Assessing alternative ways to provide daylight in a storehouse by using Radiance

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Abstract

Lighting principles and daylight generation have been described in some detail in the following study. The aspects of daylighting in buildings have been investigated with regard to the potential for application of daylighting simulation. Specifically, sky models, ground and indoor environment have been analysed in detail. An overview of existing metrics, for assessing daylight in a storehouse, which has rooflighting only, have been examined. In addition, an investigation of Daylight Factor and Glare Index drawbacks are also investigated within the present study.

Specifically, a qualitative analysis of the aspects that affect daylight in a storehouse has been undertaken. This analyses the correlation between roof geometry, shading devices, orientation and location of the storehouse.

Moreover, discussion and recommendations for effective modelling procedures and manipulation modelling tips are suggested. A sequence of script files for automating modelling calculations is provided, in order to assist the modeller to minimise the timescale of the process of model development and calculations.

An effort has been made to quantify and assess the effect of alternative roofs shape geometry under CIE Overcast and Intermediate sky conditions for high latitudes and a new convenient magnitude, General Daylight Factor (GDF) for comparison of different roof geometries has been introduced. Additionally, three-dimensional falsecolour pictures have been created by Radiance software for visualising the illuminance distribution in the interior of the examined models.

Finally, investigation of the need for shading devices for those two sky conditions and roof shape geometry are also included in the study. The dissertation concludes that there is no need for shading devices in buildings at high latitudes that have rooflights only under the two sky conditions examined because there is no visual discomfort based on Guth probability.

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Introduction

Daylight is the cheapest and most effective way of saving energy in commercial, public and residential buildings [1]. This advantage of the solar radiation has been primarily understood from the ancient era. Plenty examples of the utilization of daylight someone can find in the ancient Greek or Roman buildings where the suitable weather condition, high percentage of sunny days during the year, enhanced the understanding of sun light utilisation [2]. Even with these climate conditions the engineers of that period tried to make effective use of the solar radiation. This finding prompts the even more effective exploitation of solar energy in geographical locations with rare sunny days such as the northern part of Europe where the building of the described work is located.

Generally, buildings are extremely important beyond the fact that they accommodate and provide spaces within which human beings work and entertain. Many times, people consider them just as enclosures and they ignore the fact that they spend at least one third of their life within them.

Despite the important intellectual heritage that our ancestors left us it took long time when people started to comprehend the need for energy conscious buildings. This behaviour of the nineteenth and twentieth century engineers is justified due to the vast energy resources that were available at that period of time [4]. However, the energy crisis of 1970s in combination with recognition of the damage that has been caused in the biosphere during the last five decades have been two of the major factors encouraging an imperative return to natural light and generally to energy efficient buildings or to a recently introduced term sustainable buildings.

1.1 Aspects and benefits of daylight

1.1.1 Psychological aspect of daylight

A new phenomenon that has newly observed and encourages the use of daylight is the resistance of people to work in a wholly artificial lighting[7]. This behaviour of the people is absolutely acceptable because everybody enjoys the presence of sunlight in a building and wants at least to have a glimpse of the word outside. Moreover, considering the architectural expression that if someone wants to see how things are ‘really’ look like must try to view them under daylight conditions it can finally be comprehended the need for daylight in buildings with reference to psychological aspect of daylight [5].

It is worthwhile mentioning that all the above-mentioned findings are valid only when appropriate visual comfort exists because surplus or deficiency of sunlight will result the opposite [6]. Specifically, uncontrolled illumination, variable illumination, glare and shadowing are the most common matters that every building engineer faces in the process of building design and have to solve. A broad part of the described work has been devoted in solving or remedying that kind of problems by choosing the appropriate roof and correct utilisation of shading devices if there is a need.

1.1.2 Economic benefits of daylight utilisation

Solar radiation is the only truly free and environmentally friendly energy source that is available, and it has a lot of potential for reducing electricity consumption. The use of day lighting systems in the storehouse buildings is now becoming more common strategy to replace a considerable part of the electricity use [9]. This is justified from the fact that daylight availability coincides mainly with normal working hours and often with peak energy demand therefore use of sunlight can contribute dramatically to energy savings at the non-residential buildings.

The largest use of primary energy in the most developed countries is to produce energy for buildings for their direct needs such as electric light and indirect needs such as air-conditioning. A recent survey has shown that typical commercial buildings use between 50% and 70% of their electric energy consumption for light and air-conditioning and that correct use of daylight can reduce that amount of energy consumption by up to 50% [7]. So why not saving this amount of money and invest them in other areas and finally improving the human being life. Considering the global poverty that exists nowadays there is an imperative need to follow the solution which is called daylight use in buildings.

The paradox is that many lamps' producers have convinced owners that the answer for the reduction of electric energy in buildings is the investment in lamps of low energy consumption [1]. This is obviously a short-term solution that will never benefit the humanity in the long run since the energy consumption still exists.

Worthy reason is to mention that daylight unavoidably brings solar heat into buildings but with proper architecture it is possible to be rejected most of that solar gain. Additionally, only 0.5% of the full luminance of sun is sufficient to provide illuminance of about 500 lux on a work plane which is more than ample for the majority of work activities in buildings. Therefore, by admitting such a small amount of sun light into a building it will not offset its inherent energy efficiency value [8].

1.1.3 Environmental benefits of daylight utilisation

Consumption of energy is related directly with the aggravation of global warming. The increasing demand of electricity the last five decades has resulted the dramatic reduction of the earth energy resources and simultaneously has increased the greenhouse gases [4]. After this realisation every body is talking about energy conservation and sustainable development. Utilization of daylight in buildings will alienate the global warming and reduce the greenhouse gases due to energy conservation.

1.2 Why daylighting simulation for storehouses

The need for this analysis emerges from the fact that every industrial and particularly storehouse has significantly different utilisation and construction concept compared to public and residential buildings [9]. Additionally, considering that mainly, at storehouses there is no luxuriance for glazing surfaces on the facades everyone can easily conclude that there is an added need of sunlight utilisation, which will finally satisfy partially, or fully the psychological need of warehousemen.

The healthier and more enjoyable lighting conditions will benefit both warehousemen and storehouses' owners since there will be an increase in the productivity of the former one and consequently rise of profits for the last one.

Moreover, a lot of work has been done mainly for public buildings or offices but only few `rules-of-thumb' based on empirical conclusions and manual calculations exist for industrial building [10]. These 'rules-of-thumb' are general and do not take into account, most of the time, the building location therefore this approach has frequently led architects and building services engineers to oversized artificial lighting which in terms leads to high energy consumption [3]. Thus, there is a need for quantitative 'rules-of-thumbs' and not just qualitative that will facilitate the building and lighting designers to calculate better the need of artificial lighting and finally achieving energy conservation in storehouses.

Besides that, the visualisation of the interior will give a better understanding of the qualitative 'rules-of-thumb' compared to existing 'rules-of-thumb'. Additionally, an image is worth hundred words.

Finally, after a personal experienced I had during Christmas holidays when I visited a storehouse to leave temporarily my luggage I realised that the illuminance level was not sufficient. Discussing later my recognition with the storehouse man he expressed also his dissatisfaction about that fact and he informed me that this is a common phenomenon in many storehouses, during winter days. Really, his opinion was confirmed after the survey I did in some other storehouses.

Considering the forenamed finding it can be concluded that there is definitely a need for quantitative comparison between alternative ways to provide daylight in a storehouse and it can achieve only by simulations. Moreover a qualitative discussion of the alternative ways to provide daylight in a storehouse should be ante-ceded to the quantitative analysis for better understanding and verification of the later. Therefore, the chapter 3 has been entirely devoted in that qualitative analysis.

1.3 Goal and Aim of study

The goal of the work described in the thesis is the investigation of the most effective way to provide daylight in a storehouse. Specifically, it has been accurately simulated and calculated the visual comfort and natural illumination for a typical storehouse for various roofs geometry keeping the same glazing surface area. Additionally it has been assessed the effect of various windows arrangements and slope of roof, sustaining the same glazing surface area and it has been investigated the need for shading devices. Finally, it has been developed effectively modelling procedure for managing the vast amount of data that are required during the pre-processing analysis and the data are produced at the solving stage.

The aim of the preceding analysis is the qualitative and quantitative examination and comparison of the major factors that affect the visual comfort in a storehouse such as:

- Identification of Daylight factor in different working planes
- Assessing the appropriateness of Daylight Factor as a magnitude to assess daylight
- Assessing the illuminance level in the interior of a building and create a database that will be used by lighting engineers to predict storehouse daylighting performance throughout the year for high latitudes, like Scotland under different sky conditions.
- Selection of different sky models for daylight simulations
- Visualisation of luminance and illuminance level inside a storehouse by using Radiance software program
- Coding of the most effective combination that remedies summer glare and provides sufficient daylight during the winter period.

It is obvious that since the quantitative analysis is based on simulation, assessment of the simulation parameters such as sky models, glare indexes and some others is required. Thus, all these magnitudes are examined in chapter 2 of the present study.

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2. Daylighting in Buildings

The analysis of daylight in a building requires understanding of general terms and principles of lighting because daylight is a form of light that is generated by sun. Therefore in this chapter lighting principles are described in some detail.

2.1 Principles of light

Light is one form of energy so standard units of energy can be used for measuring it. However these units are not convenient because the effect of light on the human environment depend upon the sensitivity of human's eye. Therefore new units and terms have been introduced for the measurement of light and its effects. The need of definition of the following terms will be realised in the following sections where there will be use of these. Additionally, some of the following terms such as illuminance, luminance, radiance and irradiance are used by Radiance software program for the calculations of the present study. Therefore, they are listed below:

Luminous intensity (I) is the power of a light source or illuminated surface to emit light in a particular direction, unit [cd] [4].

The luminous intensity provides the weighting factor needed to convert between radiometric and photometric measurements.

Luminous flux (F) is the rate of flow of light energy, unit [lm] [4].

The equation that relates the luminous intensity with luminous flux is the following:

$$F = l * \omega \quad [4] \; (2.8)$$

where:

F = luminous flux emitted by a source [lm]

l = mean spherical intensity of a source [cd]

ω= solid angle containing the flux [sr]

Illuminance (E) is the density of luminous flux reaching a surface, unit [lx] [4].

The illuminance and luminous flux are related by the following formula:

$$E = \frac{F}{A} \text{ [4] } (2.9)$$

where:

E = illuminance on surface [lx]

F = luminous flux reaching the surface [lm]

A= area of the surface [m^2]

Cosine law of illumination: the illuminance on a surface is directly proportional to the cosine of angle between the direction of flux and the normal vector to surface (angle of incidence when the source is the sun) [4].

The mathematic expression of the above law is as under:

$$E = \frac{l \cdot \cos(\theta)}{d^2} \text{ [4] } (2.10)$$

where:

E = illuminance on surface [lx]

l = mean intensity of a source [cd]

θ = angle between the direction of flux and the normal vector to surface [^{o}]

d = distance between source and surface [m]

Luminance (L) is the measure of the ability of an area of light source or reflecting surface to provide the sensation of brightness, unit [cd/m^2] [4].

Radiance (B) is the radiant intensity per unit projected surface area, where projected surface area is the real surface area multiplied with the cosine of the angle of the radiation relative to the surface normal vector, unit [W/m^2/sr] [4].

The radiance measurement is independent of the distance that an observer measures it.

Irradiance (I) is the total amount of radiative flux incident upon a point on a surface from all directions above the surface, unit [W/m^2] [4].

2.2 Daylighting

A lot of parameters should be examined with regard to daylight generation and variation throughout the year. Obviously, the source for the generation of daylight is the sun therefore there is a need for understanding how sunrays generate daylight, what is the direction of those through a year and how that direction effects the variation of daylight. Additionally, the direction of sunrays is related with the earth position because the earth is rotating around the sun. Therefore this section discusses and defines these magnitudes that affect the generation and variation of daylight through a year.

2.2.1 Solar Radiation

Solar radiation is made up of several broad classes of electromagnetic radiation which all of them have some common characteristics but they differ in the effect they produce primarily because of their wavelength. These classes of the solar spectrum include ultraviolet, visible light and infrared. The wavelengths of most of the infrared, a part of the ultraviolet and the entire visible light spectrum is a range referred to as *thermal radiation* since it is the part of the electromagnetic spectrum that primarily creates a heating effect. The total thermal radiation that impinges on a surface from all directions and from all sources is called *global radiation* [1] .

The *radiant energy* that falls on a transparent surface or atmosphere (clouds) is absorbed, reflected and transmitted through it. Absorption is the transformation of the radiant energy into thermal energy stored by the molecules. Reflection is the return of radiation by a surface without change of frequency. Transmission is the passage of radiation through a medium without change of frequency. The equation that drives these three actions of radiant energy is:

$$\alpha + \rho + \tau = 1 \quad [1] \quad (2.1)$$

where:

α = the absorptance, the fraction of the total incident thermal radiation absorbed;

ρ = the reflectance, the fraction of the total incident thermal radiation reflected;

τ = the transmittance, the fraction of the total incident radiation transmitted through the a mean.

Based on the characteristics of radiant energy it has been decided in section 3.3 the place of shading devices (external or internal).

2.2.2 Solar Angles

The solar angles are widely used in the definition of sky models and sun positions in sections 2.2.3 and 2.3.1 which is a simulation of daylight that occur under different sky conditions. Thus, the understanding of these models required the definition of those angles.

The direction of the sun's rays are determined by the following three quantities:

1. Location on the earth
2. Time of the day
3. Day of the year

By using the above quantities someone can find out the sun's declination, the hour angle and the latitude useful information to perform any kind of simulation which is related to daylight building performance and accounts variations solar radiation throughout the year [2]. In the figure 2.1 is illustrated these three angles. The *latitude l* is the line between the OP and the projection of OP on the equatorial plane and its unit in SI is degrees [-90^o, +90^o]. The *hour angle h* is the angle between the projection of P on the equatorial plane and the projection on that plane of a line from the centre of the sun to the centre of the earth and its unit in SI is degrees [-180^o, +180^o]. It is easily understandable that one hour of time corresponds to fifteen degrees of hour angle. Finally, the *sun's declination d* is the angle between a line connecting the centre of the sun and earth and the projection of that line on the equatorial plane and its unit in SI is degrees [-25^o, +25^o].

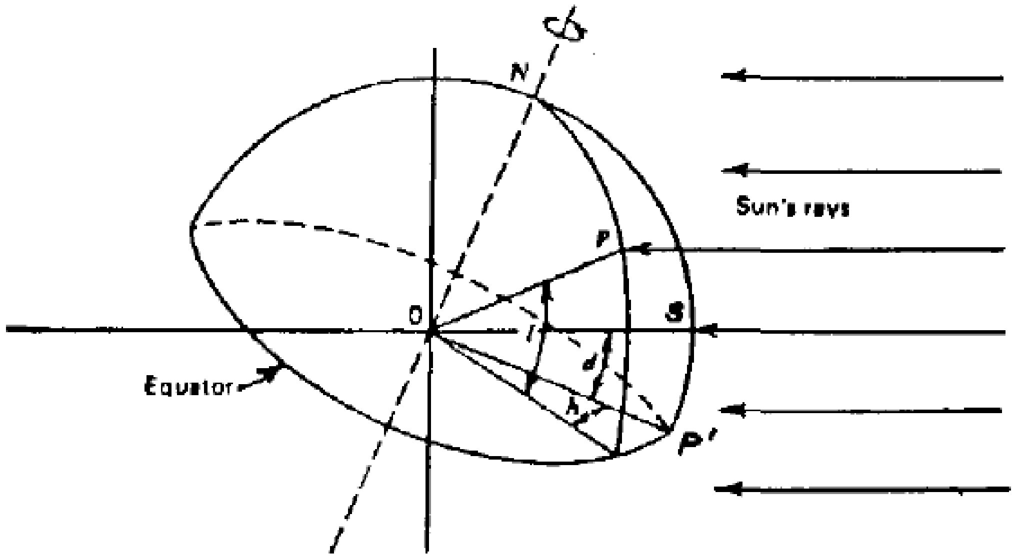

Figure 2.1 : Latitude, hour angle and sun's declination [2]

In most simulations it is convenient to define the sun's position in the sky in terms of solar altitude β and solar azimuth Φ which is a function of the previous defined quantities *l, h* and *d* [1] .

In the figure 2.2 are presented all the quantities that most of day lighting simulation software programs take into account for its calculations. It is worthwhile mention that the definition of azimuth angle in most theoretical books is measured from north [5]. Despite that most of the software programs account the azimuth angle, as it is defined in the present section in equation 2.3 and in figure 2.2.

