# A Methodology for Daylighting Optimisation in Academic Libraries: Case Study of EMU Main Library

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# ABSTRACT

Nowadays, most of the buildings are designed without considering the sustainability or responding to natural conditions which becomes a noticeable international trend. It is commonly preferable to design building in response to natural light and site potentials as views. This has impacts on the several dimensions as passive solar heating, reduction in electrical consumption and affecting the human health and psychology. As future architects and researchers, it's imperative for us to adapt sustainability measures in architectural design as daylighting to enhance the space quality needed but tactlessly the occurrence of daylighting is not always optimistic as it is anticipated. This research work aims to maximize benefits of daylighting measures of the EMU main library, through optimizing daylight usage by adopting shading strategies and reducing glare negative effects, to create appropriate visual efficiency for various tasks to be performed in the building. A well laid-out and logical methodologies will provide a great backbone of the research, and would allow to build some reliable results. Thus, this research is combining 'Problem Solving', 'Case Study' and 'Surveying' methodologies to obtain some concrete solutions. Firstly, qualitative methodology was used to identify the problem through observation and supported by questionnaire with real library building users. Then, quantitative methodology was adapted by using computer simulations to detect the problem statistically to find sustainable solution for the problems. Daylight is highly recommended to be used, but it is not appropriately being controlled for user to perform their visual tasks and replaced by the artificial lights that highly increase the energy consumption for EMU Main Library to achieve visual comfort, and the required levels of satisfaction. Certain strategies are recommended to be introduced in a way to control excessive daylight and glare effects, throughout daytime and between seasons, to achieve near optimum visual comfort in libraries indoor space. Based on annual analysis results, the study is evaluation criteria rest on universal standards combination and modifications to find proper assessment method for space visual performance.

**Keywords:** Sustainability, Visual Comfort Metrics, Glare, User’s Performance, Daylight Strategies, Daylight Control.

# ÖZ

Günümüzdeki binaların çoğu, sürdürebilirliği dikkate almaksızın veya dikkat çekici bir uluslararası trend haline gelen doğal koşullara tepki vermeksizin, tasarlanmıştır. Genel olarak, binaların tasarım şekli, doğal ışığa ve arazinin potansiyellerine yanıt verebilmesi için tercih edilir. Bu, pasif güneş ısıtması, elektrik tüketimindeki azalma ve insan sağlık ve psikolojisini etkileyen çeşitli boyutları kapsamaktadır.

Geleceğin mimarları ve araştırmacıları olarak, mimari tasarımdaki sürdürebilirlik tedbirlerini, ihtiyaç duyulan alan kalitesini artıracak şekilde, gün ışığı olarak adapte etmek zorunludur, ancak gün ışığının oluşumu beklendiği kadar her zaman iyimser değildir. Araştırma çalışması, DAÜ ana kütüphanesinin, gün ışığının faydalarından, gölgelendirmeyi benimseyerek ve gün ışığı kullanımını optimize ederek, binada gerçekleştirilecek çeşitli görevler için parlamanın olumsuz etkilerini azaltmak ve uygun görsel verimlilik oluşturmak için maksimize stratejileri bulmayı amaçlar iyi düzenlenmiş ve mantıklı bir metodoloji, araştırmaya büyük bir destek sağlayacak ve güvenilir sonuçlar üretmesine izin verecektir. Bu nedenle, bu araştırma bazı somut çözümler elde etmek için 'Problem Çözme', 'Örneklem Çalışması' ve 'Anket' yöntemlerini birleştirmektedir. Öncelikle, sorunun gözlem yoluyla belirlenmesi için nicel metodoloji kullanılmış ve gerçek kütüphane kullanıcısı anketi ile desteklenmiştir.

Ardından, nicel yöntem, problemi istatistiksel olarak tespit edebilmesi için bilgisayar simülasyonları kullanılarak uyarlanmış, problemlere sürdürülebilir çözüm bulunması amaçlanmıştır. Gün ışığının kullanılması tavsiye edilmektedir, fakat kullanıcıların görsel işlerini yerine getirebilmesini sağlayacak kadar, kontrol edilmemekte ve yerine

görsel konfor ve gerekli tatmin seviyelerini sağlamak için DAÜ ana kütüphanesinin enerji tüketimini artıran yapay ışıklar kullanılmaktadır.

Belli stratejilerin, kütüphanelerin kapalı mekanlarında en uygun görsel konfora erişmek için gündüzler ve mevsimler arasındaki aşırı gün ışığı ve parlama etkilerini kontrol altına alacak şekilde açıklanması önerilir.

**Anahtar Kelimeler:** Sürdürebilirlik, Görsel Konfor Ölçütleri, Parlama, Kullanıcı Performansı, Gün Işığı Stratejileri, Gün Işığı Kontrolü.

Every effort in life needs motivation as well as guidance and support by those who are very close to our heats and filling it with the most special gratitude feelings.

My humble work I dedicate to my sweet and loving parents,

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# INTRODUCTION

> "We were born of light. The seasons are felt through light. We only know the world as it is evoked by light …… To me natural light is the only light, because it has mood – it provides a ground of common agreement for man – it puts us in touch with the eternal. Natural light is the only light that makes architecture architecture."
>
> -- Louis I. Kahn

The human visual perception is mostly relied on distribution of brightness which is the physiological sensation generated by human visual system. This human anatomy sensation provides the ability to distinguish the contrast between the contiguous objects, photos or words in papers. Factually, everything that is visible through the contrast and brightness, yet the measurements and metrics of daylighting evaluation have minor relevance to brightness. Therefore, an advanced analysis of architectural built spaces is presented in this research in align with occupant perception of physical environment. Generally, it is preferable to incorporate the daylight qualities to architectonics and spatial design: activate the interrelation to the exterior environment through view and natural lighting, optimizing the energy consumption in the lighting purpose and providing adequate levels of visual comfort. It is evidently that natural light enhances feeling of health, welfare, focus and alertness; conversely, in the case of visual discomfort happened, these advantages are prospectively to be refuted. Quantifying the light incident on a surface, is beneficial for ensuring that there is a convenient light for navigate or task performance in the space. This illuminance measures on horizontal platform are highly recommended and standardized to assure the quality of the designing or analysing daylight buildings but very few studies that are concerns on perception and visual comfort of the space, are just recommending to avoid direct sunlight penetration to the space. Variation of microclimate, time and space parameters, beside sun irradiation management and the balance between heat transmission and daylight penetration into space, take a primary role in the shortage process of building materials and users tasks.

## 1.1 Statement of the Problem

The research work problem is the insufficient studies related to the method of daylight evaluation and optimisation correlated with visual comfort metrics and user's satisfaction. There is a problematic issue of not incorporating visual comfort measures as well in design and construction of buildings. Non-optimized daylighting is negatively affecting the performance of the building, users' behaviour, satisfaction and visual performance. Since university library is one of the buildings that relies on the natural light, the ignorance of these measures and metrics is negatively affecting the building envelope's energy efficiency, visual comfort, users' performance and user's satisfaction related to daylight conditions.

## 1.2 Research Aim and Questions

The first aim of this study is to maximize the visual performance in the building by well optimised daylighting usage in order to produce comfort environment (visually) in library buildings through evaluating the visual comfort metrics that affect the visual tasks and energy efficiency. The process to achieve this goal is dissected into three steps: evaluating the visual comfort metric related to building design, investigating occupants' behavioural satisfaction and preferences, and the plausibility of applicable strategies to enhance the space visual performance and daylight qualities.

