90	0.30	1.50	0.90	0.60	940	0.5117	1.9553
05 pm	0.85	0.30	1.50	0.85	0.65	564	0.5350	1.8710

Table 5.3: Hourly variation of optimum Design Variables and design output at optimized condition for Case Study 2

A motorised shading device (opaque screen) on the glass panel of the window can be developed, which will move to adjust Floor Clearance (FC) and Ceiling Clearance (CC) automatically as per the control signal derived from the proposed daylight prediction tool. The concept and mechanism of this kind of dynamic window is capable to ensure the best energy efficient design especially with respect of daylight utilisation in the field of Building Architectural Design.

5.3 Case Study 3: Window Optimisation with Three Variables

A sample model room with the following dimension along with a single window having following specification and other physical conditions are considered for the purpose of optimizing the window dimensions and properties to ensure energy efficient building design.

Room Dimension

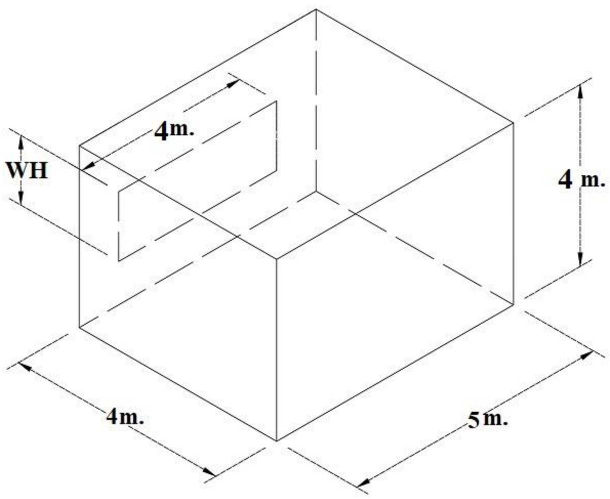
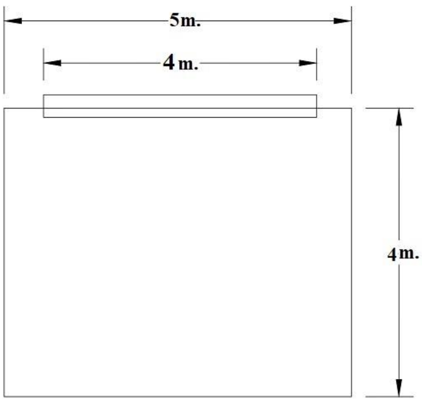


Figure 5.5: Diagram illustrating the Room Dimension

Length L = 5 m. Width W = 4 m. and Height H = 4 m.

Window Dimension



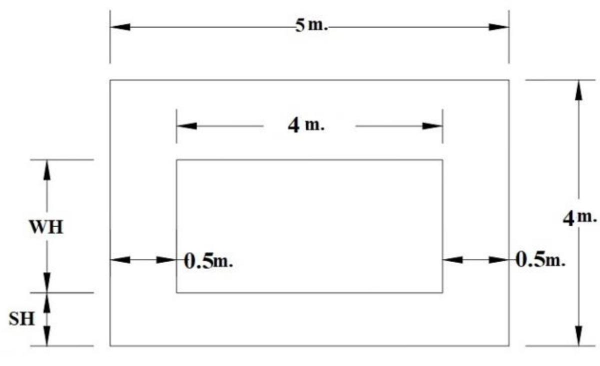


Figure 5.6 : Plan View

Figure 5.7: Window Wall elevation

Window span = 4 m. and Window Wall Area = 5 x 4 = 20 m^2

The design computation is carried out for different combination of Window Wall Ratio (WWR), Sill Height (SH) and Visual Light Transmittance of the glazing material of window or in other words **optimizing variables are WWR, SH and VLT.**

Window Wall Ratio ranges from 0.24 to 0.50 in steps of 0.02 or in other words 24% to 50% in steps of 2%. (14 possible combinations)

Therefore, Minimum Window Area = 0.24 x 20 = 4.8 m^2 or

And Maximum Window Area = 0.50 x 20 = 10.0 m^2

Window Length WL = L – (2x0.5) = (5 – 2x0.5) = 4 m.