The *solar altitude β* is the angle between the sun's ray and the projection of that ray on a horizontal surface and indicates the angle of sun above the horizon. It is calculated by the following equation:

$$\sin(\beta) = \cos(l)*\cos(h) \cos(d) + \sin(l)*\sin(d) \quad [2] \ (2.2)$$

The *solar azimuth Φ* is the angle in the horizontal plane measured between south and the projection of the sun's rays on that plane. It is calculated by the following equation:

$$\cos(\Phi) = \frac{\sin(\beta)\cdot\sin(l) - \sin(d)}{\cos(\beta)\cdot\cos(l)} \quad [2] \quad (2.3)$$

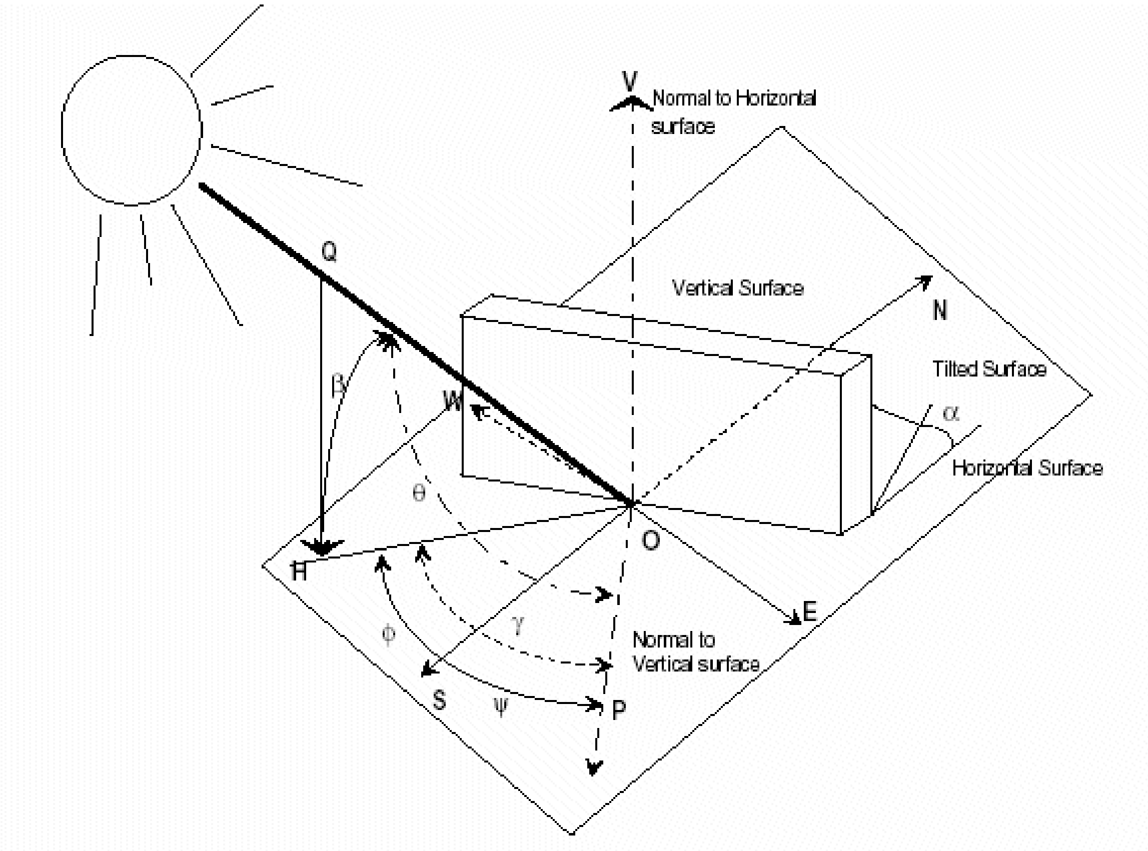

Figure 2.2: The solar altitude angle (β), solar azimuth angle (Φ), surface azimuth (Ψ), surface solar azimuth angle (γ), the angle of incidence (θ), and the tilt angle (α) for an arbitrarily tilted surface [2] .

The *surface solar azimuth γ* for a non-horizontal surface is the angle between the projection of the sun's rays on a horizontal plane and the projection of the normal to the surface in the horizontal plane. The surface *azimuth Ψ is the* angled measured in a horizontal plane between south and the normal to the vertical surface.

The surface solar azimuth is by the following equation:

$$\gamma = |\Phi - \Psi| \text{ [2] } (2.4)$$

Where:

Ψ is positive when the surface faces south west and negative when the surface faces south east.

The *angle of incidence* θ is the angle between the normal to the surface and the sun's rays. The *tilt angle* α is the angle between the normal to the surface and the normal to the horizontal surface [1] .

It has been shown by analytic geometry that the *angle of incidence* θ is calculated by the following equation:

$$\cos(\theta) = \sin(\beta)\cdot\cos(\alpha) + \cos(\beta)\cdot\cos(\gamma)\cdot\sin(\alpha) \text{ [2] } (2.5)$$

So obviously for a horizontal surface

$$\cos(\theta) = \sin(\beta) \quad (2.6)$$

and for a vertical surface

$$\cos(\theta) = \cos(\beta)\cdot\cos(\gamma) \quad (2.7)$$

2.2.3 Sun position

The angle of incidence that has been defined in the previous section has a great effect on the light entering into a building since the solar radiation obeys the Cosine law of illumination [3]. This angle varies throughout the year and it is associated with the sun path in the sky. The sun path in the sky varies during the year but it is repeated in a predictable manner. For better understanding, the sun position in the sky for three different periods (winter, spring and summer) is illustrated in the figure 2.3.

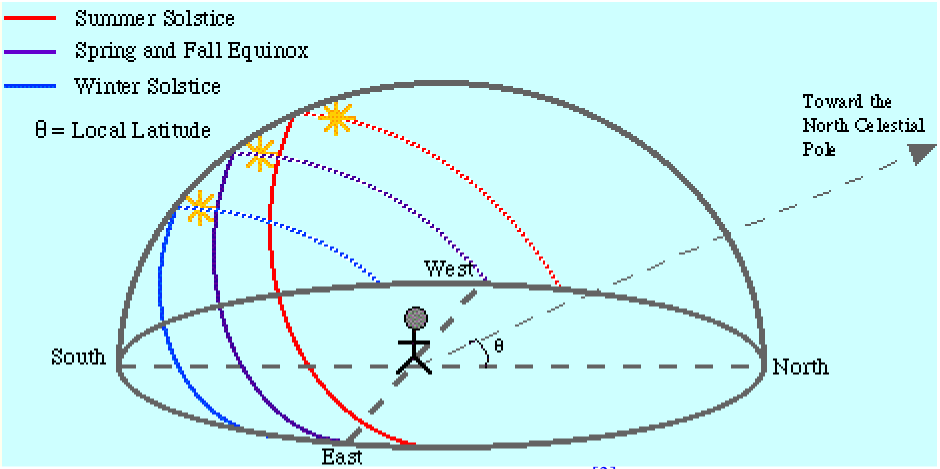

Figure 2.3 Sun paths [3]

Generally, the intensity of solar radiation is maximised when the sun's rays impinge on a surface at right angles. So during summer days a building with skylights has higher illuminance compared to winter days because the elevation of the sun is higher.

2.3 Aspects of daylighting in buildings

There are five aspects to the examination of daylighting in buildings:

1. The sun;

2. The sky;

3. The ground;

4. Transparent medium and

5. Indoor environment

The first component is responsible for the generation of daylight and in combination with the last four will consist the source of light for the interior daylighting calculations.

The solar radiation received from the sun and how it varies with the direction of sun's rays through out the year has been analysed in details in sections 2.2.1 and 2.2.3 so it will not discussed in the existing paragraph. Thus, the analysis focuses only in the rest aspects.

2.3.1 Sky Models

The radiant energy as it passes through the atmosphere it diffuses and scatters. This phenomenon results the sky luminance and it is visible to an observer as a non-uniform luminance dome or vault. The sky luminance varies with the cloud cover and density of clouds [4]. Thus, the sky luminance at the Sahara desert is lower compared to the sky luminance in a summer cloudy day in UK .

The majority of illuminance simulations and calculations use mainly two sky models, the CIE Standard Overcast Sky and the Intermediate Sky model [5].

The overcast sky adopted by the CIE as a standard in 1955 and is a good representation of conditions in many parts of north Europe [7] since comparison with real data has proven the validity of this model. The sky luminance at a point p normalized to the zenith luminance is given by the equation:

$$L_p = \frac{L_\zeta}{3} \cdot (1 + 2 \cdot \sin(\zeta)) \quad [5] \ (2.8)$$

where:

L_ζ = sky luminance at the zenith
ζ = the zenith angle

From the above equation it is obvious that the overcast sky luminance is independent of the azimuth and varies only with the zenith angle or altitude above the horizon. So for a specific zenith angle an observer will see the same sky luminance whatever compass direction he faces, this is valid for surfaces as well. Moreover, the interpretation of the standard overcast sky is that the luminance at the zenith is three times greater than the luminance at the horizon.

A more complex sky model is the intermediate sky which takes into account the location (azimuth and zenith angle) and the sun position. The luminance distribution of that sky is described by the following equation:

$$L_p = \frac{L_\varsigma \cdot A1 \cdot A2}{A3 \cdot A4} \quad [11] \ (2.9)$$

Where :

A1=[1.35*(sin(3.59*γ-0.00009)+2.31)*sin(2.6*β+0.316)+γ+4.799]/2.326
A2= exp[-0.563*μ{(β-0.008)*(γ+1.059)+0.812}]
A3=0.999224*sin(2.6*β+0.316)+2.73852
A4=exp[-0.563*(π/2-β){2.6298*(β-0.0008)+0.812}]
μ = the angle between the sun and the sky point
γ = the sky point altitude above the horizon
β = the solar altitude angle
L_ζ = Zenith Luminance

Theoretically, by implementing the inverse square law and integrating the previous two equations over that portion of the sky that is visible from the interesting point it can be determined the illuminance at this point. Practically, the integration of the intermediate sky is too difficult and that problem overcoming by using numerical method namely simulation.

In the present study it has not been considered the model of clear sky because it is not an appropriate representation of sky conditions in northern Europe and also the existing sky model does not provides accurate sky luminance values for high latitudes where the location of the models is [12].

2.3.2 Ground

Usually, the ground in the simulations is treated as a diffused medium [5]. The portion of the light that comes from the ground depends on the orientation of the transparent surface and obstruction between the sun and ground. It is obvious that when there are not transparent surfaces in the facades of the building (solely windows in the ceiling) the contribution of the ground to the interior illumination is zero. Therefore the ground has been excluded in the calculations.

2.3.3 Transparent Medium

The term transparent medium refers to any kind of window that allows the daylight to enter into the interior of building. There is a great variety of windows in the market such as single glass, double glass, triple glass and electrochromatic windows.

The effect on the interior daylight of the first three types is not significant since the transmittance value of a single glass is around 90% while for a triple glass is 70%. More significant is the difference in thermal properties of the forenamed windows. However, the electrochromatic windows influence considerably the interior daylight since they can vary their transmittance value and consequently control the illumination level inside a building.

The present study has focused on assessment ways to provide daylight in a storehouse building. This entails that electrochromatic windows are excluded from the assessment since it is not cost – effective solution and sometimes the cost of them exceed the value of stored goods. Therefore the transparent medium is not a matter of concern in the present study and it will not discussed in any further details.

2.3.4 Indoor environment

Generally, daylight may be sufficient in quantity to reduce use of artificial lighting but the quantity does not ensure quality of light and finally due to poor quality it is possible one to experience the problem of visual discomfort. So from the above thoughts it is obvious that the daylight analysis for interior spaces is divided into two parts:

- Quantitative
- Qualitative

The magnitude associated with the quantitative analysis is the illuminance [lx] [6]. The illuminance distribution across a plane is the most popular criterion used in daylighting design due to the convenience of calculations or simulations and the great variety of instruments to measure illuminance [9]. The crucial quantity that determine the illumination level in an interior space is the daylight factor which will be discussed in following paragraph.

Two are the major factors that affect the quality of light associated with the physical and psychological impact on the occupants [6]. These factors are listed below:

1. Glare
2. Luminance ratio

Glare is a subjective phenomenon since it is an expression of visual sensation and it cannot be measured directly. Glare is defined as any excessively bright source of light in the visual field [10]. Mainly, two forms of glare are exist, the ‘disability glare’ and the ‘discomfort glare’ [6].

The disability glare reduces the ability to perceive the visual information needed for a particular activity. It occurs only in spaces where a direct view of sky is inevitable and it is more severe on dull days rather than on bright days [6].

The discomfort glare is associated more with the sensation of distraction, irritation but which does not significantly reduce the ability to see information needed for activities. The four factors that affect the discomfort glare are listed below [6]:

1. The luminance of the sky
2. The size of the visible sky patch
3. The position of the sky patch and
4. The average luminance of the space surfaces

It is obvious that these factors are not independent since the luminance of the surfaces relates directly with the sky luminance and window size. This fact introduces an additional complexity in assessing the discomfort glare inside a space due to daylight. This is overcome by the use of numerical methods namely simulation. Many proposals have been introduced from different countries for the quantification of the discomfort glare inside a room. The mathematical description of which will be analysed in details in section 2.4.2.

Luminance ratio is a ratio of the luminance of a plane to the luminance of the area surrounding that plane [10]. Usually, the main concern in daylight calculations is the luminance of the window and the area surrounding the window, such as wall. However, if there are solely windows in the ceiling which are not directly visible from the working plane the luminance ratio becomes less important [7].

2.4 Quantifying Daylighting Availability

2.4.1 Daylight Factor

The illuminance inside a space can be measured by comparing it with the total available illuminance outside the space. This ratio is called daylight factor (DF) and is defined as the ratio between the actual illuminance at a point inside a building and the illuminance possible from an unobstructed hemisphere of the same sky.

$$DF = \frac{E_{in}}{E_{out}} \cdot 100 \quad (2.10)$$ [5]

It is important to mention at that stage that for the calculations of daylight factor it is used the standard CIE overcast sky. Therefore, the orientation of the glazing surface does not play any role because the luminance of that particularly sky model does not vary with the azimuth. So if someone assumes cubic space with one only window the daylight factor at work plane height will be the same even the window faces north, east, west or south. Moreover, since the overcast sky is the dullest sky that generally will occur, the calculated daylight factor is the minimum that will occur during the year in a specific location. The recommended daylight factor for full daylight is 5%. Daylight factor below 1% entails use of artificial light [5].

Generally, the daylight reaching a point inside a building is made up of four components. In the figure 2.4 is illustrated the daylight components, from these components only three of them accounted in the daylight factor calculations under overcast sky [5].

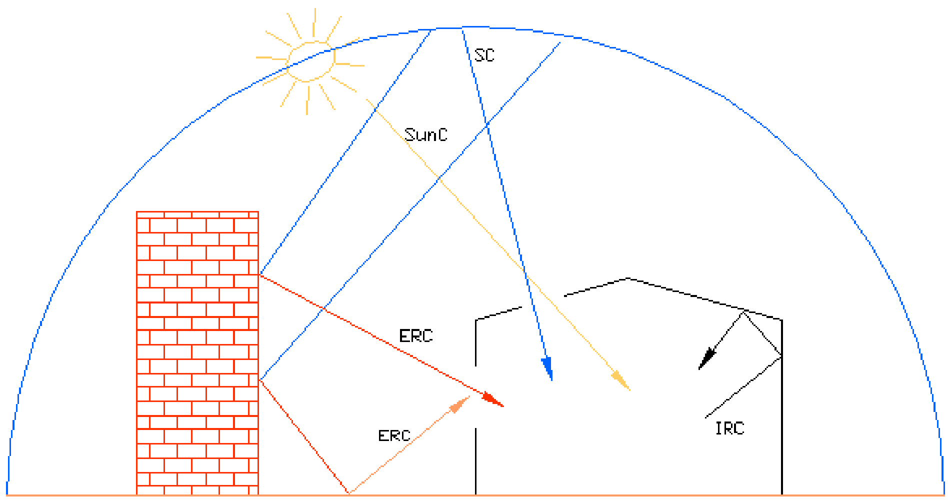

Figure 2.4: Components of Daylight

The three components are:

1. Sky component (SC): is the direct light received from the sky

2. Externally reflected component (ERC): is the light received directly by reflection from buildings, ground or combination of them outside the room.

3. Internally reflected component (IRC): is the light received by reflection from surfaces inside the room.

The usefulness of the division of daylight factor into three components is significant since they can be calculated separately. This helps a lighting designer to identify the contribution of each component in the final value of daylight factor on a surface inside a building.

2.4.2 Assessing Glare in Building

Comfortable lighting is a necessary component of a well-balanced working environment. The emphasis in building design is now on daylighting. However, daylight introduced to the interior may cause discomfort glare. Therefore, there is a great concern in identifying metrics that will assess objectively the discomfort glare in the interior of a building.