Secondly, as a supportive goal for this research, it is centred around finding the most suitable visual performance assessment method in library spaces. Therefore, both fixed and automated shading systems were tested and the EMU Main Library in Eastern Mediterranean University, Famagusta, North Cyprus will be taken as a case study. Since external shading strategies are providing the best-known daylight optimisation system in indoor space, this research is attempting to provide clear design methodology to make architectural decisions about daylight controlling system particularly the choice between automated and fixed shading strategy in correlation to visual comfort metrics. The main research questions of this research are:

1) Are the daylight levels in all parts of the library provided adequately and sufficient for user's visual tasks?
2) Are library's users facing visual difficulties in indoor spaces mainly due to glare issue?
3) Are the automated shading strategies offering more efficiency than the fixed controlling strategies in the manner of visual qualities in library's indoor spaces?
4) Do the visual comfort standards validate to assess the visual performance in library buildings?

## 1.3 Research Significance

Among all the studies about the implementation of daylighting in design, and by putting the user's comfort and energy efficiency as objectives to achieve, yet there are some difficulties in diagnosing and evaluating visual comfort metrics related to human perceptions, especially in hot-humid climatic zone. As a rule of thumb, it is the most desirable climate zone but still it provides some challenges related with natural light controlling systems to perform visual tasks due different seasons throughout the year.

This research shows the impact of daylighting strategies and controlling systems on the visual performance, glare conditions and energy consumption related to lighting in libraries. Additionally, it is conjoining all these concerns to create well-structured evaluations and testing one of the reasonable responsive strategies under same criteria, resulting a reliable methodology of study for such contemplations.

## 1.4 Research Methodology

The logical methodologies will offer a great backbone of the research, and would allow to build extremely more reliable results. This research combines ‘Problem Solving’, ‘Case Study’ and ‘Surveying’ methodologies to achieve conclusions. The EMU Main Library attracted an attention by its importance in daily-based educational life. The study field analysed to discover the problems which are refined by observation. Then a closed ended questionnaire investigates the real users’ opinions to prove the problem statement. Finally, the library simulated in computer software that gave a concrete evidence of problem in detail.

After several visits to the library building, observing the number of students and the pattern of their distribution in the study areas, it was clear that the building design has an important effect on the user’s performance. The observation documented and analysed qualitatively to understand the current situation dimensions. The building setting-out and orientation is studied in order to trace the problem related to the building location and design-related indicators.

Based on that, a questionnaire was developed to understand how the users are experiencing the study spaces. The building user’s examination tested 281 participants, which divided in two periods between April 2015 (168 participants), and April 2016

(123 participants). The questionnaire distributed during the mid-term exams preparation period since those days are observed as the participants spent the longest duration in the building with the maximum occupation of study areas. The questionnaire targeted the study areas that depends mainly on the daylighting during the noon time, which where the most occupants used the upper two floors, to measure the levels of satisfaction and visual comfort. The questions oriented to define their preferences of location, part of daytime, satisfaction of lighting levels and visual difficulties during tasks performance. While experiencing the most challenging period in the day related to daylighting and its effects on thermal comfort as well, participants were asked to scale several visual comfort metrics with daylighting considerations, focusing on the following statements:

- This is a visually comfortable environment for study task in library.
- Feeling pleased with the visual appearance of the study areas in library.
- There is no direct sunlight beam hits the eye or the study area.
- The computer screen is legible and does not has reflections (glare is prevented).

Accordingly, several parameters and concerns are developed to be tested in software simulation. Both (Autodesk Ecotect® and Revit® Architecture BIM) were implemented in to consequent stages. Firstly, the current condition of visual metrics was tested and statistically (quantitatively) evaluated. All the challenges are illustrated and analysed and clear evaluation criteria are presented. Hence responsive strategies are suggested according to evaluations to solve the problems as a second stage of study. The proposed strategies were modelled and added to the existing building digital-model and exposed to same evaluations and simulations. Subsequently, a comparative process has done for both situations with standard's evaluation methods and logical-built conclusions are resulted with certain convenient recommendations.

## 1.5 Research Limitations

The field study is consisted of four levels and mainly the study areas are allocated in the upper two floors, whilst the administrative sections and small study rooms for computer use are distributed in the ground and the first floor. Therefore, this research is limited to these upper floors which hosting the study performance in a larger manner.

The questionnaire implemented in this research was taken on four different semesters during spring and autumn seasons. Therefore, it is assumed that the users were investigated during periods when thermal comfort is not affecting their responds.

Otherwise, optimisation proposals are counting on testing the efficiency of fixed and automated shading strategies. As a limitation for the study, economical and energy consumption dimension are excluded in evaluation criteria.

Furthermore, all the computational evaluation processes have done with only daylighting in consideration and the artificial sources were excluded in order to evaluate the spaces with natural light and propose solving strategies that enhances the daylight qualities and quantities.

## 1.6 Thesis Overview

Chapter (1) interduces the research with a background, concerns and objectives. It presents the need of this study and its contribution to architectural knowledge.

Chapter (2) is the state of art in this research which review daylight components, importance and visual metrics. This section is highlighting the architectural perspective of daylight exploring the aspects related to standards, strategies, visual comfort and potentials.

Chapter (3) is data evaluation section where the case study is selected and problems are diagnosed. Steps of data collection is described the analysis of visual metrics and results are illustrated in a way of proposing problem solving suggestions.

Chapter (4) is illustrating a logical suggestion built on sequenced ideas toward enhancing the visual atmosphere in the libraries. Re-evaluations are occurred resulting easy analytical comparison and substantiations to conclude.

Chapter (5) is representing the conclusion insights into visual comfort metrics in university libraries with summaries that describes how the results of this study would be beneficial to be implemented in architectural design process and analytical framework.

# Chapter 2

# UNDERSTANDINGS ABOUT DAYLIGHT IN ARCHITECTURAL DESIGN

## 2.1 Daylighting and Shading Studies in Literature

Many studies are enriching the literature related to building apertures, glazing and shading devices as explored by Dubois in his work Solar Shading and Building Energy Use, A Literature Review, Part 1 (Dubois, 1997).Some recent studies are focusing on the effect of window configuration on the envelope energy demand as REHVA's guide book for integration of solar shading strategies in sustainable buildings (Beck, et al., 2010; Guide, 1999) and the study by Tsikaloudaki *et al.* of Assessing cooling energy performance of windows for residential buildings in the Mediterranean zone (Tsikaloudaki, et al., 2012).

Correia da Silva et al. carried over the thermal concern and the optical features of the windows with the geometrical characteristics of the space. The study was based on trial of multi solar shading strategies on behavioural models to optimize the energy consumption (Da Silva, et al.,2012). Other researches was investigating the formula between visual comfort metrics and its impacts on lighting demand (Mahdavi and Dervishi, 2011). Whereas Nielsen *et al.* (2011) tested different shading strategies in different façade categories considering the daylight factor and energy demand in their studies. A study made by Shen and Tzempelikos (2012) applied experimental methodologies on selected four shading strategies to measure their impacts on visual comfort and energy demand.

Other group of studies is combining thermal comfort and energy consumption in concern. A study done by Frontini and Kuhn (2012) proposed an evaluation methodology based on testing four internal blinds with four glazing types correlating the on-off automated strategy. Buratti *et al.* (2013) tried to validate simulation-based experiment to evaluate multiple scenarios with glazing types and several orientations in a way to measure the thermal comfort metrics and the demand on cooling energy. Fore a combination of simulation-based and excremental methods in daylight studies study, Tzempelikos *et al.* (2010) took on consideration the solar irradiation to investigate the effect of glazing characteristics on thermal comfort aspects. A calculation of the Predicted Mean Vote (PMV) was done through evaluation of glazing energy performance in fixed thermal comfort conditions without denying the solar irradiation in the study (Cappelletti, et al. ,2014).