So, Minimum Window Height = 4.8 / 4 = 1. 2 m.

And Maximum Window Height = 10.0 / 4 = 2.5 m.

Aspect Ratio AR = Window Length / Window Height = WL / WH

Therefore, Minimum AR = 4 / 1.2 = 3.33

And Maximum AR = 4 / 2.5 = 1.6

Therefore, it is ensured that Aspect Ratio is maintained as per NBC’2016.

Sill Height SH ranges from 0.8 m to 1.2 m in steps of 0.1 m. (5 possible combinations)

Visual Light Transmittance (VLT) varies from 30% to 70% in steps of 20% i.e. from 0.3 to 0.7 in steps of 0.2. (3 possible combinations)

All the values of the abovementioned parameters (WWR, SH, VLT, AR etc.) are within the range recommended in National Building Code’2016

Grid Formation of the Work plane

Here the total Floor size is taken as Work plane but at Work plane height.

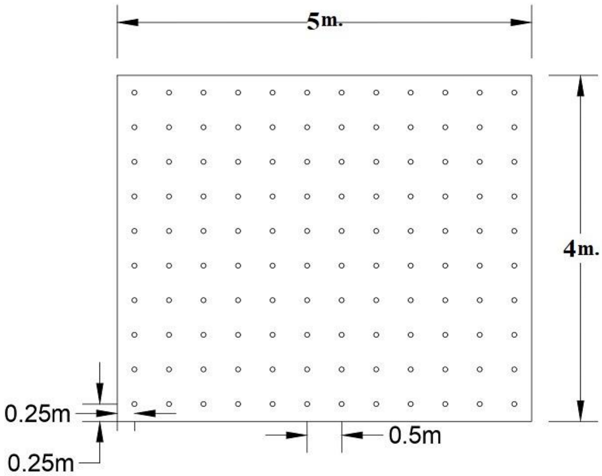


Fig. 5.8: Diagram illustrating the grid points on Work Plane.

Total no of grid points are 10x8 = 80

Design Considerations

a. Date: 15th August (Julian Day no. n = 227)
b. time: 07 am (x = 7) to 4 pm (x=16) at the interval of 1 hour.
c. Location: Kolkata (latitude i.e. $\Phi = 22.5°$ and longitude i.e. $\lambda = 88.36°$)
d. Pure clear sky (Sky Type =15)
e. Window Orientation: South Facing ($\theta = 180°$)

Other Design Considerations

- Work Plane Height WPH = 0.75 m.
- Transmittance of Window Glazing Material $\tau = 0.5$ i.e. 50 %
- Maintenance Factor MF = 0.75 i.e. 75 %
- Average Outdoor Ground Surface Reflectance $\rho_{Gavg} = 0.2$ i.e. 20 %
- Average Room Floor Reflectance $\rho_F = 0.2$ (20%)
- Average Room Wall Reflectance $\rho_W = 0.5$ (50%)
- Average Room Ceiling Reflectance $\rho_C = 0.8$ (80%)

Optimizing Design Variables or Decision Variables

1. Window Wall Ratio (WWR)
2. Sill Height of Window (SH)
3. Transmittance of Glazing Material (Ʈ)

Design Output

- Optimized window dimensions –
- Average Illuminance on work plane (Eavg) at optimized condition.
- Overall Uniformity (U_O) at optimized condition.
- Value of Minimized Objective Function (F) at optimized condition.

5.3.1. Window Optimisation

Grid Search Optimisation technique is applied in MATLAB Environment to maximise the combination of two output design parameters - Average illuminance (Eavg) and Overall Uniformity (U_O) to get the optimized dimensions and property of window – Window Wall ratio (WWR), Sill Height (SH) and Light Transmittance of glass from total (14 x 5 x 3) or 210 different combinations of input optimizing variables.