Many efforts have been made from different countries to establish their own discomfort glare expressions. Some of them refer solely to artificial light, other to daylight and only few combine both. Since the exclusive purpose of the present study is to assess the daylight effect into the interior of a storehouse, the study has been restricted only to expression with reference to daylight. The formula that is used for calculating glare due to daylight has been developed by Hopkinson in 1971 and is called Daylight Glare index (DGI) [7]. This can be expressed by the following equation:

$$DGI = 10 \cdot \log 0.478 \cdot \sum \frac{L_s^{1.6} \cdot \Omega^{0.8}}{L_b + 0.07 \cdot \omega^{0.5} \cdot L_s} \quad [7]\ (2.11)$$

where:

L_s=is the luminance of each glare source in the field of view

L_b=is the luminance of the background excluding the glare source

Ω= is the solid angle subtended by the glare source (window)modified by the position factor

ω = is the total solid angle subtended by the window at the eye of observer

However, the Daylight Glare Index has a limitation since it does not take into account the direct light from the sun [13]. So this qualitative method is recommended mainly for assessing visual comfort inside a building only during the winter days where the standard overcast CIE sky is a realistic approximation.

This drawback of the Daylight Glare Index has been covered by the introduction of the Unified Glare Index [8]. Actually, after the recommendation of the CIE the Unified Glare Index has become widely acceptable as a general formula for assessing glare. The formula is the following:

$$UCR = 8\log\frac{0.25}{Lb}\sum\frac{Lu^{2}}{p^{2}}*\Omega \quad [8] \quad (2.12)$$

where:

Lu = luminance of the glare source

Lb = background luminance

Ω = solid angle

p^2 = position index

The background luminance is calculated from the illuminance at the eye of the observer and the formula is the following:

$$Lb = \frac{Eobs}{\pi \cdot \Omega_o} \quad [8] \quad (2.13)$$

where:

Eobs = illuminance at the eye of observer

Ω_o = solid angle

The forenamed formula requires the prior calculation of the luminance and position of each potential glare source. Therefore it is suitable for use within computer software like Radiance because after having created the image of a scene the program has already calculate the luminance and position of each glare source (pixel).

A more immediately understandable assessing glare metric and widely used is the American visual comfort probability (VCP) system [9]. This system has been developed by Guth in 1970 and expresses the probability of an observer to consider a given visual environment comfortable to perform a task. The result of that system is not a number as the former systems but a percentage and this makes it easily interpreted. The Guth's formula that is only for a single source is:

$$GlareSensation = \frac{0.5 Ls \cdot Q}{p \cdot F^{0.44}}$$ [9] (2.14)

where:

Ls = luminance of the glare source

p = position index with respect to the line of sight

F = the average luminance of the entire field including the glare source

Q = a function of the solid angle ω_s that subtends the source in the observer's eye and is given by the following formula:

$$Q = 20.4\, \omega_s + 1.52\, \omega_s^{0.2} - 0.075$$ [9] (2.15)

For calculating the glare level for a number of glare sources the glare sensation values must be summed and finally the Discomfort Glare Rating (DGR) is obtained:

$$DGR = (\Sigma M^{n})^{-0.0914}$$ [9] (2.16)

Where:

M = Glare Sensation

n = number of glare sources in the visual field

From the above discussion it derives that for a partially sunny day the only suitable metrics for immediately understandable assessment of visual discomfort is the last glare index (DGR) and therefore it has been used to assess the visual comfort in the present study.

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3. Qualitative analysis of the issues that affect daylight in a storehouse

3.1 The role of shading devices

The main role of shading devices is to improve thermal comfort and visual comfort by reducing overheating and glare in the interior of a building. These can be achieved by shading solely either the transparent and opaque surfaces or both of them. So the objectives of every type of shading devices are [1]:

- Minimise direct solar radiation
- Minimise diffuse and reflected radiation
- Redistribute sunrays

It is obvious that there will be a great variety of shading devices that can satisfy all these objectives.

3.2 Types of shading devices

The shading strategy of a building is determined by the site location, use of building, orientation and sky conditions. Generally, shading devices are divided into two types, external and internal [2]. These in terms can be fixed, removable or adjustable.

Fixed devices are more preferential due to their simplicity, robustness, maintenance and low construction cost [2]. On the other hand they reduce significantly the daylight factor during winter days when the sky is mainly overcast. So removable devices are an alternative solution to this problem and also incorporate all the advantages of the fixed shading devices.

Perceptibly, adjustable devices are less simple and robust, have higher maintenance and construction cost but they can precisely control the daylight during the year [3].

The table 3.1 summarise the advantages and disadvantages of fixed and adjustable shading devices.

Factors	**Fixed/Removable devices**	**Adjustable Devices**
Simplicity	High	Low
Robustness	High	Low
Maintenance Cost	Low	High
Construction Cost	Low	High
Daylight Factor (DF) Control	Low	Medium or High depends on the complexity of device

Table 3.1 Fixed versus adjustable shading devices

The table 3.1 indicates that the adjustable shading devices may be utilised in buildings where the daylight control is the major concern otherwise fixed/removable devices is more feasible solution. This entails that for a storehouse it is the only solution since the cost of an adjustable device sometimes may exceed the entire construction cost of the building. Moreover, it is probable that none of the storehouse owners are available to pay such luxuriance. Therefore, the described study will examine only fixed/removable devices.

Fixed devices may be internal or external. Studies have shown that external shading devices are much more effective compared to internal [4]. The figure 3.1 illustrated the process of solar gain for a window which has external and internal shading device.

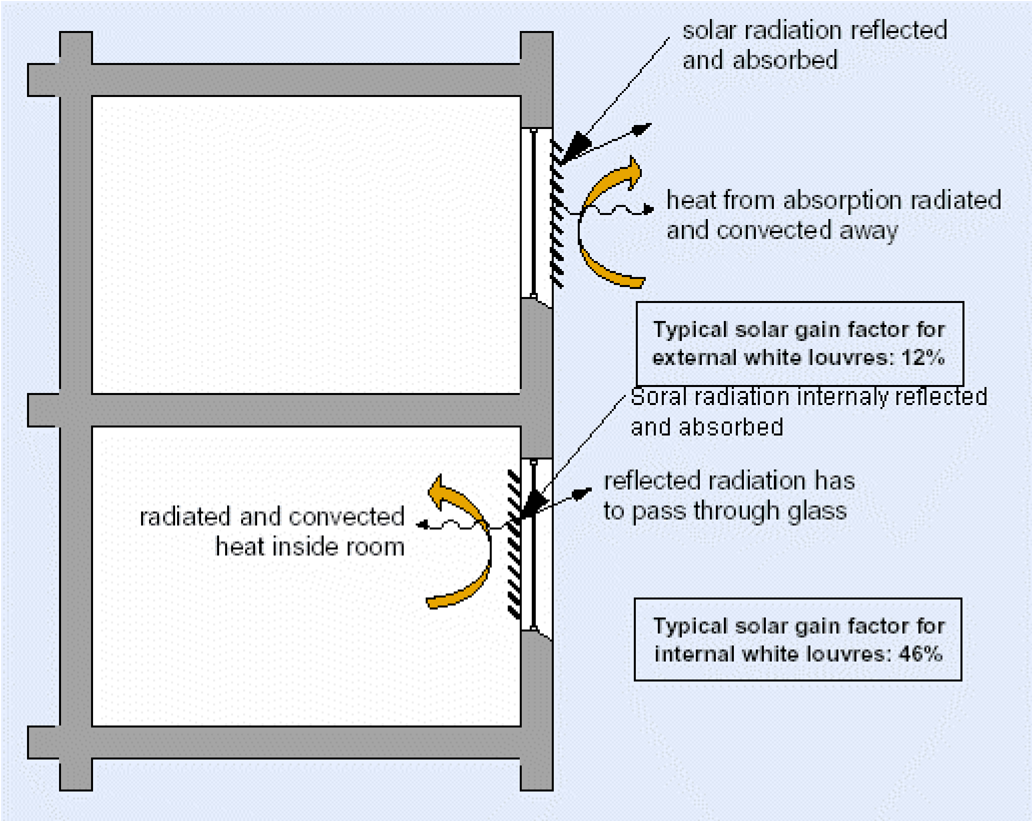

Figure 3.1 External versus Internal shading device [2]

In the first case of the external shading device the solar radiation partially reflected externally and partially absorbed from the external device. Heat from the absorbed part of solar radiation radiated and convected in the atmosphere but since it is outside of the building, it does not add any significant solar gain. Thus, the proportion of radiation which eventually enters the space (solar gain factor) is relatively low.

On the other hand, in the second case the solar radiation reflected and absorbed internally, inside the building. This enhances the solar gain of the space since the reflected radiation has to pass through the window which means that a part of that reflected radiation will be reflected again to the interior. Additionally, heat from the absorbed part of solar radiation radiated and convected inside the building and finally the internal shading device acts as a radiator. These two phenomena entail the rise of solar gain factor and finally the temperature in the interior.

The aforesaid analysis indicates the need of external only shading devices in order to avoid summer overheating, therefore internal shading devices have been excluded by the present study.

3.3 Correlation of shading devices and roof configuration

External shading devices associated directly with the geometry and orientation of glazing surfaces, the term orientation refers to the azimuth and elevation of the surface. So for a building which has mainly glazing surfaces in its roof, the orientation of these surfaces are correlated directly with the geometry of roof. Thus, one should examine in conjunction the roof geometry and shading devices.

Generally, the alternative roof shapes for daylight utilisation are four [1],[6]:

i. Shed
ii. Horizontal roof with translucent domes or pyramids
iii. Sawtooth
iv. Monitor

The figure 3.2 demonstrates the four most common roof types.

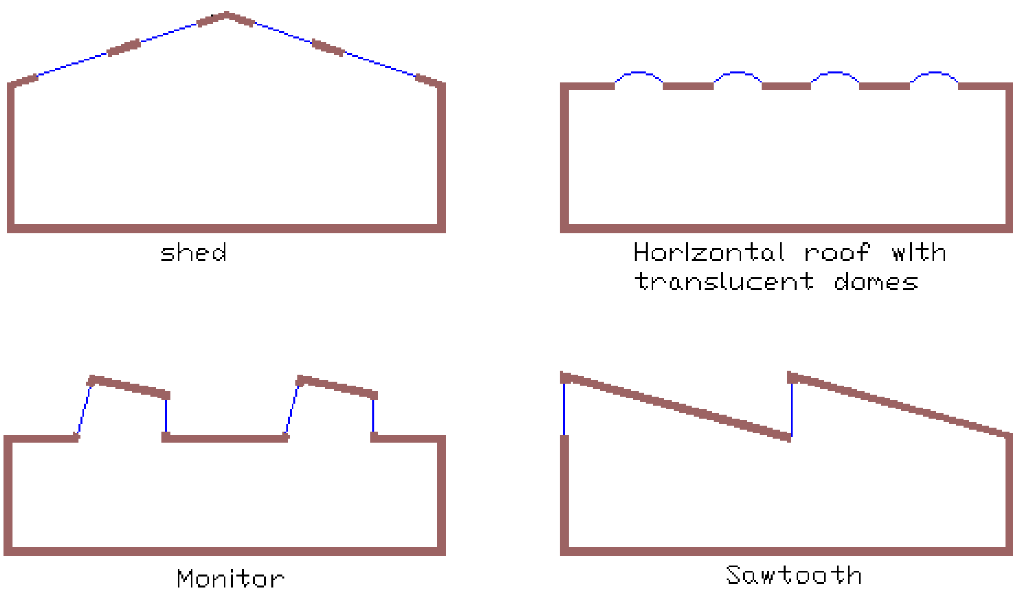

Figure 3.2 Roof types

During the last three decades there have been a lot of qualitative studies for these roof types but not many quantitative [1] . Therefore the present study will try to quantify these types and identify how much better is one type of roof compare to other. It is important before the quantification of them to list the pros and cons of different roof types, in other words the qualitative comparison, so that one can assess easier the quantitative results and also realize the need, if there is any, for shading devices.

3.3.1 Pros and Cons of shed roof arrangement [1], [5], [6], [7], [8]

Pros:

- Cheap construction
- Higher daylight factor compared to the rest roof geometry, so better use of daylight since the glazing surfaces provides light from the brighter sky and also high solar penetration exists. Higher altitude closer to zenith entails higher sky luminance.
- Orientation is not a critical issue

Cons:

- Usually, overheating and glare discomfort occur in summer due to high direct sunlight that provides.
- Indoor glazing surfaces are difficult to reach for cleaning. Thus, It is not preferential for dirty environment because the dust that will be subsided on the surfaces it will reduces the transmittance of them. As a result of it is the reduction of daylight factor and loss of its advantages.

3.3.2 Pros and cons of horizontal roof arrangement [1], [5], [6], [7], [8]

Pros:

- High average daylight factor because this roof shape provides light from the brighter sky and it has high sky view.
- Orientation is not a critical issue .

Cons:

- Summer overheating is very common phenomenon so provision of effective shading devices are needed.
- It is considered an elaborate and expensive construction especially if domes are used.

3.3.3 Pros and Cons of sawtooth roof arrangement [1], [5], [6], [7], [8]

Pros:

- Reduction of direct solar gain with the presupposition that the glass surfaces face north in the northern hemisphere and south in the southern hemisphere.

Cons:

- Orientation is a critical issue therefore it is not always feasible design. It is not recommended in cases where there are tall adjacent buildings in the north facade because they will reduce drastically the portion of sky that is visible from the glazing surfaces. This automatically implies decline of daylight factor.
- Direct light is undirected so glare discomfort often occurs. Tall interior obstructions cause heavy shadows. This is very common in storehouses so definitely it must consider as the latest cost-effective solution in storehouses.
- Need of large glass surfaces for achieving acceptable daylight factor.
- Aesthetic drawbacks, many designers have described that roof geometry as " dark satanic mills".

3.3.4 Pros and Cons of monitor roof arrangement [1], [5], [6], [7], [8]

Pros:

- Sufficient daylight factor and acceptable visual comfort by utilizing the great amount of illumination of being derived from the north and a small proportion from the south providing directional and colour corrections to the north light.
- Easy and safe access to roof for cleaning the outside of windows.
- Sufficient control to sunlight, especially with asymmetrical monitors

Cons:

- Relatively, expensive structure because for equal areas of glazing surfaces it provides less daylight.
- Aesthetic outcome, specifically designed to provide a modern image mainly for industrial buildings.

Since it has been defined the geometry of roof it is easily now to discuss the alternative external shading devices that fit to each geometry.

3.4 Qualitative tips for shading device selection [3]

The assessment of different shading devices is associated directly with the site and glazing orientation. For the monitor and sawtooth roof shape the glazing surfaces are usually vertical or have a slight tilt from the vertical axis. Thus, all the available shading devices for a vertical window at dwelling houses are expectant for utilisation. In the following pages are discussed some of the most common shading arrangements.

Standard horizontal shading devices (see figure 3.3 and 3.4) suit better for low latitude (between +10^o and –10^o degrees) and for vertical glazing surfaces that face south in the northern hemisphere and north in the southern hemisphere. Specifically, at that latitude the sun altitude, during the working hours (between 09:00 and 16:00), throughout the year is always greater than 40^o degrees as it can be seen from the figure 3.5 and 3.6. The interpretation of theses figures is that there is a protection need from sun of high elevation.