Recently, multi objective studies took a place among the efforts in the field of daylighting with the concerns of shading strategies, visual comfort aspects, thermal comfort and energy demand. Shen and Tzempelikos (2012) worked on the verifications of thermal and visual comfort under several varieties of climate, glazing and daylight controls in simulated office. In other study, a statistical metrics is proposed by Sicurella *et al.* (2012) for indoor thermal and visual comfort evaluation. The study focused on the timeline and the discomfort possibilities in thermal and visual conditions. The multi objective approach is clear in a research accomplished by Yao (2014) when it carried out energy, shading strategies and both thermal and visual comfort measurements on simulation-based analysis.

Related with this thesis study, the research 'Considerations on design optimization criteria for windows providing low energy consumption and high visual comfort' by Ochoa *et al.* (2012) presented a sample of focused study related to daylight control and shading strategies' performance assessment. It is correlating both illuminance-based and glare discomfort criteria for evaluation and assessment along with energy consumption in a small test room. The study provided logical assessment process but in a hypothetical and small size space. Another study done by Oh *et al.* (2012) took the same approach.

### 2.1.1 Visual Performance and Comfort Criteria: Quantity and Quality

Linking the visual tasks performed in indoor spaces with comfort aspects is requiring to separate the evaluation methods into quantity (illuminance-based) and quality (glare-based) measures due to the differences in concerns related to satisfaction (Newsham, et al., 2009).

**Illuminance-based criteria** is tacking in consideration the quantity of light that is required to perform visual tasks on the work surface. The exact illuminances are well defined in various standards and design guidebooks. For instance, 500 lux is the agreed-on recommendation on task surface for office-work performance (EN 12464-1:2011) which any light level below this value should be supported by artificial lighting. Various standards will be explored in later sections.

The classical illuminance-based methods that relied on the Daylight Factor (DF) has facing many criticisms. It is agreed that this classic method is reliable for design comparison methodologies working under the over-casted sky conditions but it is missing the required illuminance for particular visual task. Therefore, the Daylight Autonomy (DA) had been proposed as a new performance metric (with the continuous daylight autonomy $DA_{con}$) to overcome the conflicts between the visual and thermal comfort that faces the DF metric under certain conditions (Reinhart, et al., 2006).

**Glare-based criteria** are based on visual comfort needs to describe the lighting system quality in the space. Glare-controlling strategies as blinds are affecting the visual performance as well as the energy consumption. Glare indexes are invented to propose ratios to evaluate the lighting quality by measure surroundings of work environment illuminance related to the illuminance provided on the work-plane (Ochoa, et al., 2012).

Glare indexes are giving semantic ratios rather than the absolute numbers of illuminance. Thus, these indexes are expressive when comparing different lighting conditions or systems. Otherwise, there is no specific glare measure that is universally agreed about due to it dependent on positioning and surrounding conditions. Detailed description about glare indexes in later sections (Osterhaus, 2005).

## 2.2 Daylight Environmental Aspects Related to Indoor Space Quality

Several reasons are reorienting the interest in daylighting, the fact that electrical sources have a limited life span, instability of fossil based energy sources and the general awareness about the harm impacts of these sources in environment. Furthermore, the less tangible impacts of daylighting which is dealing more with human spirit and the increase of life quality in recent years. Various environmental factors could contribute to the space quality in architecture. None of these aspects by their own could play dominant role, but it clearly appears when they combined in a holistic perspective toward the interior environment quality (Phillips, 2004).

### 2.2.1 Changeability and Variability

Probably the most important aspect related to daylighting in the capability to change resulting an unlimited number of variables in the way to create indoor spaces suites the human needs in both performance and quality issues. The capacity of change is in the core of the daylighting concept as well as the human body has naturally these adaptation features in response with initial need to experience it, especially the eye vision (Phillips, 2004).

Human perception can respond to limited rage of changes. Naturally, there are alterations happening in the indoor environments correlated with time. The inhabit experience of the interior spaces definitely changes when the light changes during time providing confident sense of exploration in space, unlike the qualities that found in the same space with static quantities of light completely by artificial sources or where is isolated from exterior environment. The human eye has a photochemical perception process in a way it adapts to perceive daylighting changes.

The changes in nature that case alterations and variations in human life could be categorised as:

- Day-to-night change, from the first light in the day until the daylight fades out and the artificial lighting take over to cover the demand of light for visual performance.
- Weather association alterations, from clear and bright sky to cloudy, rainy and dark sky.
- Seasonal changes, it is closely to the weather changes as from winter to summer and visa versa. Each of the seasons has its own characteristics and effects the human accommodation with a different way. Here the importance of openings and windows come to the surface providing all the information needed to keep connected with

outdoor environment, whilst guiding to subtle changes in the indoor appearance and experience.

In general, these changes have both impacts on human physically and psychologically. The adaptation happens when moving form dark to bright space or when the brightness comes on the morning, is normally correlates with a raise in human spiritualties (Phillips, 2004).

### 2.2.2 Light Formation

Designing any shape is originally derived from the physical geometry form, whether circular, rectangular or otherwise, in addition to the effect of the light when plays on its surfaces. This rule is applicable on objects with different geometries as buildings besides interior spaces. Unambiguously, the human eye perceives an object form or modelling when it is derived from daylight, sunlight or one side lighting. Once more, this experience is absolutely different from perceiving an object or space that is lighted by artificial source or may be multiple light sources (Phillips, 2004).

In architectural bases, the vertical window is considered as the typical daylight modelling at one of the indoor space surfaces, providing light projection from single direction. However, the window is helping light to penetrate the space, yet it is adding to the daylight modelling which taken from the same source and shaping the overall light formation.

In order to emphasize this concept, the daylight overhead source to light a sculpture of the Charioteer from Delphi in Museum of Modern Art, New York, gives a clear example. Basically, the human sympathies about geometries and spaces are built on the meanings that is given by daylight directional flow. This meaning could be emphasized even more and more by direct sunlight. Generally, the theme and mood of interior spaces are judged as gloomy, bright or pleasant by the role of light formation and by the ability to see the spaces or objects using the light during the day time related to the experience of natural light in real world (Phillips, 2004).

### 2.2.3 Orientation

There is no doubt about the importance of the building orientation in architectural design process, when the building is located on the site to maximize the availability of useful natural light to the interior spaces.

Numerous challenges may face the architect while setting out the building on the site as locating the building into a rigid urban pattern or where there are external limitations and obstacles. Rather all these circumstances the optimum daylight utilization is needed to be considered in design as a fundamental requirement. The architectural design possibilities are giving the architect a wide range of flexibility in positioning the desired building on site in order to take the maximum advantage of daylighting and integrate the sunlight benefits in his design.

For instance, a regular house zoning organisation that is being located in the northern hemisphere, and considering the fact that the sun is moving from east to west in a daily base, it is recommended to position the spaces as kitchen, morning room or may be the bedrooms in the eastern part of the building that might maximize the benefits from early morning sunlight. Accordingly, it is preferred to locate the spaces which most likely to be utilised in evening time in other part or facing south as living rooms for example.