Optimisation Protocol

Optimized dimensions are derived to achieve the best result i.e. highest combination of Eavg and U_O, ensuring Eavg is not more than 3000 Lux but not less than 750 Lux and U_O is not less than 0.3. Eavg more than 3000 Lux may create visual discomfort and less than 750 lux is not sufficient for visual task in an office building. For proper indoor design U_0 should be more than 0.5, but it is hard to achieve the value with single window. So, minimum value of U_O is considered here as 0.3. Therefore, the necessary conditions are as follows.

Optimizing Design Variables are – (i) WWR (ii) SH (iii) VLT i.e. Ʈ

i. Maximisation of Eavg and U_O
ii. Elimination of the case when Eavg > 3000 Lux
iii. Elimination of the case when Eavg < 750 Lux
iv. Elimination of the case when U < 0.3

$F_1(x)$ = Eavg , $F_2(x)$ = Overall Uniformity U_O

Penalty Factor 1 for condition (ii), PF_1 = 100

Penalty Factor 1 for condition (iii), PF_2 = 100

Penalty Factor 1 for condition (iii), PF_3 = 100

The objective function F is developed as –

$$Minimise\ F = \frac{1}{F_1(\mathrm{x})} + \frac{1}{F_2(\mathrm{x})} + PF_1 + PF_2 + PF_3$$

The initial value of F is taken as 100.This Function is to be minimised by using grid search optimisation technique to fulfil the conditions and hence we get the optimized window dimensions (WWR and SH) and glazing property (VLT).

5.3.2 Smart Window

The facade systems which include switchable windows and shading systems such as motorised shades, electrochromic coatings etc. are called Smart Windows. It has variable optical and thermal properties that can be changed in response to climate, occupant preferences or building system requirements. The most promising switchable window technology today is elrctrochromic (EC) windows. The electrochromic stack consists of thin metallic coatings of nickel or tungsten oxide sandwiched between two transparent electrical conductors. When a voltage is applied between the transparent electrical conductors, a distributed electrical field is set up. The effect is that the glazing switches between a clear and transparent prussian blue-tinted state with no degradation in view. Visual Transmittance (Ʈ) is considerably changed. Another advantage is that they typically only require low- voltage power (0 – 10 volts DC).

SH varies from 0.8 m. to 1.2 m. and WH varies from 1.2 m. to 2.5 m.

Floor clearance (FC) = Sill Height (SH)

Ceiling Clearance (CC) = Room Height – (Window Height + Sill Height)

= H – (WH + SH)

Therefore, FC varies from 0.8 m to 1.2 m. in the steps of 0.05m.

Minimum value of CC = H – (WHmax + SHmax)

= 4 – (1.2 +2.5) = 0.3 m. i.e. 30 cm.

Maximum value of CC = H – (WHmin + SHmin)

= 4 – (0.8 + 1.2) = 2.0 m. i.e. 200 cm.

Therefore, CC varies from 0.3 m. to 2.0 m.

Transmittance varies from 30% to 70% in step of 20%.

The best suitable dimension of the window is selected from the result derived from the proposed tool for different time throughout the daytime on 15th August at Kolkata with South facing window for Pure Clear Sky (Sky Type 15). Moreover, Transmittance of window glass is also optimized.

As per the prediction of the proposed tool, motorised shading device can automatically adjust the window dimension and application of varying current can develop required Transmittance value of window glazing in Electrochromic (EC) smart window.