A modification of horizontal shading forms is presented in figure 3.7

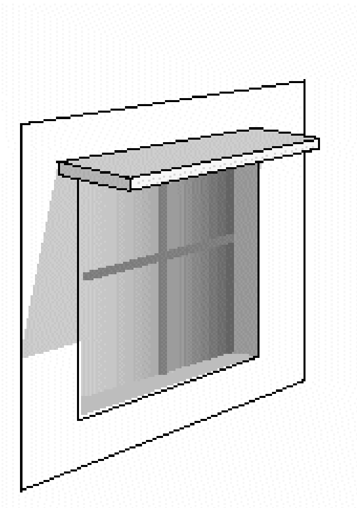

Figure 3.3: Solid horizontal overhang [3]

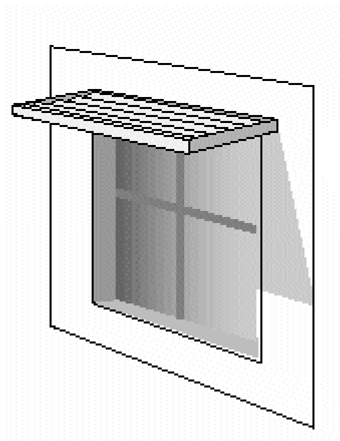

Figure 3.4: Louvers horizontal overhang For more diffuse light still shading [3]

These shapes are more preferential for sites with latitude (between +20^o and +10^o degrees or between -20^o and -10^o degrees) because the elevation of sun at these sites is slightly lower, approximately 10^o degrees. Generally in dwellings or offices that difference is able to cause glare especially during the winter period so a slope down or drop off the edge of shading device is sufficient to prevent unwanted glare from the low sun without really

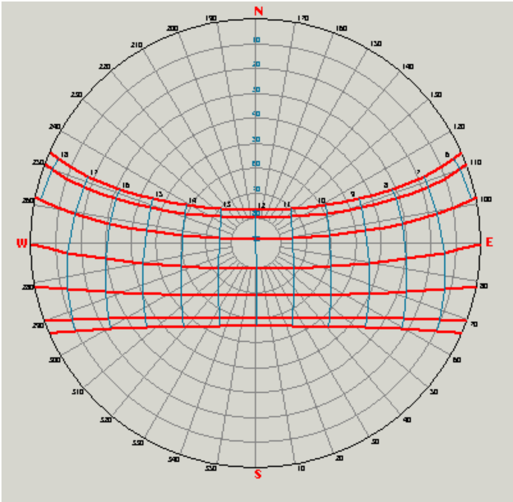

Figure 3.5: Sun Path diagram (Latitude 10^{o} N) [9]

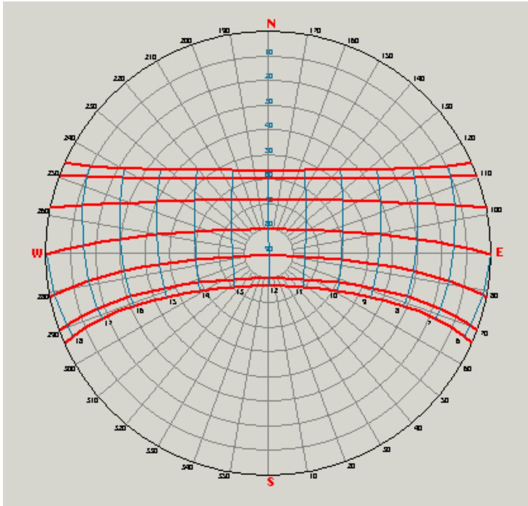

Figure 3.6: Sun Path diagram (Latitude -10^{o} N) [9]

affecting significantly the daylight factor in the interior of the building. However, this is not true for a storehouse because there are windows only in roof so the tilted ceiling will be illuminated and will act as luminaire. Taking into consideration that low sun exist mainly in winter, a removable horizontal device seems to be a promising solution in building with monitor or sawtooth roof. Detailed diagrams, that justify the statements of the present study, of sun elevation above the horizon for different latitudes can be found in the appendix-1.

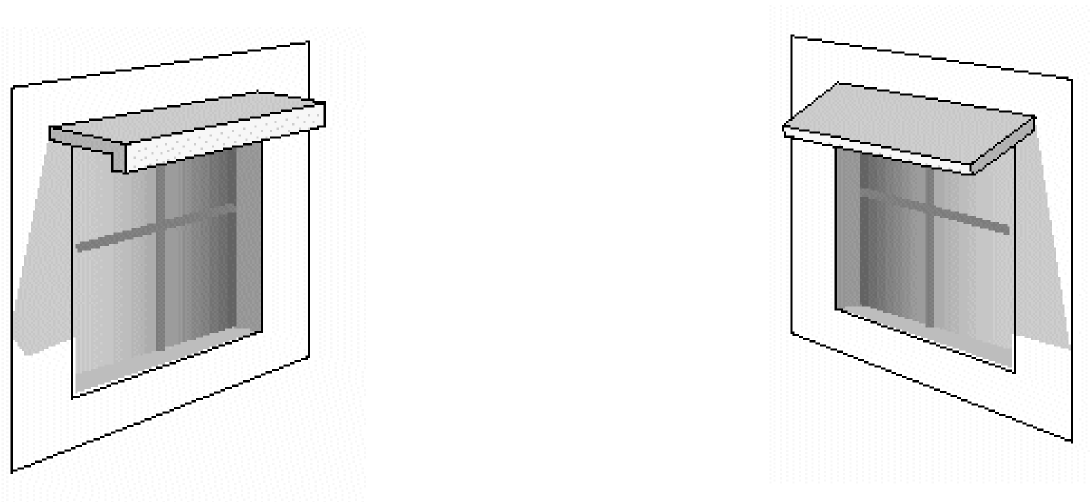

Figure 3.7: Solid slopping overhang [3]

Additionally, for the previous sites a more uniform distribution of light inside a building can be achieved by using more than one solid horizontal overhang placing in parallel. This arrangement is shown in the figure 3.8. A portion of the reflected solar radiation, from the series of shading devices, illuminates the ceiling and the background of the space and this results the better light distribution and the minimization of glare surfaces.

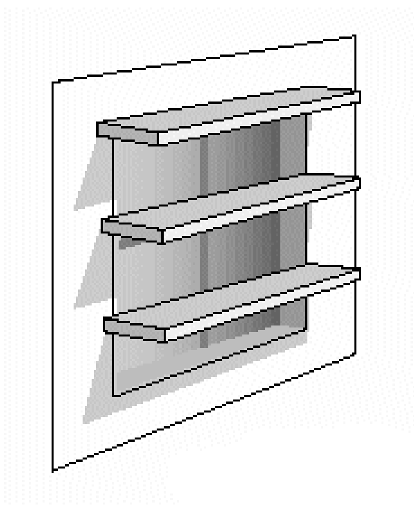

Figure 3.8: Parallel horizontal overhangs for better light distribution [3]

Vertical shading devices are fitted better in dwelling and offices on west and east facade at high altitude [3]. On the other hand they are not effective for monitor and sawtooth roof shape, with the same orientation, because direct sun rarely reach the working plane at that time. Regarding the sawtooth geometry it is obvious that careful design of roof can act as vertical shading device during the morning and afternoon hours where the elevation of sun is low. Regarding, the monitor roof shape low sun elevation it is nearly impossible to cause glare discomfort on working plane due to its geometry. Despite that generally, the recommendations of vertical shading arrangements are mainly for west and east facades they will be very effective for vertical windows that face south in the northern hemisphere, at site with high latitude, during sunny winter days due to the low sun elevation. The figure 3.9 illustrates a typical vertical shading device.

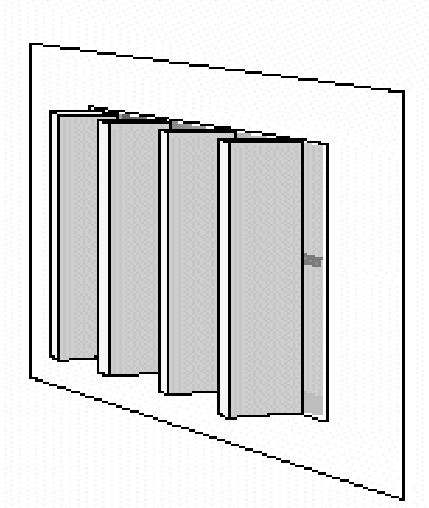

Figure 3.9: Vertical shading device (louvers)
for east and west facades [3]

For horizontal and shed roofs of low inclination (between $+5^o$ and $+15^o$ degrees) use of shading devices with high slope are more effective mainly at sites of high latitude. The low winter and high summer sunrays can effectively reflect and enter into building as diffuse light without causing glare mainly during the summer. Moreover, they allow admittance of sky light from higher altitude closer to zenith where the sky luminance is greater.

However, the closer to equator the building is the lower slope is required for reduction of glare, because the sun altitude during the working hours throughout the year is greater than $+70^0$ degrees. This implies that for a cloudy day less skylight enters from lower altitude which is less bright.

The figure 3.10 illustrates how the sunrays enter into a building with shed roof.

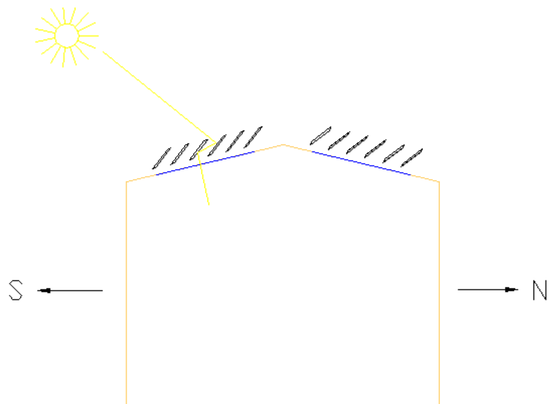

Figure 3.10: Shed roof with
slopping shading

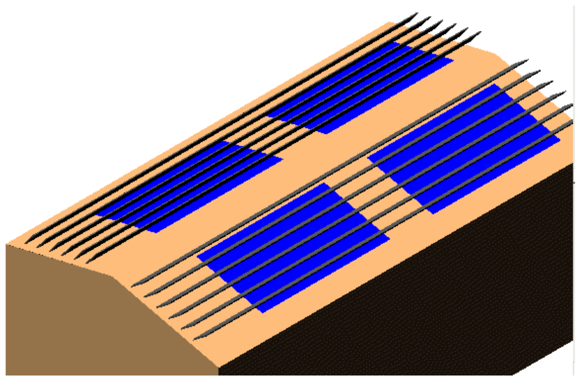

Figure 3.11: Perspective view of shed
roof with slopping shading

Figure 3.11 demonstrates a perspective view of a building with shed roof and slopping shading approximately 45^o degrees.

On first sight, one may wonder what are the benefits of using shading along the roof and not restricts it only above windows. Actually there are two benefits, firstly this continuous shading reduces glare from morning and afternoon sun and secondly diminishes summer overheating since less roof area is exposed to solar radiation. Additionally, taking into account the fact that the sun altitude during summer is between 65^0 to 90^o degrees, at most sites, it can be concluded that the sun rays will strike the ceiling perpendicularly enhancing the heat gain and rise the interior temperature.

Up to this point it has qualitatively been discussed the benefits of different shading devices in combination with roof geometry. Unfortunately, the qualitative analysis does not have objective metrics that can be used to form rules of thumb. Therefore, a quantitative analysis is required. For the purpose of that analysis it has been generated and simulated different models based on which it has been extracted the conclusions of the present study. Despite that in the present Chapter the thermal comfort has been examined in the qualitative analysis, the present dissertation has not considered it in the quantitative analysis because by its self consists an entire thesis.

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4. Pre-Processing Analysis

4.1 Selection of models

A major concern initially for the quantitative analysis of daylight under different roof geometries and shading devices was the selection and creation of appropriate models for simulation. Thus, the modelling procedure was to create at least one model for each roof shape. This would not be sufficient to extract objective information about the comparison of daylight illumination in the interior of each model because variation in slope of shed roof, different window arrangements and orientation of glazing surfaces is known that affect the interior illumination. [1], [2]

Therefore, three different models were created for shed roof shape with five, fifteen and twenty five degrees slope in order to understand better the effect of slope on the illuminance level. More over there are windows from both sides of the roof so that the quantitative results will be independent of the orientation. Additionally, the glazing surface area is $40m^2$ and occupies 44% , 43% and 40% of the total roof area respectively. The other dimensions of the storehouse are 15m width, 6m depth and 3.6m height. The perspective three-dimensional view of each shed roof model is illustrated in the Appendix-2 in figures (1-2-3).

There has been created four model variants for flat roof. By varying the number of windows whilst keeping constant the glazing area, the quantification of the illuminance distribution in the interior of the storehouse was possible. Specifically, the models consist of two, four, eight and sixteen equal area windows. The rest dimensions of the building are the same as the previous building with shed roof in order to achieve neutral comparison between buildings. The perspective three-dimensional view of each flat roof model is illustrated in the Appendix-2 in figures (4-5-6-7).

For the sawtooth roof two models have been created. The first consists of two horizontal windows facing North and the second one of three horizontal windows facing North as well. In both models the glazing area has been kept equal to $40m^2$. The variation in the number of windows is arisen from the need to investigate which model provides more uniform daylight in the interior. Moreover, the North orientation of windows has been chosen because is the best orientation for that kind of roof in order to avoid glare discomfort. The perspective three-dimensional view of each sawtooth roof model is illustrated in the Appendix-2 in figures (8-9).

Finally, based on the qualitative discussion of chapter 3 the less popular monitor roof has a lot of drawbacks therefore only one model consisting of four windows from which two face East and the other two West has been created. This is also the best orientation for the windows of a monitor roof because there is less probability of having direct sun in the interior. The purpose of that model was solely to gain a quantitative idea of how much worse is its Daylight performance. The perspective three-dimensional view of the monitor roof model is illustrated in the Appendix-2 in figure 10.

Summarising the models, it is expected in advance that the last two types of roof to give better results compared to other roof types in terms of glare under intermediate sky conditions but the purpose of the study is to quantify that better performance.

The table 4.1 synopsises the ten models that have been examined in this study under different sky conditions.

Roof Type	Arrangement	Sky models	Location and Orientation
Shed	5^0 degrees slope	Overcast CIE & Intermediate	Latitude 56^0 and longitude 0^0. Windows face north and south respectively
	15^0 degrees slope		
	25^0 degrees slope		
Flat	2 windows	Overcast CIE & Intermediate	Latitude 56^0 and longitude 0^0
	4 windows		
	8 windows		
	16 windows		
Sawtooth	2 ‘saws’	Overcast CIE & Intermediate	Latitude 56^0 and longitude 0^0. Windows face north and ‘saws’ have 45^0 degrees slope.
	3 ‘saws’		

Monitor	2 'monitors'	Overcast CIE & Intermediate	Latitude 56^0 and longitude 0^0. Two windows face east and two west.

Table 4.1: Synopsis of models

4.2 Simulation tools

A very common problem that a researcher faces when has taken the decision to use simulation method for assessing daylight in the interior of a building is the choice of software package. Many times, the results and so the conclusions are not accurate or valid due to wrong choice of software. Therefore, despite there is a variety of available software in the market such as Daylight, Lightscape [3], Radiance and some other, for the need of the present simulations Radiance has been used. It is the most reliable [3] software at present and also it is provided free of charge by the Lawrence Buckley National Laboratory [3]. These two factors have taken into account for its use at the described study. The only major drawback of it is that it is not user friendly because it does not contain graphical interface and also it runs in Unix environment. Thus, it is refers to users familiar with Unix operating system and requires programming skills specifically C-shell for organisation and manipulation of models. Further details and tips are given in section 4.4.

However, the much more friendly Esp-r software for energy simulations in buildings that has been developed by the Energy Systems Research Unit (ESRU) based within the Department of Mechanical Engineering at the University of Strathclyde provides the facility to convert three-dimensional geometry compatible for Radiance geometry. Due to that it is strongly recommend the use of former software program as a converter. This will minimise the three-dimensional geometry creation time significantly.

A brief description of Radiance is necessitated for helping every reader to understand that powerful software tool. Specifically, Radiance was developed by the Lawrence Buckley National Laboratory as a research tool for predicting the distribution of visible radiation in lit spaces. Based on the three-dimensional geometry of the physical environment produces a map of spectral radiance values in a colour image. The technique of 'Ray Tracing' is used for rendering images by following individual rays of light from the viewpoint backwards to the light source(s). As source or sources can be considered the sunlight, a luminaire or a window.

Specifically, the process for producing an image consists mainly of four steps. The first involves creating or converting a three dimensional description of a scene (geometry of space, roof and furniture) into simple elements that can be interpreted by the Radiance software. Such elements include polygons, spheres, cylinders and cones. These must then be assigned a specific material or property such as glass, wood, plastic and metal. The detailed description of those files is presented in table 4.2 and Appendix-4. The second step also includes the setting up of specific light source(s), their strength, type and distribution if necessary. As source or sources can be considered the sunlight, a luminaire or a window. The third step is to convert and join all the above files into a specific file that is called octree and it is used for rendering the scene by rpict [4] program. The final step is to render the scene to produce an image. This image may then be 'analysed' and 'filtered' in a variety of ways depending on the required application. This process is an interactive one so the designer can easily change the geometry, material and source(s) specifications until the required design has been reached. For a complete description of the Radiance files refer to the Appendix-4 of this dissertation.

Due to the ability of Radiance to produce realistic images from a simple description it has popularised in a wide range of applications in graphic arts, lighting design, computer aided engineering and architecture.

4.3 Simulation procedure

Chapter 2 discussed that overcast standard CIE sky is a good representation of conditions in many parts of north Europe. Despite that the Radiance calculations gives sky zenith luminance value approximately ten to twenty percent lower than really exist in high latitude it is still valid for our quantification because the sky conditions remain constant for all models [6] . This drawback has to been taken into account only for assessing the visual comfort and has no effect on the quantification comparison between different roof geometry.

Moreover, it has considered another type of sky condition the intermediate sky, partially cloudy sky (30 % cloud cover) with sun in order to cover sky conditions mainly during the summer period. It has not calculated the illuminance in the interior of the models under clear sky with sun because this condition does not really exist in high latitude such as Scotland where the examined models are located. Additionally, the function that generates sky luminance distribution of Radiance does not provide reasonable illuminance values and since one of the purposes of the present study is the understanding and quantification of sun effect in the interior illuminance this will lead to wrong conclusions [6] .

Finally, it has calculated the illuminance in different illuminated spaces for the twelve months of year under the forenamed sky conditions for three different hours, nine in the morning, noontime and five in the afternoon. The choice of hours is not random but coincides with the hours of occupancy of storehouses or covers them to the highest extent. In addition, based on these hours a researcher can derives conclusions and quantify the effect of low as well as of high elevation sun in the interior illuminance throughout the year.