This of course would open some arguments about locating some spaces in specific orientation that is contradicting with other considerations like the limitations that would affect the design concepts, the client preferences or if it conflicts with the orientation of the most enjoyable view on site.

Essentially, along with architectural design, some compromises are needed to be done in order to meet demands of the functions hosted in the building. In both cases, building orientation and space organisation, daylighting is taking the priority in considerations at building outset stage in design. In any programmatic issue, building interiority has particular orientation needs and this gets more critical and significant when the design space is requiring a fixed inhabitant's use as a school or office spaces. Furthermore, the indoor space occupants have subconsciously a desire to keep visual contact with the outdoor spaces, whether to enhance the sense of time during the day time or to understand the weather conditions. Commonly, when the spaces are located inside a large-scale building, very deep and cut out of daylight, the users of the building are suffering from disorientation feelings and losing directions of exits and early 1960's shopping centres are good example of this issue. Thus, there is some awareness about the importance of daylighting in recent buildings with similar scale, integrating the daylighting supported with artificial light in display areas, whilst the public zones oriented to be assisted by delivered daylight (Phillips, 2004).

### 2.2.4 Sunlight Effect

An interesting question was inquired by Bill Lam in *Sunlight as Formgiver for Architecture (1986)* about the issue of sunlight, "The Sun: Problem or Opportunity?". He tried to find the critical edge line in the role of the sun between being great opportunity and when it turns into a real problematic issue in architectural design. Evidently, for instance, in the hot arid climatic zone of the globe where there are an excessive sunlight causing overheating in indoor spaces throughout the day, the sunlight become a problem and mostly unwelcomed.

On the other hand, in the cold zones where are very low levels of sunlight, the sun is turning to be the most welcomed environmental element. Hence the building is normally oriented facing the sun and encouraging the sunlight penetration into the interior spaces. The experience of the building interiority is definitely differed when sunlight is the main source of light that varies during the day adding more to spaces as well as to other environmental aspects as daylight modelling and formation, variability and changeability (Lam, W. M., 1986).

Throughout human history, the sunlight effect has been involved in the architectural designs to create a particular experience interiorly. The main southern window in the churches and cathedrals would show an example of implementing sunlight in architecture by creating shafts of light into the space, and similarly the usage of skylight windows in the recent house designs to provide enough daylighting in the deep spaces, where otherwise very rare daylight would be obtainable.

Commonly, it is not preferred to perceive a direct sunlight in the eye, but it could be more delighted wherever a view with sunlight landscape view or building is seen through window, moreover it is getting disenchanted when it is excluded without a reason. In the opposite side, sunlight is allied with overheating and glare effect, according to the building orientation, façade glazing system and the nature of the people performance inside the building is restricted to a still position. Here, the direct sunlight is giving undesired effects that need effective control strategies in some circumstances at different periods seasonally, which further study will be discussed later in this research. For instance, the heat gain issue is recommended to be solved beyond the apertures with sufficiently flexible solutions and without inhibiting the required view. Other strategy can be adopted to control glare is implementing certain type of glass which expurgated light transmission with a constraint of creating a dim indoor space if it is not calculated carefully. There are other types of glass that are reacting to sunlight, which might cause glare, automatically to prevent bright sunlight whenever is needed.

To summarise, there is a great importance to admit sunlight into the indoor spaces, it must be a fundamental consideration during design stages when orienting the building and organizing the functions layout, yet several controls are needed under certain circumstances (Phillips, 2004).

### 2.2.5 Colour

Rather the changes in colours of daylighting from morning to evening accompanied with alterations in sky and weather moods, it is commonly claimed that the daylight colour is the 'real colour'. From early history, light shafts are created in the building roofs for the best objects display underneath it, and this attributed to the quality and the suitability of daylighting compared to the artificial sources.

But later when the large-scale buildings as shopping areas introduced to civilization, the advantages of natural colours which created by the daylight, are tended to be ignored in design. The display areas are majorly depending on artificial light to in enhance the product's image. Wherefore there is sometime an initiative need to take the product to the light to see the natural colours, otherwise the sales man who remains long time in this environmental condition is not recognizing the absence of this advantage (Phillips, 2004).

Likewise, in the office spaces, where the employees tend to stay for a long-time duration in the same atmospheric conditions. In the case of the employee is sitting in a far distance from the windows and the impression of daylighting is significantly decreased, a sense of displeasure or depression would be inevitable. This would be very noticeable during the coffee brakes when the employee is experiencing other place with better impression of daylighting, the change of atmosphere is affecting him/her mood positively.

A further feature of colours created by natural daylight is the enhancement of good contract for better visual recognition. It is claimed that daylight is permitting low levels of illumination while enhancing visibility (Tregenza, et al.,2013).

### 2.2.6 Importance of View

The importance of looking out from indoor spaces has been argued in different dimensions. Looking through a window to outdoor spaces offers the information, as mentioned before, about weather, seasons, day and night times.

The effect of the view can be discussed in various levels. Physiologically, human beings have the natural need to experience the adaptation and re-adaptation of the eye focal distance, allowing a clear visual experience. Therefore, there is a need to provide any view to exterior environment, of course the level of clarity can diverge. At a different level, several researches evidenced the positive effects of being near to a window with a view on patient’s recovery process in healthcare buildings.

Since the importance of the view is coming from the provided information, this could measure the success of it. Yet looking to blank wall is better than being excluded from outside completely, but it is most preferable to have a view to a countryside or green yard, this would definitely give better taste for the visual experience. By analysing numerous views in terms of information obtained and according to the aperture height, there are two types of views with two different experiences depending on the content of the scene from the interior space. Firstly, the sky experience where the view may consist the sky entirely as in the tall buildings and the ground experience when the window has a view in lower levels.

The building surroundings are controlling the quality of the views which perceived from interior spaces. It is important to consider the good views in the context whenever it is available and not to exploit them. In some cases of large complexes, some spaces are facing each other, this might satisfy the physiological need for adaptation and re-adaptation but the experience lacks the amenities of changeability, variability and the formation which inform the natural wold outside.

The consideration of the view is imposing the architect during designing the building interiority, orienting the building and when refining the window details. In mid-eighteenth century in Britain, a glazing bar was utilised to capture the daylight and orient it inside the buildings. This technique was helping to light the interior spaces by natural light, otherwise it was ignoring the view completely. Nowadays, with all the development in the manufacturing technology, the glass has several varieties to have wide span transparent panels without any obstacles.

In some architectural approaches, there is a claim that the view might has a side effect of losing concentration when it is needed in some building types, as the school classroom. In his work '*Daylighting: Natural Light in Architecture'* (2004), Derek Phillips explained his own experience in classroom during early twentieth century. His classroom was build according to old architectural program and it had high level windows that prevent the view out until he moved to a newer building programme of 1960s. Other building programmes as factories and some laboratories which needs controlled light levels to enhance the performance or used for short times during the day, the denying of the view can be understandable, and the availability of the daylight and the view can be potentially dangerous on the workers with the machinery if they lost their concentration.

Additional question raises to the mind, what will happen to the privacy if it is known that the 'view-out' is automatically associated with 'view-in'? The question of the privacy which is in some conditions could become a priority and essentially needed. During daytime, this will commonly be solved by the huge difference in light levels where it is much higher in outside than inside but the problem appears at night time when the situation inverted. In this condition, other controlling strategy is needed to meet this undesirable effect as using internal blinds whenever is needed (Phillips, 2004).