The following table (Table 5.4) shows the hourly variation of required dimension (SH, WWR, Ʈ, WH, FC, CC) along with the relevant design outputs (Eavg, U_O) and Minimised objective function value F **on 15^{th} August at Kolkata with South facing window for Pure Clear Sky (Sky Type 15).**

Date: 15^{th} August	**Optimizing Design Variables or Decision Variables**						**Design Outputs**		
TIME	**SH (m.)**	**WWR (%)**	**Ʈ (%)**	**WH (m.)**	**FC (m.)**	**CC (m.)**	**E (Lux)**	**U0**	**Minimised F**
7 am	0.90	50	70	2.5	0.90	0.60	1037	0.2980	2.5136
8 am	1.00	50	70	2.5	1.00	0.50	1313	0.3606	2.7737
9 am	1.00	50	70	2.5	1.00	0.50	1639	0.3507	2.8520
10 am	1.10	50	70	2.5	1.10	0.40	1704	0.3600	2.7787
11 am	1.20	50	70	2.5	1.20	0.30	1791	0.4006	2.4971
12 noon	1.20	50	70	2.5	1.20	0.30	1868	0.4085	2.4483
01 pm	1.10	50	70	2.5	1.10	0.40	1731	0.3628	2.7568
02 pm	1.00	50	70	2.5	1.00	0.50	1693	0.3457	2.8934
03 pm	1.00	50	70	2.5	1.00	0.50	1392	0.3565	2.8054
04 pm	0.90	50	70	2.5	0.90	0.60	1138	0.3873	2.5831

Table 5.4: Hourly variation of optimum Design Variables and design output at optimized condition for Case Study 3

Thus, the proposed daylight prediction tool based on CIE SSLD model can be smartly used to optimize the window dimension and property to achieve the best energy efficient architectural design in any office building, which the declared prime objectives of this project work.

Chapter – 6

Conclusion

6.1 Conclusion

After completion of the work the following conclusions can be drawn at the end of this thesis work.

- The proposed daylight prediction tool based on the CIE SSLD model considers almost all of the relevant factors for daylight simulation process except the portion of the external reflection component which may enter into the room after being reflected from the walls or surfaces of the nearby building or any structure (if any).
- The daylight distribution pattern derived from the simulated model for different physical conditions are almost identical with that of DIALux software for the same conditions.
- The pattern of hourly variation of daylight availability for various dates, locations, window orientations and sky types closely matches with our physical and logical perception based on knowledge of solar algorithm.
- The absolute value of illuminance derived from the proposed model is always higher than the same from DIALux output (based on Perez's Model for all weather condition) for different design considerations.
- The model has also be used for optimizing Window Dimension, Sill Height and Light Transmittance to achieve the best energy efficient design for different room dimension, date, time, location, window orientation, sky types etc.
- The concept of motorised shading device and Electrochromic (EC) glass has been suggested to introduce in order to develop a smart window, which can automatically adjust the window dimension and window glazing property at different date and time for a particular room and window at a particular location as per the optimizing signals (results) derived the proposed daylight prediction model developed in this project work.

6.2 Scope of Future Work

- The proposed daylight simulation model can be extended for the options of multiple windows on the other walls of the room. This is also essential for improved uniformity of daylight distribution.
- In this project window span is taken fixed. So the variation of Window Wall ratio (WWR) only signifies the proportionate variation of Window Height. But the tool can be improved for the variation of both window span i.e. length and window height keeping the aspect ratio unaltered.
- The result obtained from the simulation model should be verified with the same derived from different well known daylight prediction software. It is very much necessary to validate the result of the proposed tool.
- Practical set up for the daylight experimentation must be developed so that real time data can be collected and compared with the result of the proposed tool. It is extremely essential to ensure the reliability of the proposed model. But, identifying the exact sky type is a hard challenge in this work.
- If real time data collection throughout the year for any particular place is possible, then the tool can be used to identify the standard average sky model for representing three broadly classified sky types – overcast, mixed and clear sky for that particular location.
- The optimizing mechanism used in this model can be extended for more optimizing variables – window span, window height, sill height, light transmittance of glazing material, window orientation angle etc. to achieve the best energy efficient indoor design.
- Optimisation of light transmittance value using this tool can be utilised to wisely manage the trade-off between the daylight penetration and solar heat gain or/and the glare effect within the interior of any room.

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