4.4 Manipulation modelling tips

Very often, someone may find guidelines about modelling procedure and what aspects may consider but rarely can meet texts regarding the organising and manipulation of all the files and data that are required for simulation analysis. Thus, the present study outlines an effective approach for modelling file organisation and results data manipulation. It is worth mentioning that the following tips refer to readers that are familiar with Radiance and C-shell programming otherwise a prior study of Radiance manual and C-shell programming book [5] is required for better understanding.

The proposal, for each model, that derives from the existing dissertation is that a analyser would better use eleven files. Five are Radiance files containing the three-dimensional geometry and material of the scene, ground and sky. Four are script files that automate the calculations of the general daylight factor, the generation of luminance and illuminance pictures for different sky conditions and time. Two are supporting files for scripts. The description of files is presented in the Table 4.2. The detailed description of commands does not discussed in this section because it derives from the content of scripts files that are presented in Appendix-4. Therefore, consultation of Appendix-4 is necessary.

Finally, by following the below procedure an analyser will save time and effort for his calculations which is very important especially when there are time constrains.

Files Name	Description
Radiance files	
Model_in.rad	Contains the interior composition of the scene or space.
Model_out.rad	Contains the exterior composition of the scene or space.
Model.mat	Contains the material properties of the scene or space.
Ground.rad	Contains the ground geometry and material plus the material and source descriptions of the sky.
Frozen.oct	This is the frozen octree created by the former files and is used by the following script files.
Script Files	
Gen_script_DF	It shows how to automate the calculations for the general Daylight Factor (see following paragraph for more information about that magnitude).
Sum_DF	Summarised the results of the general Daylight Factor for the whole year in one file.
Script_rpict	It shows how to automate the generation of luminance and illuminance pictures for different sky conditions and time.
Rview_pic	It shows how to automate the display of the generated pics for the entire year under different time and sky conditions

Supporting Files for Scripts	
Samp.txt	It provides the coordinates of the positions at which the general Daylight Factor will be calculated
Rpict.opt	It provides the options for rendering the pictures. It is very useful for understanding and determining the sensitivity of the prediction to the number of different options that are taken into account during the rendering process.

Table 4.2 : Recommended files for automate modelling calculations

4.5 General Daylight Factor versus Daylight Factor

Many recommendations of predicting daylight have been introduced by CIE [2] based on Daylight Factor (DF) under overcast sky conditions which have been discussed in detail in section 2.4.1 . Some of them are graphical methods that are not so accurate and require real time conditions. This value of daylight factor then is used for manual calculation of the desired area of skylights (windows in ceiling) to provide sufficient natural lighting in the interior of a building.

This magnitude is sufficient for qualitative comparison between buildings in terms of which space has higher illuminance at a working plane. Unfortunately, it does not provides any quantitative information about the illuminance level in the interior of a building at a specific day and time because there is always the need to know the horizontal illuminance of an unobstructed sky which is varies in reality throughout the year. Additionally, it is not suitable for building assessment because it does not indicate if there will be enough light inside a space because despite many authors suggest that DF greater than five percent 5% is sufficient for full daylighting in building, it is not a general rule [4]. Actually, in January the zenith illuminance does not exceed the value of 5,000 Lux therefore if someone follows the previous rule he will lead to conclusion that the light in the interior is sufficient for full daylight.

However this is not altogether correct because the illuminance level is sufficient only for activities required illuminance less than 250 Lux.

The drawback of DF can be overcome by using illuminance level but this magnitude has the shortcoming that it is not easily interpreted, especially from people without lighting engineering background. It is quite complicated to apprehend the difference of 8,000 Lux and 12,000 Lux because these are numbers that mainly instruments easily comprehend. A person certainly has the sight of the overcast sky zenith illuminance in the northern Europe. Due to that a magnitude that is expressed as a percentage of the average zenith illuminance of the overcast sky would be more convenient for a person without lighting engineering and also for lighting engineers because they can accurately calculate the illuminance level by multiplying that magnitude by the average zenith illuminance of the overcast sky.

Thus, for the quantitative comparison of the models and under different sky conditions it has been introduced a new size which is the general Daylight Factor. This is defines as:

$$\text{General Daylight Factor} = \frac{\text{illuminance at the working plane}}{\text{Average zenith illuminance of overcast CIE sky}} * 100 \quad [\%]$$

where average zenith illuminance of overcast CIE sky equals to 10,000 Lux [4].

This general Daylight Factor provides the facility of neutral comparison between different roofs geometry because by just multiplying it by 10,000 someone calculates the illuminance level in the interior without knowing the zenith illuminance for a specific day and time. Moreover, it takes into account overcast and intermidate sky conditions. It units is also percentage and someone can determine the gain in the illuminance level under partially sunny day compared to an overcast day by just subtracting the two values. Finally, this magnitude can easily be interpreted even from a person who does not have lighting background for instance if under a partially cloudy day with sun the illuminance level at a position is ninety percent 90% this creates almost similar result on the eye of an observer who is looking at the zenith of the sky in April month.

4.6 Determination of rtrace parameters

The most crucial stage of a simulation with Radiance is the correct or precise determination of rtrace parameters which are listed in this section below. Rtrace is a Radiance program that computes individual radiance or irradiance values for daylighting analysis. Input is a scene octree plus the positions of the desired point calculations (see Frozen.oct and Samp.txt in table 4.2 and Appendix-4). Obviously, erroneous setting up of those parameters gives wrong results of luminance or illuminance at a plane. Unfortunately, there is no ‘rule-of-thumb’ for them but just recommendations because these parameters related directly with the model and the analysis that a user want to implement. So, prior determination of those parameters has been done for all the work described in chapter 5 in order the analysis to be based on valid results. There are two approaches for this the first is to set up the strictest values for them and the second is someone based on the attributes of those parameters to use the ‘try and error’ method and examine the results. Definitely the first approach will lead an analyser to endless calculations without distinguishing difference in the accuracy of results because the error will be so small and the difference in time calculations will be incredibly high.

The most important parameters that affect the calculation of illuminance and so the General Daylight Factor (GDF) are described below. These parameters are [4] :

- ab the number of ambient bounces which is related with the inter-reflection;
- ad the number of ambient divisions which is related with the additional rays that are sent in random directions for sampling the openings and sky;
- aa the ambient accuracy which determines the maximum error permitted in the indirect irradiance interpolation;
- av the constant ambient approximation which is related with the constant ambient illuminance assuming uniform sky conditions;
- as the number of ambient super samples which is related with the extra rays that are used for sampling areas with high radiance variance and

- ar the ambient resolution which is related with the accuracy of indirect irradiance interpolation.

Further details a reader can be found in the Radiance manual [7] . The most crucial parameters from the above is the number of ambient divisions, super samples and bounces which can gives completely different illuminance values for the same model specifically if the interior materials of the scene have high reflectance such as white light walls. The figure 4.1 illustrates the sensitivity of the General Daylight Factor prediction for different number of ambient bounces, ambient divisions equal 1024 and ambient super samples equal 64. The Rpict.opt files in Appendix-4 contains all the parameters that have been used by rtrace in this study.

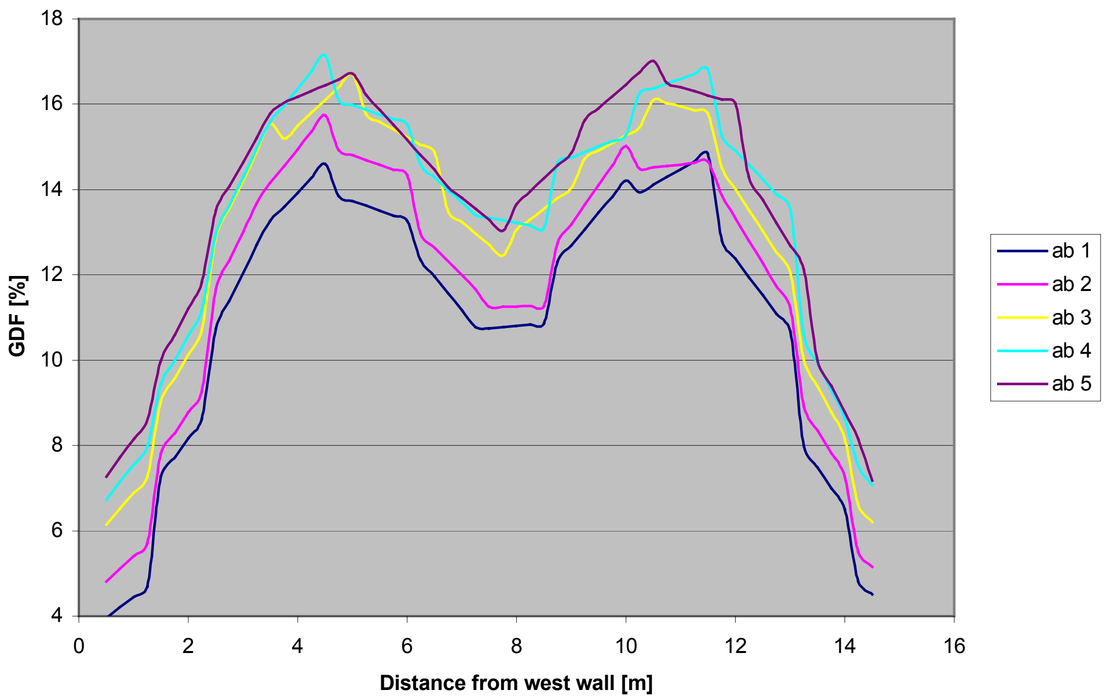


Figure 4.1: General Daylight Factor plots for different ambient bounces number

From that figure 4.1 is obvious that if an analyser bases his analysis in number of ambient bounces less than four he will introduce quite high percentage of error his conclusions. The figure 4.2 presents the error that arises for different ambient values.

The error in the calculations of General Daylight Factor is significantly high for positions near the west or east wall and reduces for positions closer to windows. The positions under the glazing surfaces or close to them received direct light from the sky, which is the predominant factor for the final value of General Daylight Factor on the other hand the rest of positions receive light through inter-reflection. Therefore for the existing analysis it has been chosen between four and five number of ambient bounces in order to represent the reality and minimise the error in calculations. So the criterion will be solely the smoother plot since the error that introduces is very small. Obviously, the number of five ambient bounces gives the smoothest plot and this value has been used for the calculations of the present study. A researcher can further increases the smoothness of the plot by reducing the ambient accuracy, increasing the number of ambient divisions and super samples but he will rise dramatically the time of calculations and it is not worth doing it.

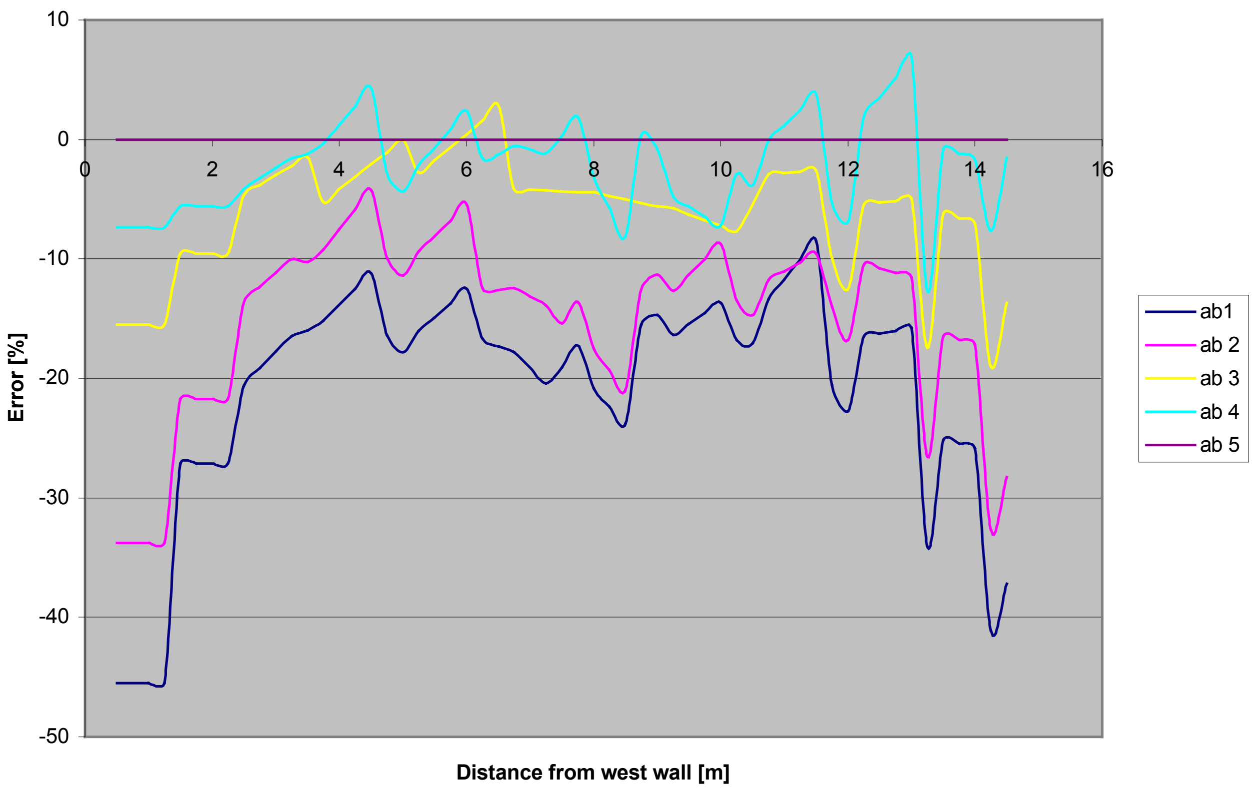


Figure 4.2 : General Daylight Factor error for different number of ambient bounces

The above procedure is very important for any lighting simulations and justifies that the results of the present study have been filtered and validated in terms of their accuracy. So the quantification of the roof geometry and the shading devices that is discussed in the following chapter based upon valid results.

References:

1. Stanley L. Lynos, ‘Handook of Industrial Lighting’ ,Butterworth & Co 1981

2. ‘Daylight internal recommendations for the calculation of natural Daylight’, CIE No. 16, 1970

3. J. Mardaljevic, ‘Daylight Simulation: Validation, Sky Models and Daylight Coefficients, PhD, 1999

4. G W Larson & R Shakespeare, ‘Rendering with Radiance’, Morgan Kaufmann Publishers, 1997

5. P. Dubois, ‘Using csh & tcsh’, O’Reilly, 1995

6. http://radsite.lbl.gov/radiance/digests_html

7. http://radsite.lbl.gov/radiance/man_html/whatis_some.html

5. Results Analysis

The models discussed in Chapter four generated totally sixty graphs of General Daylight Factor along the middle position of the storehouse under overcast standard CIE and intermediate sky for the fifteenth day of each month at 09:00, 13:00 and 17:00 hours.

This chapter analyses the performance of each model and identify the best solution of roof solely in terms of illuminance level, and illuminance distribution because none of the roof shape causes visual discomfort based on Guth's formula under overcast and intermediate sky conditions for a person who is moving along the middle point of the space, where it is assumed that the corridor is, and looking to the west and east wall. The performance criteria used for assessing illuminance level and illuminance distribution are the average General Daylight Factor and the standard deviation of the General Daylight Factor respectively.

Firstly, the analysis will determine which is the best solution among similar roofs shape and then will consider and compare different roof shapes. So its roof shape will discuss individually at the first stage. Based on that analysis it has classified the performance of its roof and has determined the need, if there is any, for shading devices. Before that analysis a qualitative overview of the results is needed for easier introduction to the quantitative analysis

5.1 Qualitative overview

It is tangible from the graphs in Appendix-3 that in the region of Scotland a storehouse having one of the previous mentioned roofs cannot base its lighting entirely to daylight. Specifically, during the months October, November, December, January and February use of artificial lighting is need during the afternoon hours after 16:00pm because there is not sufficient illuminance level in the interior for storehouse activities.

The variation of illuminance with shed, flat and monitor roof is much greater for intermediate sky compared to overcast sky for the summer months compared to winter due to sun gain and higher elevation of the sun during the summer months as it has referred in chapter 2. Specifically for shed, flat and monitor roof that variation is higher while for sawtooth is much lower. This difference in the variation of illuminance between the first three models and the last one indicates that the last one allows fewer sunrays to enter into the building during the partially sunny summer days. These differences are analysed in the following paragraphs.

5.2 Individual roof analysis

It has not included in the main part of analysis the plots of GDF for each model because the statistical analysis of them have considered more important and the conclusions have derived from it. However, the plots of GDF for the examined models under different sky conditions are presented in Appendix-3.

Moreover the individual analysis has been divided in two parts, overcast sky and intermediate sky. The table 4.3 summarises the sequence of individual roof analysis between similar roof geometry.