### 2.2.7 Health

The daylight has always been linked with health in both physiological and psychological manners. Among the researches which have done about this issue, it is mentioned by Dr Hobday in his book, '*The Healing Sun'* (1999), that Vitruvius was the first one to study the relationship between daylighting and health in his ten books on architecture. He declared the classic principles of balance, symmetry and harmonic proportions beside the recommendations for the architect to choose a healthy site to locate the building and carefully design it to prevent sickness. Obviously, the healthy site which mentioned by Vitruvius was where the building is oriented to be able to perceive daylight. Hence Vitruvius was the pioneer to analyse the qualitative and quantitative aspects of natural light in the built environment, was in the first century BC.

The studies move a great deal further nowadays, yet the basic principle is the same where the lack of enough sunlight or daylight is affecting the human and responsible for a medical condition called SAD, 'Seasonal Affected Disorder'. By natural intuition, if the people have the choice to select their places of work, they prefer to be near to windows. Therefore, the availability of daylighting inside the building is a necessity and it has its importance in the interior environment (Edwards & Torcellini, 2002).

The user's performance in the space is another aspect to study during designing the space, or it can be called user's satisfaction. For instance, in workspaces where the productivity of the workers is important, at least financially, if they are working under inadequate lighting levels, it is expected to deteriorate productivity and outputs. This decline may occur from implementing the energy efficient lighting. Health wise, long durations of visual discomfort in poor lighting levels may lead to illness called '*Sick Building Syndrome'*. Thus, even energy efficiency approaches in architectural design cannot be taken purely without considering the user's health impacts, but considering together efficient and comfortable environment (Phillips, 2004).

## 2.3 Design for the Daylight Aspects

As mentioned previously, the daylight nature has several environmental aspects to consider during design, requiring certain control strategies should be applied on a well-studied size and orientation for daylight aperture. Essentially, there are three main issues while designing for daylighting:

- Sunlight control, to moderate the levels of gains and to prevent direct glare effects.
- Glare control, to ensure a comfortable visual experience with adequate levels and distribution of lighting including the view to the bright sky.
- Variation control, to prevent user's conceptions resulted by insufficient light levels.

It is possible to consider the apertures in building exterior surfaces as in-situ light sources powered by renewable energy obtained from the sun. In addition to the three principles mentioned above, building's design should ensure well distribution of apertures to provide effective light levels and diffuses in the spaces. The success of implementing these principal issues can be achieved by configuring background lighting as opposed to the particular task performed, when it is enhanced by the artificial light in inelegant manner. Correlated to lighting sources, daylight is providing acceptable variabilities with easy ways to control which can be smoothly enhanced by artificial sources integration.

The upcoming sections discuss the daylight qualities standards and the strategies are used to achieve it in architectural design (Dean, 2005).

## 2.4 Lighting Qualities

Natural and artificial sources can gain lighting, but it is recommended to use natural light for certain facts. It is agreed that daylighting is the most efficient, easy, effective and economic source of light that improve visual performance tasks. Artificial lighting would be as an alternative whenever daylight is not adequate at night period or during rainy seasons.

"For any library's visual tasks, such as reading or writing, need luminance levels on the desks between 300 and 750 (lux); the average value should be about 500 lux" (Balocco,2008; Balocco,2010).

Environments with visual tasks perceptions present the importance of sunlight utilization. Basically, the control of daylight distribution and thermal conditions directly connected to visual tasks performance in indoor spaces as reading in the library. Considerable reduction in artificial lighting and energy consumption could be achieved by utilization of daylight deflection (D.H.W. Li., et al., 2004; D. Camuffo, et al., 2005).

## 2.5 Visual Comfort

Frequently, lighting levels considered as a major factor affects the experience of visual performance. In both cases of too much brightness or dimness, the human eye strain and feel discomfort. Artificial lighting can precisely meet the required illuminance but with the sun/sky light, the measurements are varied between fluctuation of different conditions. However, because of variability in sunlight conditions, a complex challenge appears to assure the adequate levels of illuminance by taking the daylight as light source, as are all metrics of visual comfort.

Incorporating this in addition to other aspects that affect visual comfort probability is an effective and critical knowledge in design stages. These embrace the glare free, veiling reflections free and without colour rendering, mostly when artificial lighting is used. Additionally, the architectural intention mainly is expressed by the role of both natural and artificial sources of light which reflect its traces on the pleasure of users.

Essentially, the role of controlling the daylight and providing outer view is taken by the windows of the building which positively remark in occupant's psychology. The pleasant view can cover on some of the negativities of the windows related to daylighting. Some strategic objectives should be achieved by optimising daylight utilisation as follow:

- Building design should ensure the availability of daylight provided by the majority of the daytime at workspaces.
- Adequate illumination to perform particular visual tasks must be provided to the occupants.
- Large vertical glazing surfaces need well studied design to provide deep comfort daylighting. Yet, over brightness and glare effect should be solved by utilising control strategy.
- Glare prevention by studying the internal and external surfaces positioning and reflectance.
- Low glare and suitable colour rendering are necessities in spaces of long time of occupancy when artificial lighting is in use. Therefore, lighting fixture and luminaire should be chosen accordingly.
- Automated daylight controlling strategy should be designed without irritation and interference effects to the occupants.
- Lighting design, both natural and artificial, should response directly to the task to be carried out in the space with a wider consideration to human preferences (Baker, et al.,2003).

## 2.6 Glare, Luminance and Illuminance

According to Hopkinson and Collins (1972), luminance is directly related to the human sensation of brightness. Technically, luminance is the glowing intensity per area unit in particular direction; it is an indication for the power of luminous perceived by the observer facing the surface from specific advantage point in the space described by candela per meter squire in SI system ($cd/m^2$).

During the human adaptation process, physically and psychologically, lighting preferences have been changed. For instance, in bright natural light, reading task requires constriction (physical adaptation), light preceptors are less sensitive to brightness (psychological adaptation), human eyes break down in response to luminance variation (chemical adaptation) (Boyce, 2014).

The following *fig.1* demonstrates the correlation between object luminance and luminous perception or adaptation luminance which is the average luminance of objects in the direct field of visual range. Despite the complexity of measuring the luminance, it is considered as an exceptional way to analyse visual comfort and light perception.

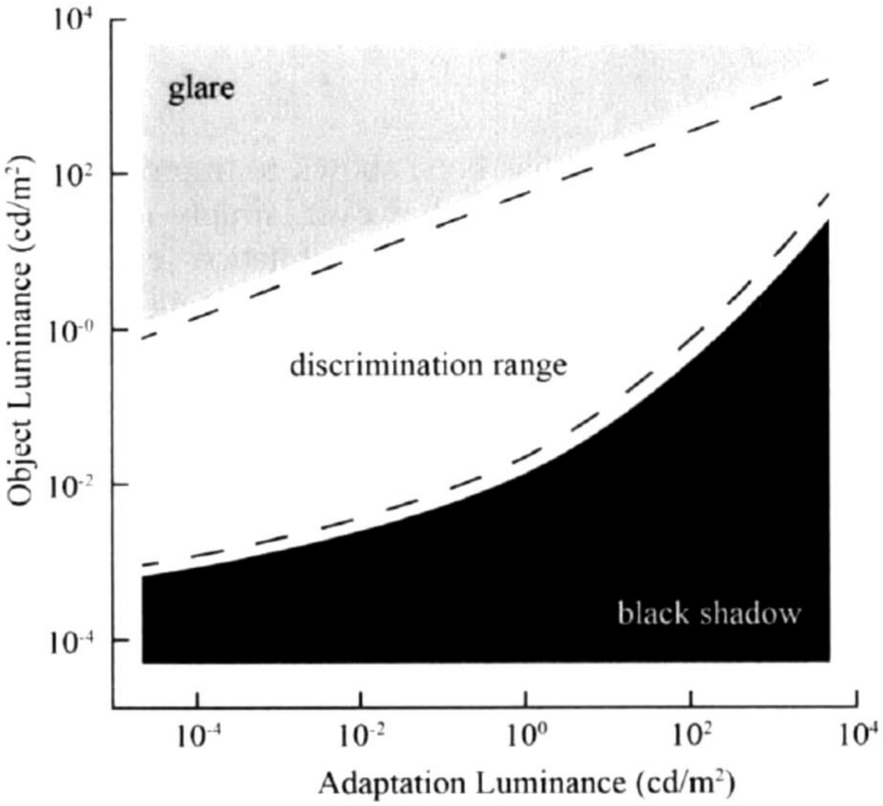



Figure 1: The Relation between Luminance and Luminous Perception (Retrieved from Jakubiec, 2014).

Contrarily, the sum of all light hits specific point from all directions in relation to area unit is known as illuminance; it is an indication of the quantity of light hits the surface and in this study, it is measured by lux (equals $lm/m^2$ in SI system). Regarding the natural or artificial lights, architecture design decisions are mostly based on illuminance measurements. Even automated shading strategies are commonly utilising the illuminance aspects. Here, the illuminance measures are raising to control the analysis process in this research in relation to visual comfort metrics and daylight optimisation reliability (Jakubiec, 2014).

### 2.6.1 Glare and Discomfort Metrics

The harmful beam of light that hits directly the eye generate annoying feeling and uncomforting condition to perform visual tasks, universally called glare. This effect can be caused by direct sunlight that penetrates the building through apertures, in natural source of lighting. Furthermore, it may result from reflectance of light from surfaces inside and outside the building; mostly form objects of attention as monitors and screens. Unlike heat and thermal issues, glare can be prevented easily by building design and orientation (Phillips, 2004).

Scientifically, glare is commonly represented as the relation of luminance, size and position of glare sources in the range of vision compared to the typical luminance deprived of the glare source. The expression of this can be simplified in equation as:

$$Glare = \sum_{i=1}^{n} \frac{L_{s,i}^{exp}\,\omega_{s,i}}{L_{b}^{exp} P_{i}^{exp}}$$

While:

- *exp* = the scaling exponent for each variable.
- $n$ = number of luminaires.
- $\omega_s$ = solid direct angle of luminaire with $L_s$ luminance.
- $L_b$ = standing for background luminance.
- $P$ = the location index (according to Guth index) of the glare source as it is approaching into the field of the view (Jakubiec, 2014).

### 2.6.2 Daylight Glare Index (DGI or Cornell Equation)

The formula of Daylight Glare Index (DGI) is fundamentally created by Hopkinson in 1972 built on his previous studies of small glare sources at Building Research Station (Hopkinson 1972**)**. The condition of sky, as large glare source, added to considerations and possibilities of DGI. This metric was oriented from subjectivity of human studies in interior spaces with diffused backlight screens (Hopkinson 1971**).** The simulation of skylight was measured and characterised by size and location index (*pos*). The reliability of DGI was discredited whenever the direct light or specular reflections appears in the vision field due to the Hopkinson's research is based on diffused light denying the direct light and interior specular reflections. Therefore, DGI is quite acceptable in internal daylight calculations (Hopkinson 1972). The Hopkinson equation is correlating luminance, size and location of light source facing the diffused backlight luminance in vision field, resulting values >31 express intolerable glare and <18 declare that glare is barely distinguishable (Jakubiec, 2014).

$$DGI = 10 \times \log_{10} 0.48 \sum_{i=1}^{n} \frac{L_{s,i}^{1.6} \omega_{pos\ s,i}^{0.8}}{L_b + (0.07\omega_{s,i}^{0.5} L_{s,i})}$$

While:

- $n$ = the number of luminaires.
- $\omega_s$ = solid direct angle of luminaire with $L_s$ luminance.
- $L_b$ = standing for background luminance.
- $pos$ = the location index.

### 2.6.3 New Daylight Glare Index ($DGI_N$)

In 2001, Nazzal et al. formulated the New Daylight Glare Index which is a developed amendment in Hopkinson's equation with additive variables:

- $L_{adapt}$ , the middling luminance of viewing field expresses the adaptation luminance.
- $L_{exterior}$ , the middling of exterior luminance
- $L_{window}$ , the middling window luminance by considering the window light as a undeviating source of light and the exact location of the window to the geometry is correlated in this calculation.

The results obtained by $DGI_N$ are correlated and validated only in comparison to the DGI approach; dipping any human studies performed, thus $DGI_N$ may offers considerable errors in relation to discomfort (Nazzal, et al. 2005). Three different sensors are implemented to measure total vertical luminance, window luminance and the exterior luminance which somewhat allows to consider the sunlight. Yet, the specular reflections and direct luminance are not accurately calculated (Jakubiec, 2014).

$$DGI_N = 8\times\ \log_{10} 0.25 \sum_{i=1}^{n} \frac{L^2_{exterior,i}\omega_{s,i}}{L_{adapt} + 0.07(\sum_{i=1}^{n} \omega_{s,i} L^2_{window,i})^{0.5}}$$

### 2.6.4 CIE Glare Index (CGI)

Issued in 1979, motivated by taking into account all early mentioned researches in a way to formulate a standard glare index, Einhorn's researches resulted an equation approved by the Commission Internationale de l'Eclairage (CIE) (Einhorn 1979). The novel consideration was the summation of glare sources luminance solid angles (ω) were an advocate of one in mathematical way, besides the value of adaptation glaring sources was adapted to be multiplied by the summation of all ratios of vertical receipted illuminance. In Einhorn's equation, the scale of values is >28 for excessive glare while <13 for imperceptible glare where:

- $C_1$=2 and $C_2$= 8 are optional weighing values by Einhorn.
- $E_d$ = the average level of illumination distinguished in the field of view.
- $E_i$ = the illumination of the luminaire in the field of view.
- $\omega_s$ = solid direct angle of luminaire with $L_s$ luminance.
- $P$ = the location index (according to Guth index) of the glare source as it is approaching into the field of the view.

However, the human studies were not in use in this research and even CIE discussed it with correlation of later studies to develop UGR metric (Jakubiec, 2014).

$$CG1 = C_1 \times \log_{10} C_2 \frac{(1 + \frac{E_d}{500})}{E_d + E_i} \sum_{i=1}^{n} \frac{L^2_{s,i}\ \omega_{s,i}}{P^2}$$

### 2.6.5 Visual Comfort Probability (VCP)

The term of Visual Comfort Probability describes the condition where the regular viewer does not experience any effects of discomfort while looking at lighting system under this specific condition (Harrold, et al., 2003). Rather the complexity of factors assemblage, VCP basically valuate the size and luminance of glare source compared to its position in the viewing field and the average of luminance solid angle of 5 Steradian. The only limitation is that; it is valid for specific condition of typically-sized, ceiling type with uniform luminance distribution, artificial lighting system. Thus, it is not working with smaller or very large sources of luminance as daylight for instance. The VCP scaling values fall between 0 to 100, describing the percentage of observers who would experience comfort under comparable lighting circumstances.

$$VCP = 279 - 110[log_{10} \sum_{i=1}^{n} [\frac{0.5L_{s,i}(20.4\omega_{s,i} + 1.5\omega_{s,i}^{0.2} - 0.075)}{P \times E_{AVG}^{0.44}}]^{n^{-0.0914}}$$

While:

- $n$ = the number of luminaires.
- $\omega_s$ = solid direct angle of luminaire with $L_s$ luminance.
- $E_{AVG}$ = the average level of illumination distinguished in the field of view.
- $P$ = the location index (according to Guth index) of the glare source as it is approaching into the field of the view (Jakubiec, 2014).