Individual Analysis	**Sky Conditions**	
	Overcast CIE standard	**Intermediate**
Shed roof	Comparison between 5^o, 15^o and 25^o degrees slope	Comparison between 5^o, 15^o and 25^o degrees slope
Flat roof	Comparison between 2, 4, 8 and 16 windows	Comparison between 2, 4, 8 and 16 windows
Sawtooth roof	Comparison between 2 and 3 'saws'	Comparison between 2 and 3 'saws'

Table 4.3: Summarisation of individual roof analysis between similar roof geometry

From the individual roof analysis it will be derived which roof geometry, between similar roof arrangements, gives better daylight performance with regard to illuminance level and illuminance distribution. These roof geometries will be then compared to find out the best roof arrangement.

5.2.1 Shed Roof with Overcast CIE Sky

From the graphs in the Appendix-3 for overcast CIE sky and for shed roof someone can observe that the Daylight Factor reduces with the rise of roof slope. This happens because rise of slope entails that the midpoints along the space view sky portion of lower zenith angle and based on the equations 2.12 in chapter 2 those portion of sky has lower luminance compared to sky of higher zenith angle [3]. It was tried to classify that illuminance reduction with the slope of roof based on the average illuminance of those points for each month, day and hour. After statistical analysis that has been done it has realised that this reduction is independent of month, day and hour and it is a function only of slope because the sky luminance despite that it increases from winter to summer it reduces at equal portions with the reduction of zenith angle at those months. Therefore, the figure 5.1 presents the variation of General Daylight Factor of the three models for 15th January at 09:00 which is a representative example of that reduction.

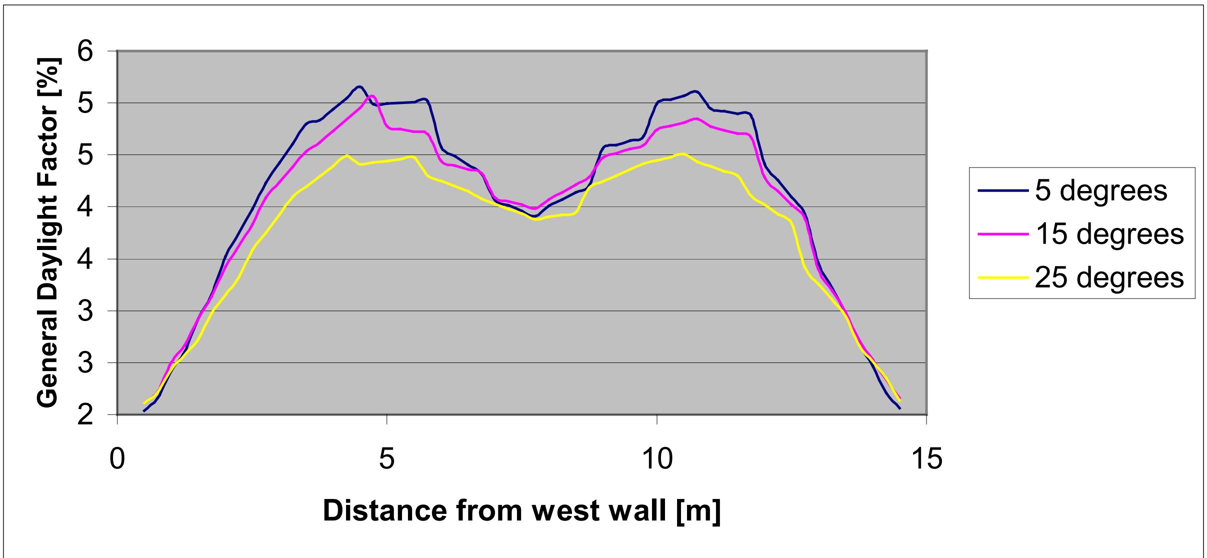


Figure 5.1 : Variation of GDF of shed models with 5, 15 and 25 degrees roof slope

The average General Daylight Factor or illuminance of 15 and 25 degrees slope shed roof normalized to the average General Daylight Factor or illuminance of 5 degrees slope is shown in the figure 5.2. From that figure it is concluded that the reduction is not a linear function of slope since it reduces by 2% and 9% percent respectively. In terms of illuminance level the 5 degrees slope is the best.

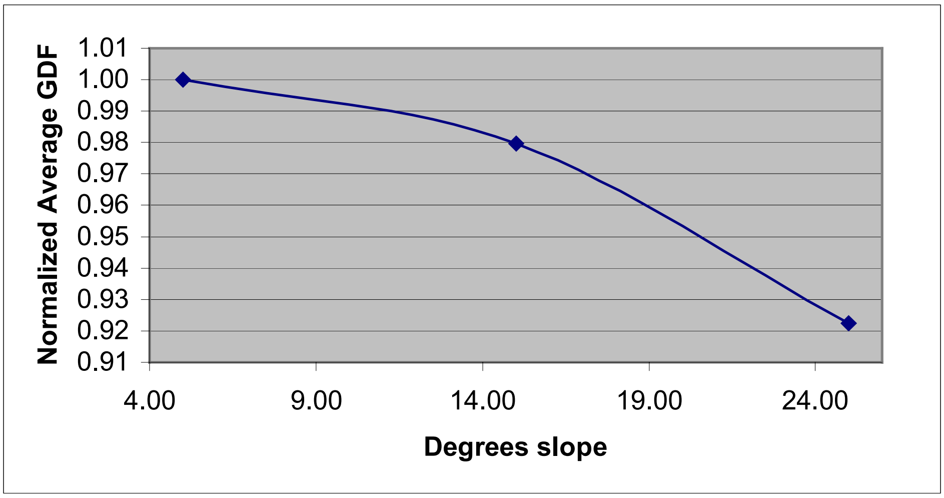


Figure 5.2 : Normalized average General Daylight Factor reduction with roof slope

The General Daylight Factor or illuminance distribution has been assessed based on standard deviation. After statistical analysis it is concluded that the standard deviation varies with the month and time but the normalized standard deviation of 5 and 15 degrees slope to 25 degrees slope remains constant with the month and hour. The figure 5.3 illustrates the variation of this normalized standard deviation. The interpretation of the figure is that it can be achieved more uniform illuminance level in the interior of the space with 25 degrees slope compared to the rest roofs geometry.

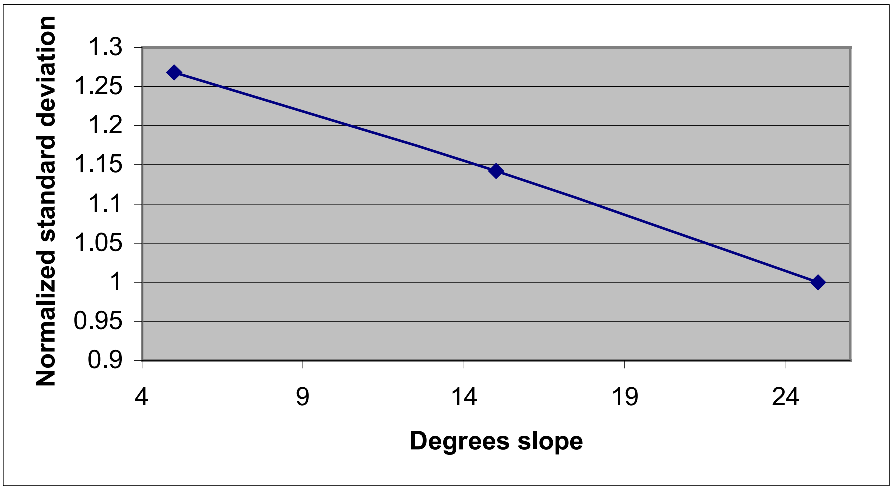
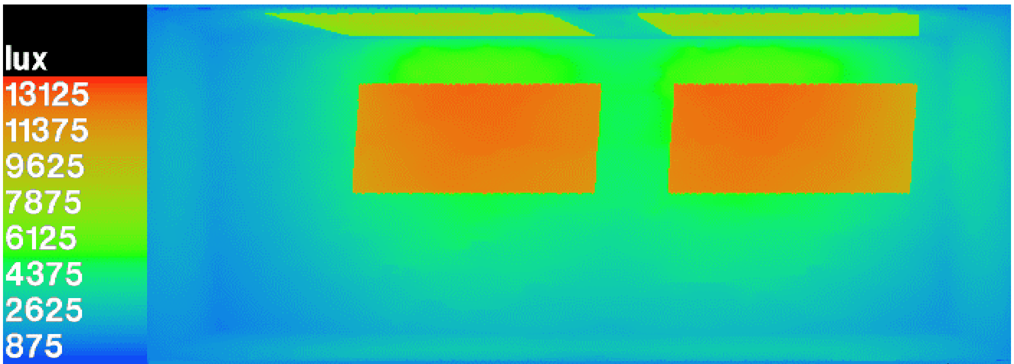


Figure 5.3 Normalized Standard deviation of General Daylight Factor with roof slope

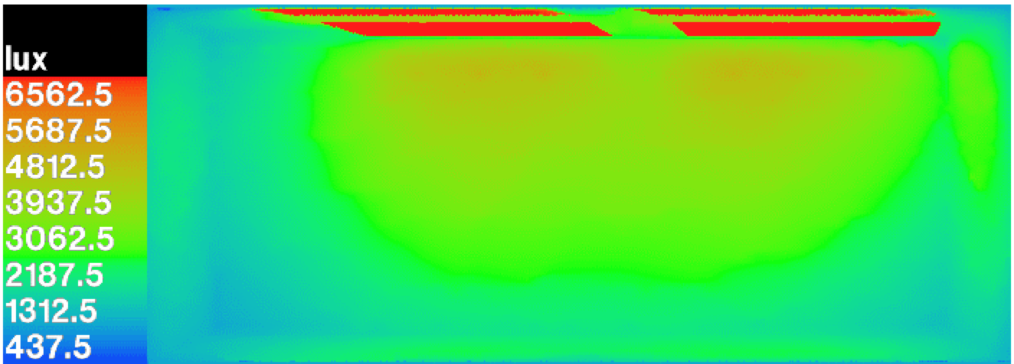
Generally, it is desired in the interior of a space the illuminance level to be as more uniform as possible [1]. So the criterion for choosing the roof geometry will be the illuminance distribution since the normalized average daylight factor reduction with the slope is small and also all the three models provides sufficient illuminance level for storehouse activities, greater than 150 Lux [1] . So after the above analysis the conclusion is that the shed roof with 25 degrees slope is the best solution among them and also is cheaper in construction due to higher stiffness that the slope provides [2] .

5.2.2 Shed Roof with Intermediate Sky

By screening the graphs that refer to storehouse with shed roof it can be realized that the effect of sun is severe during the months April, May, June, July and August. Moreover, the statistic analysis shows that there is no distinguishing difference between the level and the distribution of illuminance so all the three models has similar performance. Worth mentioning for these three models is the increase of the illuminance level during the forenamed months. Specifically, the average GDF rises by 300% causing high disturbance in the illuminance distribution without causing visual discomfort. The pictures 5.1 and 5.2 visualise the rise of the illuminance level and the distribution of illuminance in the interior during the summer and spring months .



Picture 5.1 : Illuminance level in the interior of a space with shed roof on 15th of June at 13:00



Picture 5.2 : Illuminance level in the interior of a space with shed roof on 15th of March at 13:00

The red patches represent the direct sun in the interior and thus there is so great difference in illuminance level. Despite that there is no visual discomfort it is strongly recommended the use of shading devices for achieving more uniform illuminance distribution during the summer months. The horizontal slopping shading devices seems a promising solution.

Summarising the performance of the models it is concluded that for both overcast standard CIE sky and intermediate sky the roof slope of 25 degrees seems to give the best Daylighting performance throughout the year.

5.2.3 Flat Roof with Overcast CIE Sky

The statistical analysis shows that for the four models with flat roof there is a reduction in the average General Daylight Factor or illuminance level with the rise of number of windows. Specifically, based on the normalized average General Daylight Factor along the middle points of space with flat roof consisted of two horizontal windows it is concluded that this reduction is independent of month, time. The figure 5.4 shows the quantification reduction of the normalized average General Daylight Factor for these four models.

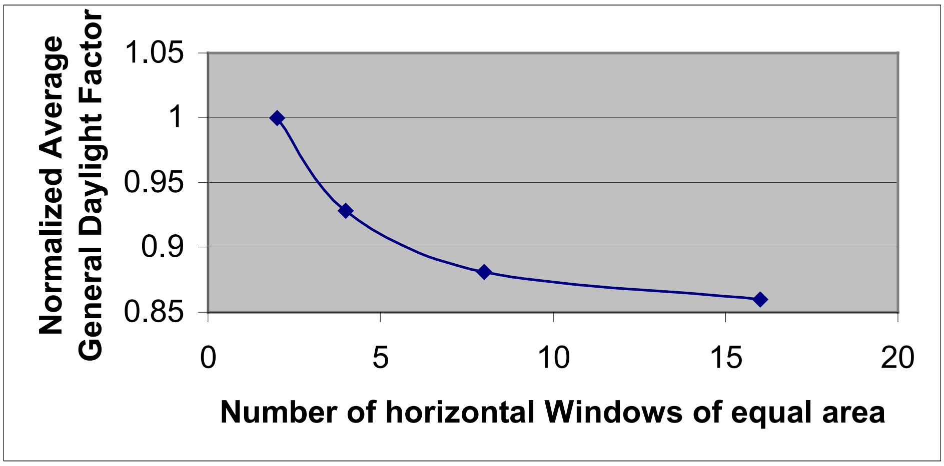


Figure 5.4 : Normalized average General Daylight Factor reduction with the number of horizontal windows of equal area

Moreover, the reduction is not a linear function with the number of windows and also it goes to a plateau at around sixteen windows.

Again, for these set of models the illuminance distribution has considered as well. The figure 5.5 illustrates the variation of the General Daylight Factor.

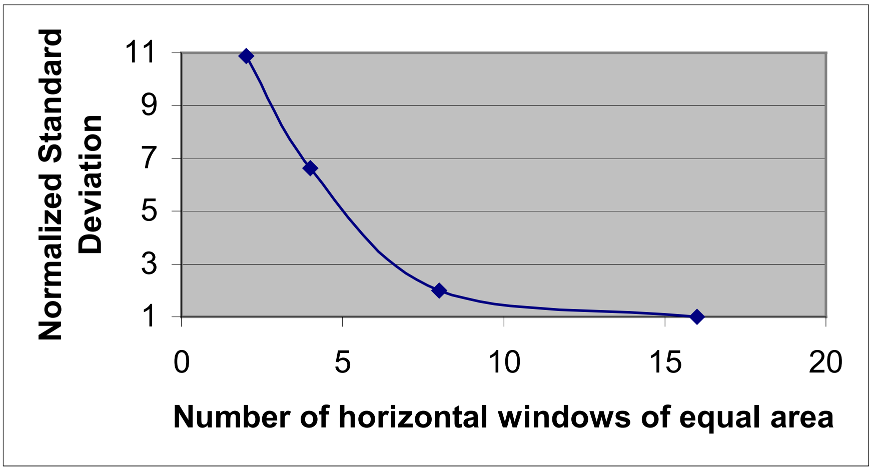
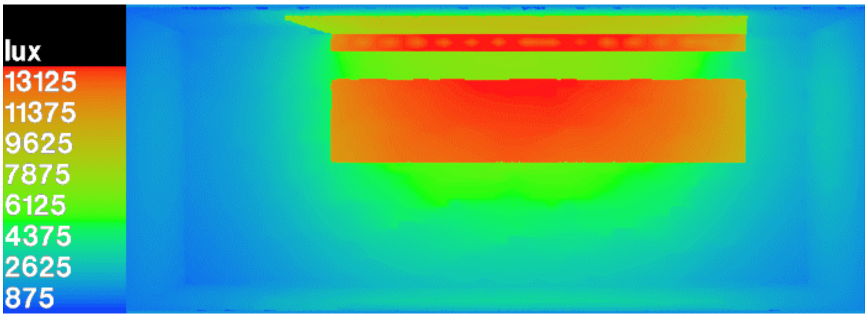


Figure 5.5: Normalized Standard deviation of General Daylight Factor with the number of horizontal windows of equal area

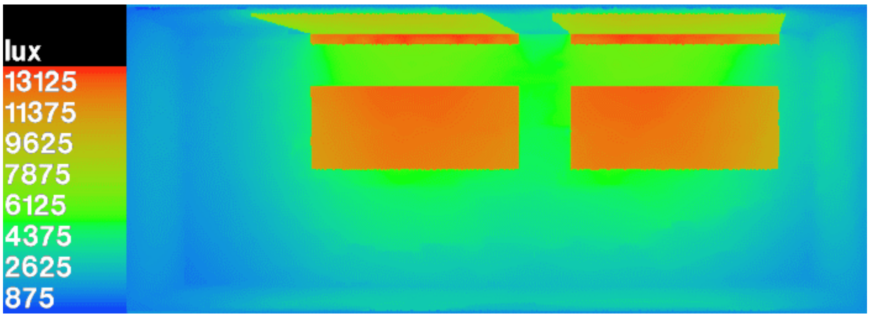
Comparing the reduction of General Daylight Factor to the distribution of it one can realise that the criterion for choosing the roof geometry will be the illuminance distribution because the existing illuminance level is sufficient for working activities. Additionally, there is no distinguishing difference between the distribution of eight and sixteen windows and taking into account that rise of number of windows increases the roof cost [2] the model with eight horizontal windows is better than the rest.