### 2.6.6 CIE Unified Glare Rating System (UGR)

Responding to the difficulties in including direct sources of light in GCI formula, the Commission Internationale de l'Eclairage Technical Committee 3-13 1995 developed a novel metric called Unified Glare Rating. Accordingly, the visual adaptation to direct source of luminance is not existing in this metric anymore. Rather the CIE TC3-3 development of UGR equation, the validation of metric appeared when applied in a space with usual average of luminance required for working interiors. Therefore, UGR generally expects more probability of visual comfort than CGI does. Essentially, UGR is a way to simplify the CGI; nevertheless, with current computer applications it is easy to split the direct glare source and other reflected diffuses. Yet, the values of UGR are the same as CGI in conditions description.

$$UGR = 8\times\ log_{10}\frac{0.25}{L_b}\sum_{i=1}^{n}\frac{L_{s,i}^2\omega_{s,i}}{P^2}$$

While:

- $n$ = the number of luminaires.
- $\omega_s$ = solid direct angle of luminaire with $L_s$ luminance.
- $L_b$ = standing for background luminance.
- $P$ = the location index (according to Guth index) of the glare source as it is approaching into the field of the view (Jakubiec, 2014).

Table 1 is showing the range of values that given by this formula and the criteria of luminaire's glare description. When the values are below 10 that means, the glare is imperceptible and when it exceeds 31, it indicates intolerable conditions as seen in table 1 (Hafiz, 2015).

Table 1: UGR Threshold and Criterion (Retrieved from Hafiz, 2015)

| Glare Condition | UGR |
|---|---|
| Just imperceptible | 10 |
| Perceptible | 16 |
| Just acceptable | 19 |
| Unacceptable | 22 |
| Just uncomfortable | 25 |
| Uncomfortable | 28 |
| Just intolerable | 31 |

### 2.6.7 Daylight Glare Probability (DGP)

The Daylight Glare Probability can be defined as a measuring metric which is based on subjective evaluations when the space occupants are exposed to sidelight source (Wienold & Christoffersen 2006). In relevance to other metrics, DGP is defined by the ratio between the bright spots luminance in the space to the entire vertical illuminance falling from the hemisphere. Thus, this metric can assess direct sunlight and the specular reflection as glare sources on the working surface, and simultaneously the blurry or dim sky would not be considered as such (Jakubiec, 2014).

Other main improvement in DGP, by taking in calculation the direct sunlight as source of glare in the first section of the equation as ($E_V$), a predictability factor is added to this metric. Thus, exceeded brightness and discomfort can be foreseen without noticeable contrast. By adding these additions to the glare indexes that seen in the second part of the equation, DGP is providing the most reliable metric to evaluate the discomfort due to its holistic considerations. Furthermore, DGP is answering Hopkinson's main axinites about direct sunlight in DGI metric. Daylight Glare Probability is sharing with other metrics the same value scale, where 0.45 (intolerable glare) is representing the 45% of users are suffering from glare and the value of 0.35 for the imperceptible.

$$DGP = 5.87\times 10^{-5}\, E_V + 0.0918 \times \log_{10}(1 + \sum_{i=1}^{n} \frac{L_{s,i}^2 \omega_{s,i}}{E_v^{1.87} P_i^2}) + 0.16$$

While:

- $n$ = the number of luminaires.
- $\omega_s$ = solid direct angle of luminaire with $L_s$ luminance.
- $E_v$ = the average level of illumination distinguished in the field of view.
- $P$ = the location index (according to Guth index) of the glare source as it is

approaching into the field of the view (Jakubiec, 2014).

In daylighting analysis framework, it is important to understand the relation between all these measures as illustrated below in table 2. This will help to determine the best daylighting performance metrics which required to meet the varieties of user's needs (Hafiz, 2015).

Table 2: Glare Index Values Relation (Retrieved from Hafiz, 2015).

| | DGP[1] | DGI[2] | UGR[3] | VCP[4] | CGI[5] |
|---|---|---|---|---|---|
| Imperceptible | <0.35 | <18 | <13 | 80-100 | <13 |
| Perceptible | 0.35-0.40 | 18-24 | 13-22 | 60-80 | 12-22 |
| Disturbing | 0.40-0.45 | 24-31 | 22-28 | 40-60 | 22-28 |
| Intolerable | >0.45 | >31 | >28 | <40 | >28 |

1. DGP = Daylight Glare Probability
2. DGI = Daylight Glare Index
3. UGR = CIE Unified Glare Rating System
4. VCP = Visual Comfort Probability
5. CGI = CIE Glare Index

## 2.7 Daylight Control

### 2.7.1 Daylight Nature

Generally, it is agreed that natural sunlight affects humans positively, both psychological and physiological. The natural light is consisted of several components as illustrated in *fig.2*. Different techniques of daylight control are necessity to eliminate side effects of high levels of daylight in the space like overheating, glare and over brightness.

In the way to protect users from over sunshine effects, control devices can be integrated in the building form and elements or simply added as internal blinds through to smart computerize shading systems and heliodors (Phillips, 2004).

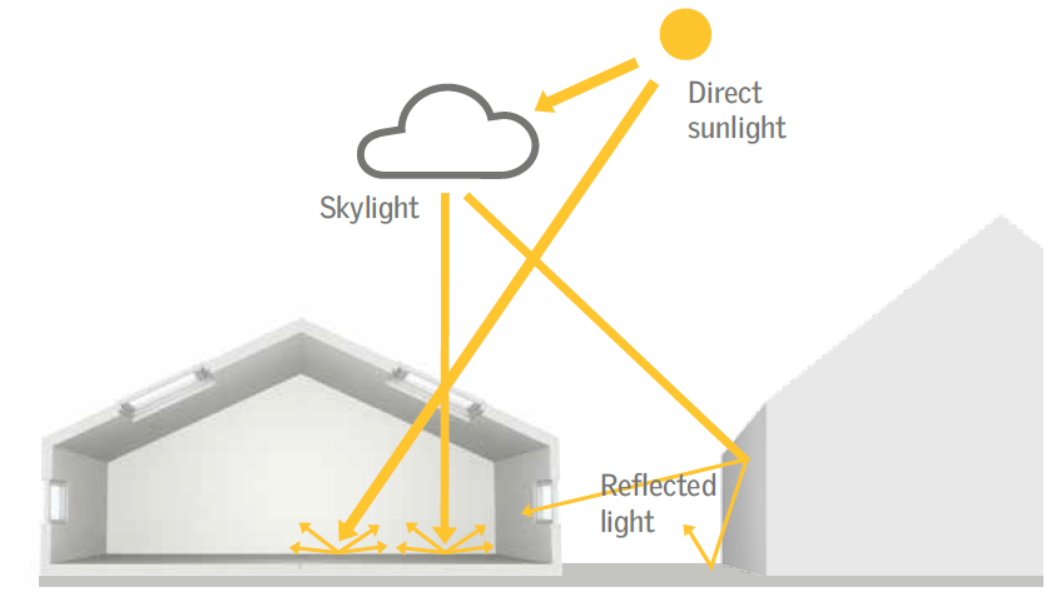



Figure 2: Natural Light Components (Retrieved from Phillips, 2004)

### 2.7.2 Daylight Factor

Customary in design analysis, daylight factor term appears to specify the daylighting in inner spaces of the building. The 'Daylight Factor' (DF) is defined as the approximate ratio, in percentage, of indoor illuminance to the outdoor illuminance, available simultaneously. Essentially, three major factors are defining the daylight factor: the externally reflected component, the direct skylight (sky component) and the internally reflected component.