5.2.4 Flat roof Intermediate Sky

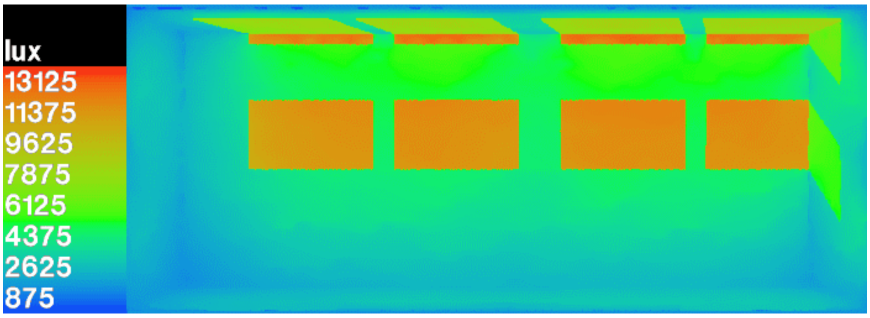
The graphs in the Appendix-3 shows also that the sun gain in the illuminance level is severe during the months April, May, June, July and August for all the models. In these months the average illuminance increases by 400 % compared to summer months. It is not easily quantifiable the performance of these models due to the absent of glare discomfort. Therefore, a visualisation of results that is illustrated in pictures 5.3, 5.4 5.5 and 5.6 will help up to understand the huge difference of illuminance distribution in these spaces and how the sun patches varies under different model.



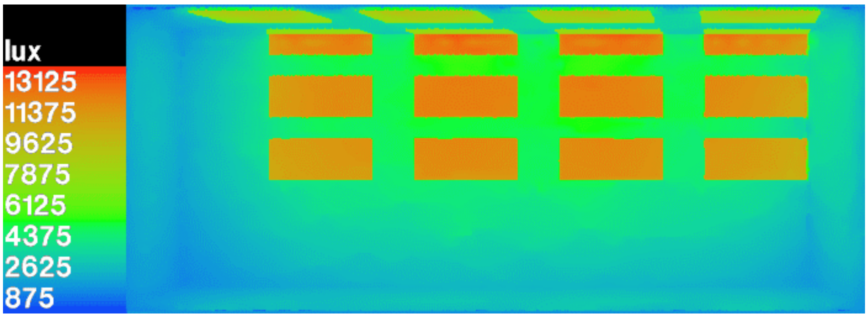
Picture 5.3 : Illuminance level with flat roof and two horizontal windows on 15th of June at 13:00



Picture 5.4: Illuminance level with flat roof and four horizontal windows on 15th of June at 13:00



Picture 5.5: Illuminance level with flat roof and eight horizontal windows on 15th of June at 13:00



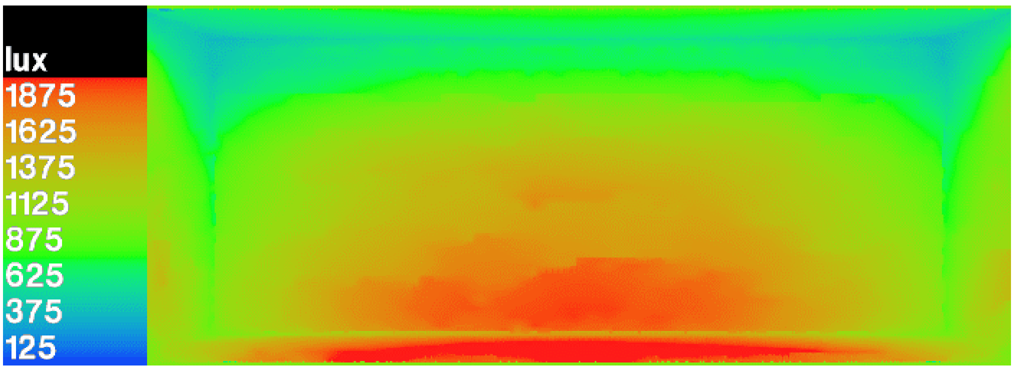
Picture 5.6: Illuminance level with flat roof and sixteen horizontal windows on 15th of June at 13:00

The pictures show that despite with eight and sixteen windows there are more sun patches, red orthogonal shapes, these patches have lower illuminance level compared to patches occurred under two and four windows. This fact causes the more uniform illuminance of the space. Further smoothing of illuminance level in the interior of the storehouse can be achieved by the using of horizontal slopping shading devices.

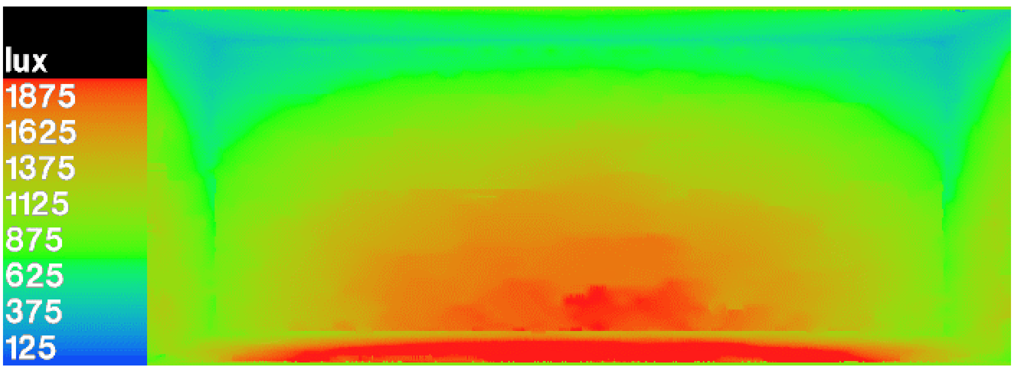
Summarising the performance of these four models it is concluded that for both overcast standard CIE sky and intermediate sky the flat roof with eight windows seems to give the best Daylighting performance throughout the year.

5.2.5 Sawtooth Roof with Overcast CIE Sky

The statistical analysis shows that there is no distinguishing difference, less than 0.5%, in the normalised average Daylight Factor and normalised deviation of it during the year. The visualisation results of illuminance level justify the statistic analysis. The pictures 5.7 and 5.8 illustrate the illuminance variation in the interior of a space with two and three 'saws' respectively.

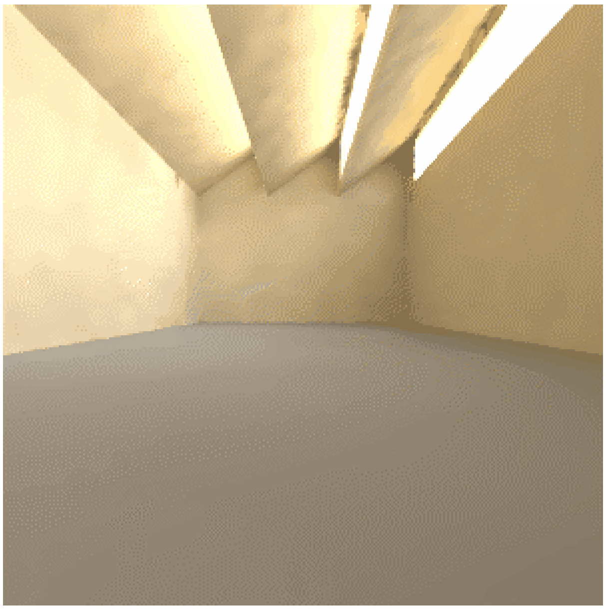


Picture 5.7 : Illuminance distribution with two 'saws' on 15th of June at 13:00



Picture 5.8 : Illuminance distribution with three 'saws' on 15th of June at 13:00

The dark red areas in both pictures indicate that the glazing surfaces are opposite those surfaces and the light arrives at them is mainly direct light from the overcast sky on the other hand the light green areas receive light through inter-reflection. This is easily understandable if someone observes the north wall which none of the positions on it has direct view of sky. Thus, the number of ‘saws’ has no significant effect in the calculations of General Daylight Factor of the positions because none of them have direct view of sky. For better understanding see picture 5.9 that shows how in reality a space with three ‘saws’ is illuminated on 15th of June at 13:00.



Picture 5.9 : Perspective view looking west on 15th of June at 13:00

Since there is no difference between them the cost will determine the best roof shape. Based on the recommendations [1] the best solution is with three ‘saws’.

5.2.6 Sawtooth Roof with Intermediate Sky

The statistical analysis shows that the three ‘saws’ provides slightly higher average illuminance level through out the year compared to two ‘saws’ the average General Daylight Factor for these two models throughout the year at 13:00 is illustrated in the figure 5.6. It must be mentioned that the phenomenon is more severe at 13:00 compared to 09:00 and 17:00 and for this reason it is presented the variation of 13:00.

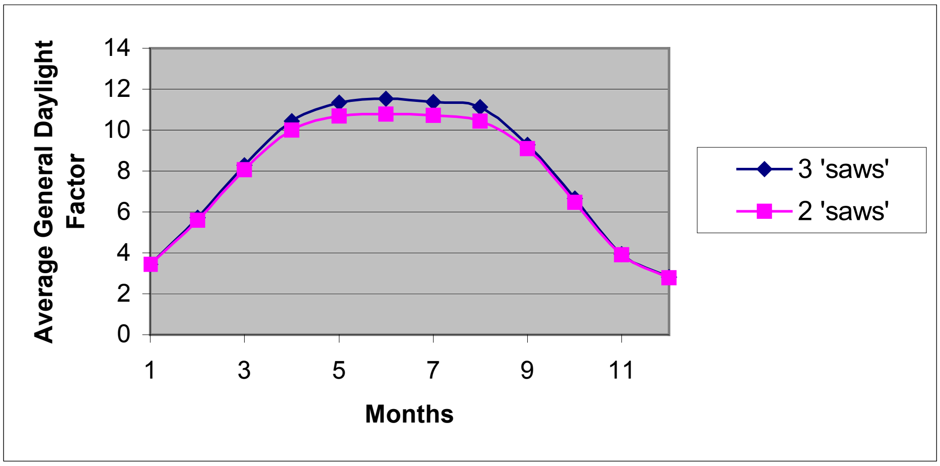


Figure 5.6 : Average General Daylight Factor variation for a year at 13:00

The variation is greater during the summer months, sun of high altitude, and minimises for the rest months. This can be explained with the figure 5.7 which shows how the sun rays of a sun with high altitude admit into the interior for these two models.

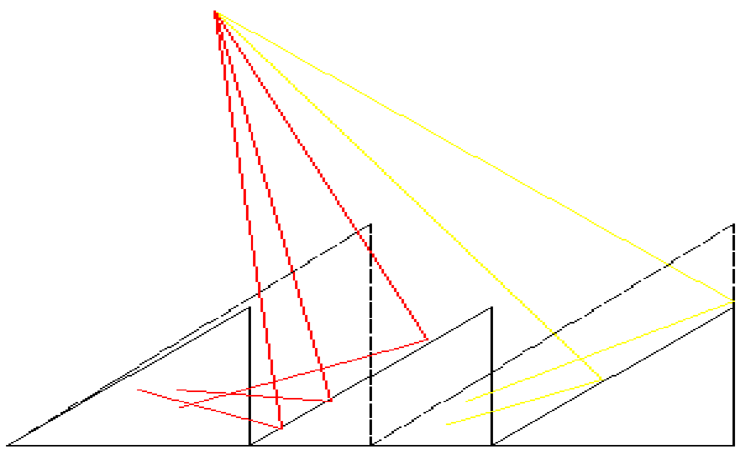


Figure 5.7 : Reflection of sun rays of high altitude of a sawtooth roof with two and three 'saws'

The dashed and solid lines represent a sawtooth roof with two and three 'saws' respectively. The coloured lines show the direction of sunrays that are reflected. It is obvious from the figure that the red sunrays do not enter into space when the sawtooth roof has two 'saws' because they are obstructed by the first 'saw'. On the other hand having three ‘saws’ allow that rays to enter by reflection into the space that causes the slight rise of average illuminance.

Moreover, the standard deviation of the General Daylight Factor remains constant through the year for the two models and there are not sun patches in the interior because the orientation of the roof is north. So even for the intermediate sky the three ‘saws’ is the best solution.

Worth mentioning is that the illuminance level is higher in the interior under overcast sky compared to intermediate sky because there is no direct sun entering into interior and also the luminance of a partially cloudy sky is less than the overcast sky [3] at high altitudes. Based on equation 2.11 in chapter 2 the above distinguishing difference is visualised in figure 5.8.

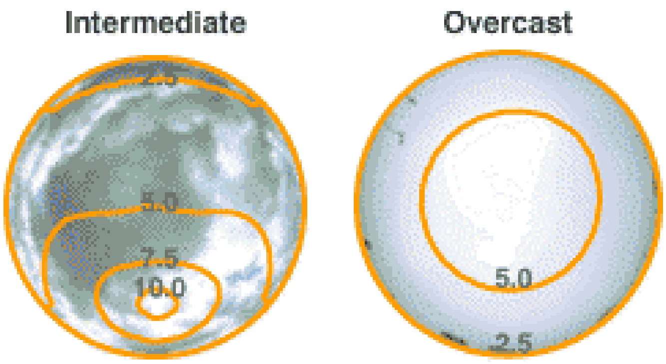


Figure 5.8 Luminance distributions for Intermediate and Overcast sky [kcd/m^2] [4]

Summarising, for both sky conditions the sawtooth roof with three ‘saws’ has slightly better Daylight performance, therefore it is concluded that this is the best roof shape among the swatooth models.

5.2.7 Monitor Roof

Based on chapter 4 there is no need for individual analysis of monitor roof since there is only one model. By screening the graphs in the Appendix –3 one realises that for both overcast sky and intermediate sky the variation in the illuminance distribution is very high and the qualitative analysis in chapter 3 is justified. Moreover despite that the orientation of glazing surfaces has thoroughly chosen to avoid direct sun in the interior, this is inevitable for the summer months May, June, July and August so provision of slopping overhang shading devices will improve the Daylight performance in the interior.

5.3 Analysis among different roof shapes

The first stage of the quantitative analysis has shown which is the best solution among similar roof type geometry the next stage of the present study is to try to quantify the performance these best solutions under overcast and intermediate sky conditions. The models that have been derived from the individual roof analysis from section 5.2 are: shed roof with 25 degrees slope, flat roof with eight horizontal windows, sawtooth roof with three 'saws' and monitor roof.

5.3.1 Overcast CIE sky

The Average General Daylight Factor in the interior for the four-roof types is illustrated in the figure 5.9. The figure shows that the flat roof provides slightly higher illuminance level in the interior compared to shed roof.

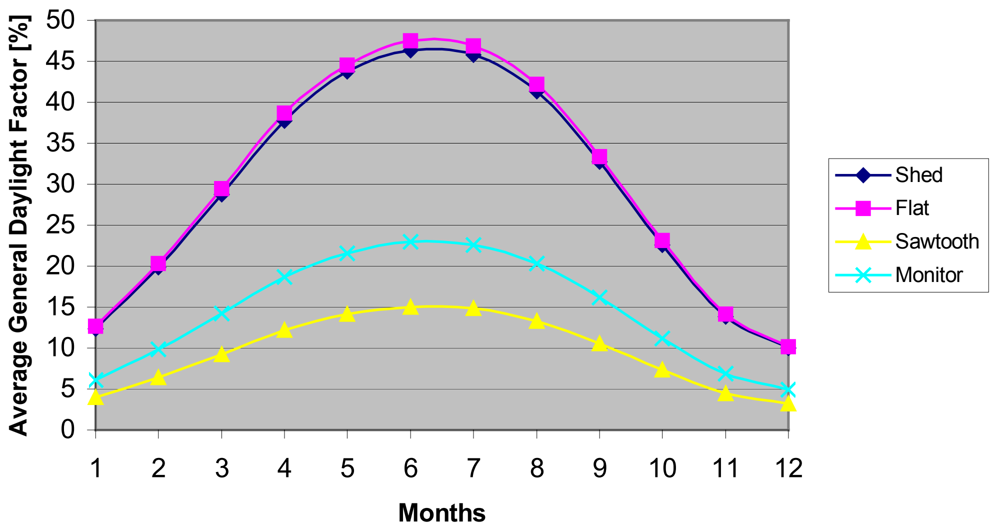


Figure 5.9 : Average General Daylight Factor through out the year

Moreover, there is significant difference in the illuminance level between the first two models and the second two. The monitor roof provides higher illuminance level compared to sawtooth because the windows of the former roof has an inclination of thirty degrees to zenith and this results view of sky with higher luminance. A quantitative comparison of them is shown in the figure 5.10.

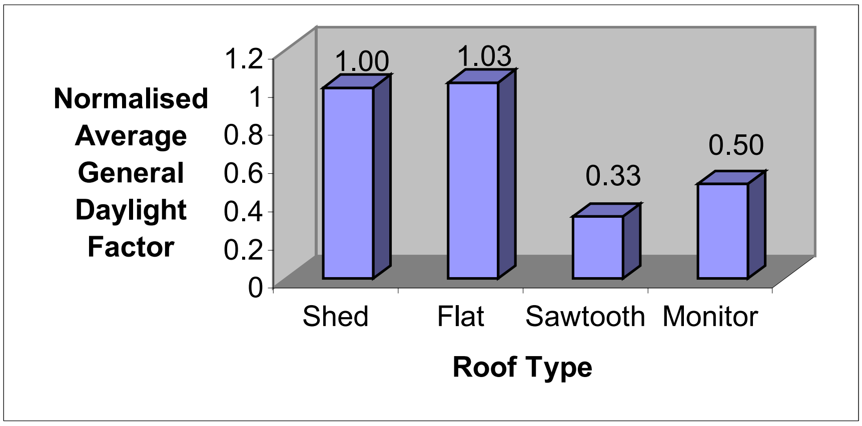


Figure 5.10: Normalised average General Daylight Factor for different type of roof geometry

The normalised average daylight factor remains nearly constant throughout the year and it is an indicator of the day lighting performance in terms of illuminance level. The interpretation of the figure is that there is not distinguishing difference in the illuminance level between shed and flat roof because that difference can be caused by error in the calculations of simulations. On the other hand definitely the sawtooth and monitor roof provides around 300% and 200% less illuminance level compared to shed roof respectively. Worth mentioning is that all of them are acceptable because they provide sufficient illuminance for storehouse activities.

The standard deviation of General Daylight Factor is an indicator of illuminance distribution along the space and is illustrated in figure 5.11. The best distribution

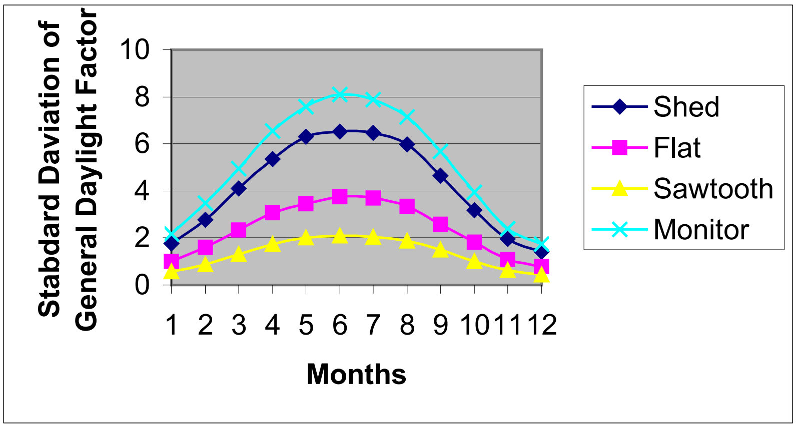


Figure 5.11 : Standard deviation of General Daylight Factor for different roof geometry

can be achieved by sawtooth roof because the deviation is the lowest. Moreover, flat roof provides reasonable uniform illuminance distribution while shed and monitor has the worst performance in terms of illuminance variation. The distribution varies through the year because the zenith luminance of the overcast sky varies with months considerably this affect the light that provided through inter-reflection in the interior. The normalised standard deviation of General Daylight Factor is shown in figure 5.12 gives a quantitative indicator of these models.

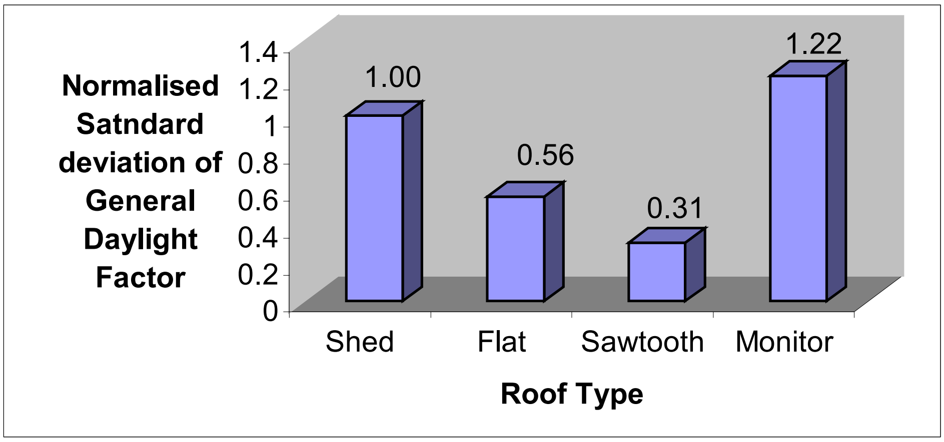


Figure 5.12 : Normalised standard deviation of General daylight factor for different type of roof geometry

The shed roof has no significant difference with monitor roof because despite that has quite uniform illuminance level in the centre of the space, mainly under the glazing surfaces it provides very low illuminance value near the west and east wall that causes the disturbance of that uniformity. So the sawtooth roof is the best solution for overcast sky conditions among these models.

5.3.2 Intermediate sky

The graphs of General Daylight Factor in Appendix-3 show that the worst conditions for all models in terms of illuminance distribution exist at 13:00pm therefore the quantitative comparison has based on that time of day since all models give illuminance value that are above the lower limit of 150 Lux through the year. The figure 5.13 shows the normalised average daylight factor to shed roof with 25^{o} degrees slope for different roof geometry. The conclusions that derive from the charter is that the normalised average General Daylight Factor varies thought the year because it is affected from the sun elevation.

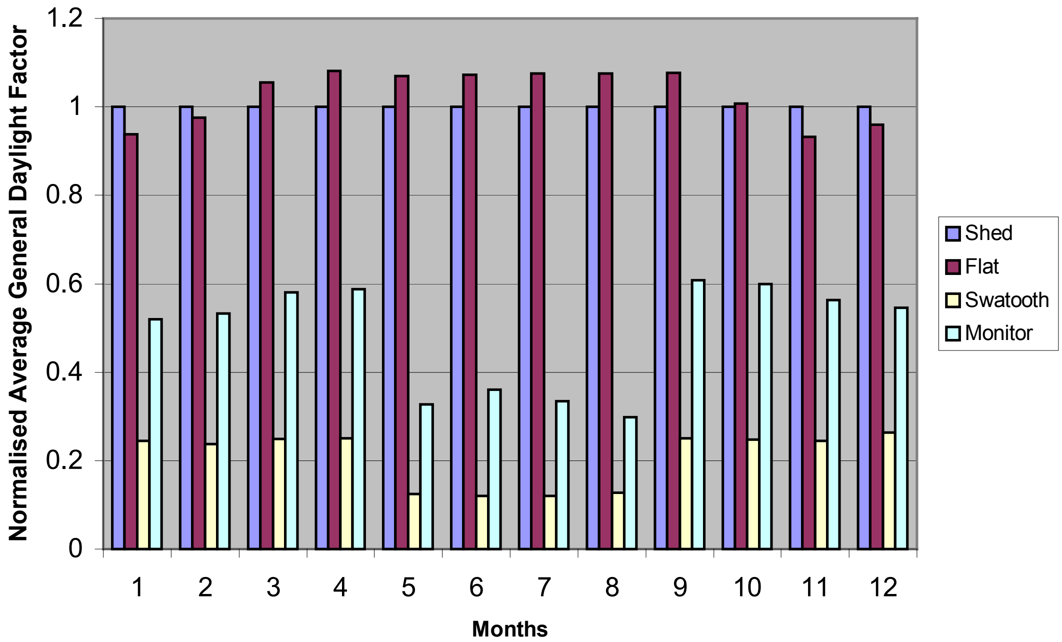


Figure 5.13 : Normalised average General Daylight Factor through the year at 13:00pm

Additionally, the flat roof benefited more from sun of high elevation but there is no distinguishing difference between the shed and flat roof through the year whereas the sawtooth roof has significantly lower average daylight factor compared to the previous two. Finally, the monitor roof gives performance nearly half as good as the first two in terms of average daylight factor.

The distribution of light is presented along the space in figure 5.14. Like in the overcast sky similarly the best illuminance distribution can be achieved by the sawtooth roof geometry because there is no direct sunlight that can reach the working plane along the space through the year. The difference is greater during the summer months due to the existence of sun patches in the rest of roof models. So definitely, in terms of illuminance distribution the saw tooth roof consists the best solution among them.

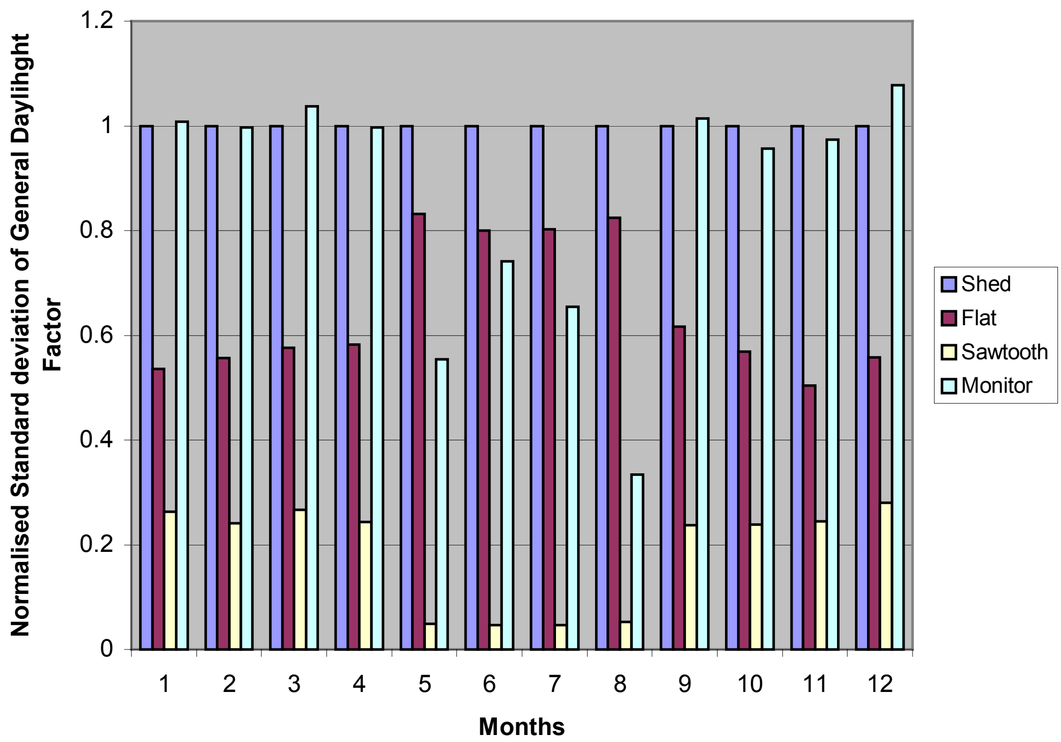


Figure 5.14: Normalised standard deviation of General Daylight Factor

The following table 5.1 summarised the results of the previous analysis for overcast and intermediate sky. All the comparison has been done taking the shed roof as a reference point.

	Overcast CIE Sky		Intermediate Sky	
	Average GDF	**Distribution**	**Average GDF**	**Distribution**
Shed	100%	100%	100%	100%
Flat	100%	200% better	100%	150% better
Sawtooth	300% inferior	300% better	200%-250% inferior	600% better
Monitor	200% inferior	120% inferior	500% inferior	100%

Table 5.1 : Daylight performance of different roof geometry based on Average General Daylight Factor (GDF) and Illuminance Distribution along the middle point of space

References

1. Michael J Cox, 'Visual Ergonomics', University of Bradford, 1999
2. Stanley L. Lynos, 'Handook of Industrial Lighting', Butterworth & Co 1981
3. 'Reference to EnergyPlus Calculations', University of Illinois, 2001
4. http://www.satel-light.com

6. Conclusion

6.1 Summary

The accurate prediction of daylight illuminance distribution and illuminance level, in the interior of a storehouse having rooflights only, under overcast and intermediate sky conditions was one of the main goals for this dissertation. The simulation tool used for these calculations was the Radiance software program.

From the examination of performance criteria in chapter 2 for assessing daylight in a space that has rooflights only, a new size has been derived, the general daylight factor which is described in detail in chapter 4. This general daylight factor overcomes the drawback of daylight factor and is easily understood by readers without a strong lighting engineering background.

On the basis of section 4.4 and 4.6 an effective procedure derives for daylight modelling simulation. Following the procedure outlined in these sections, less-than-expert Radiance users should be able to produce reliable calculations with regard to illuminance level and illuminance distribution, not only for a storehouse but also for the majority of current buildings. Specifically, the proposal that derives from the existing dissertation is that an analyser would be better using the eleven files described in section 4.4 and Appendix-4.

Moreover, the accuracy of calculations are affected by the rtrace parameters investigated in section 4.6. The study shows that the most crucial parameters, in sequence of importance are, the number of ambient divisions (-ad), super samples (-as) and bounces (-ab).

Based on the results analysis of chapter 5 it can be concluded that it is not possible for a storehouse, with latitude greater than 55^{o} degrees, to be illuminated entirely from daylight under overcast sky conditions with a ratio glazing to floor area of less than 0.5 and without glazing surfaces in the perimeter. Provision of artificial light is needed during the afternoon hours in winter. The results are similar in terms of adequate illuminance level for intermediate sky conditions

Moreover from chapter 5 derives that none of the typical roof geometry analysed causes visual comfort, based on Guth probability in the interior of the space, under the former sky conditions so there is no need for shading devices. Shading devices will definitely improve the illuminance level distribution under intermediate sky conditions but as there is an absence of glare discomfort they are not considered a cost effective solution.

Additionally, under overcast sky conditions there is no distinguishing difference in the average illuminance level that is provided from the shed and flat roof. Rise in the slope of shed roof reduces slightly the illuminance level but improve the illuminance distribution. Also increasing the number of windows results in a reduction of the illuminance level in the middle points of the room but gives better illuminance distribution. The sawtooth and monitor roof provides around three and two times respectively lower illuminance level compared to the previous two roofs. In terms of illuminance distribution the sawtooth and flat roof has three and two times better standard deviation of illuminance than the shed and monitor roof.

For the intermediate sky the sawtooth roof gives better illuminance distribution compared to the rest of the roof geometries, approximately five times better standard deviation, because there are no sun patches in the interior of the space.

It should be mentioned that since there is an absence of visual discomfort for both sky conditions, an absolute comparison in terms of illuminance distribution does not exist because the standard deviation of the general daylight factor is affected considerably by the high illuminance values of sun patches. Therefore, the values under intermediate sky are just an indicator of the better daylight performance of the roof geometry under the specifications of the models.

Finally, it has been concluded that absolute comparison between different roof geometries cannot be achieved for high latitude areas such as Scotland because the sky models that are recommended do not cause visual discomfort with these roof geometries.

Despite this can be extracted, from the results of the simulations, the qualitative conclusion that the best solution with regard to illuminance distribution and sufficient illuminance level for storehouse activities for both sky conditions is the sawtooth with forty-five degree slope.

6.2 Suggestions for further work

There is a need for additional work on formulae to assess visual comfort under intermediate sky in cases where the Guth probability does not give visual discomfort. As has been discussed in chapter 5 the absence of visual discomfort complicate the absolute quantification of alternative ways to provide daylight in a storehouse under intermediate sky, therefore new formulae have to be introduced.

It would be constructive to consider the effect of thermal comfort of daylight in the interior of the described models and based on the results of the present study to provide an integrated solution for storehouses and generally for buildings based their lighting solely on skylights. The ESP-r software programme is recommended, as it is reliable and well established in energy simulation in buildings. Moreover, it has been mentioned in chapter 4 that ESP-r provides the facility to convert three-dimensional geometry compatible for Radiance geometry, therefore the geometry of models for thermal simulations already exists. This results reduction of pre-processing time of thermal simulations for a future researcher.

As noted in chapter 2 the formula for clear sunny sky of Radiance does not provide accurate sky luminance values for high latitudes, thus value added would be the insertion of new sky models for those locations. Additionally, examination of daylight under those sky models is required for assessing the need of shading devices and how these devices affect the thermal comfort in summer months.

Finally, in terms of available software for lighting simulations Radiance is the most reliable but its main drawback is the usability as it is not user friendly. Thus, the development of a graphical user interface for Unix and Linux platforms will minimise significantly the simulation time process. At present, ESP-r has bridged this drawback of Radiance to an extent but there are still areas for improvement.