By taking a significant point inside the space, 'Daylight Factor' is the ratio of direct illumination received from the sky of specified illuminance distribution to the horizontal illumination under clear sky hemisphere. Correspondingly, internal component and external component are, respectively, the percentages of illuminance hits significant point by reflected light from internal and external surfaces to the horizontal illumination under clear sky hemisphere (Muneer, 2007).

The apertures, unlike artificial lighting, does not provide stable stream of light; the sky illumination controls the internal component. Therefore, the ratio of **Daylight Factor** often calculated by: $D = \frac{E_i}{E_{dh}} \times 100\%$

where $E_i$ is the internally reflected component, and $E_{dh}$ is the simultaneous illuminance from the whole sky (the illuminance on an unbarred horizontal surface outside). This factor is used to specify the lighting in indoor spaces under sky overcast conditions, where the sky is represented by standard CIE Overcast Sky, table 3. The contours in *fig.3* represent edges of distinguished levels of daylight factor (Tregenza, et al.,2013).

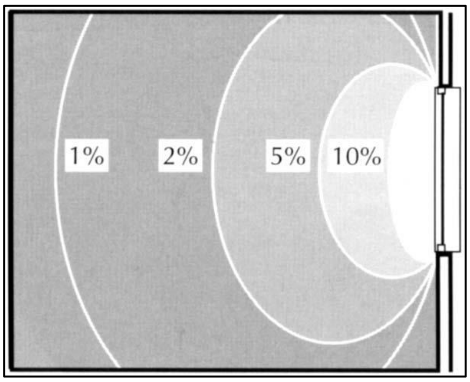



Figure 3: Steady Distributed Daylight Factor from Rectangular Window (Retrieved from Tregenza, Et Al.,2013).

Table 3: Average Daylight Factor for Indoor Spaces (Retrieved from Emmitt, 2013)

| Building Type | Space | Average Daylight Factor |
|---|---|---|
| Dwellings | Living rooms | 1.5 |
| | Bedrooms | 1 |
| | Kitchens | 2 |
| Workplaces | Offices | 5 |
| | Libraries | |
| | Schools | |
| | Hospitals | |
| | Factories | |
| All buildings | Residential | 2 |
| All buildings | Entrances | 2 |
| | Public areas | |
| | Stairs | |

## 2.8 Daylighting Strategies

### 2.8.1 Glazing and Windows

The main purpose of glazing is for daylight admission to inner spaces and to connect interior with exterior environments. However, human nature appreciates the natural surrounding components, with all variation of colour, light and shade, through form of glass applied to windows or facades (Phillips, 2004). Glazing classified in three main types as follows:

- Clear Glazing.
- Tended Glass.
- Miscellaneous Glazing, includes:
    - Patterned Glass
    - Wired Glass
    - Laminated Glass
    - Glass Blocks

### 2.8.2 Sidelighting Strategies

#### 2.8.2.1 Side Window

Side windows control the permitted sunlight under several factors and conditions. The factors that characterise the role of daylight in the space are the effective window proportions and location on the wall beside sky overcast and orientation. Generally, daylight from one side window in the space cause visual discomfort because of high contrast between bright light from the window and darkness deep inside the space, *fig.4* and *fig.5*. However, it is recommended to locate windows in two different sides that can reduce glare and balance light distribution in the space, *fig.6* (Mohamed, 2008).

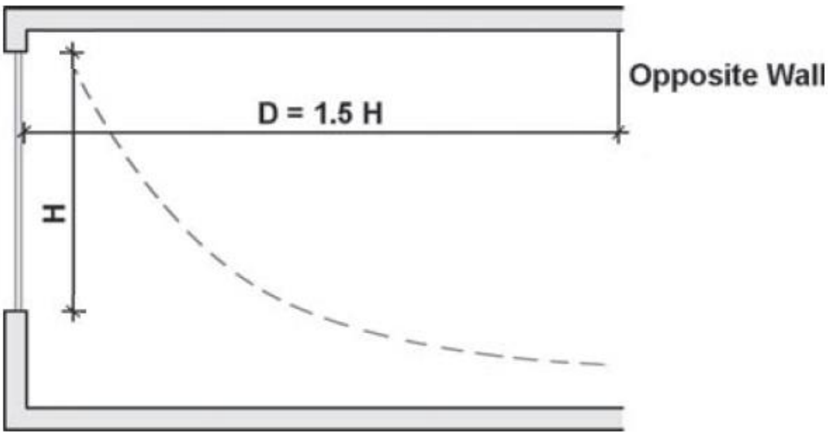



Figure 4: Daylight Effective Depth (D) when Penetrate through Side Window with (H) Height (Retrieved from Mohamed, 2008).

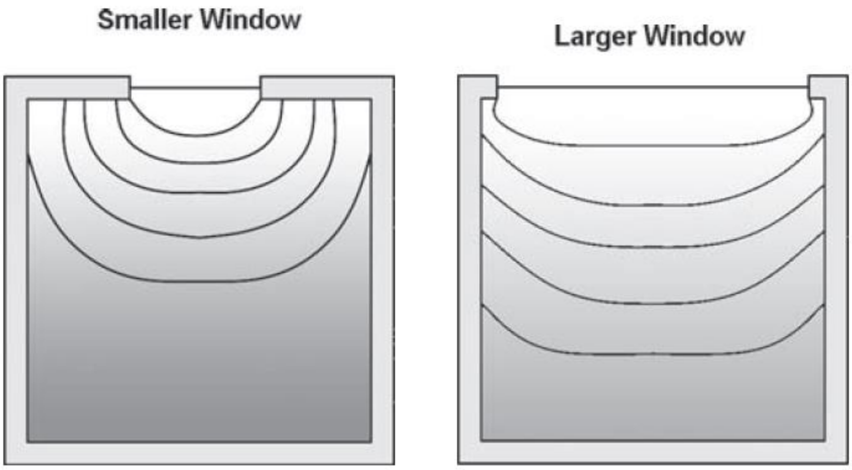



Figure 5: Isocontour Curves of Daylight Pattern through Small and Large Windows (Retrieved from Mohamed, 2008).

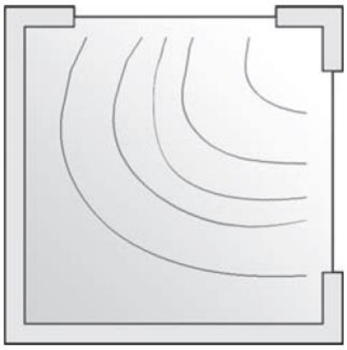


Figure 6: Balanced Daylighting Distribution by Two Adjacent Side Windows (Retrieved from Mohamed, 2008).

#### 2.8.2.2 Clerestory System

Side windows that placed in higher levels in the walls are called clearstory. It supplies daylight deeper to the core of the space, but also has almost the same limits and challenges of normal side windows, as orientation limitations and treatment solutions, *fig.7*. Clearstory window efficiency of merging daylight into the space depends on its size, window length and width, and the clear height from the floor (Mohamed, 2008).

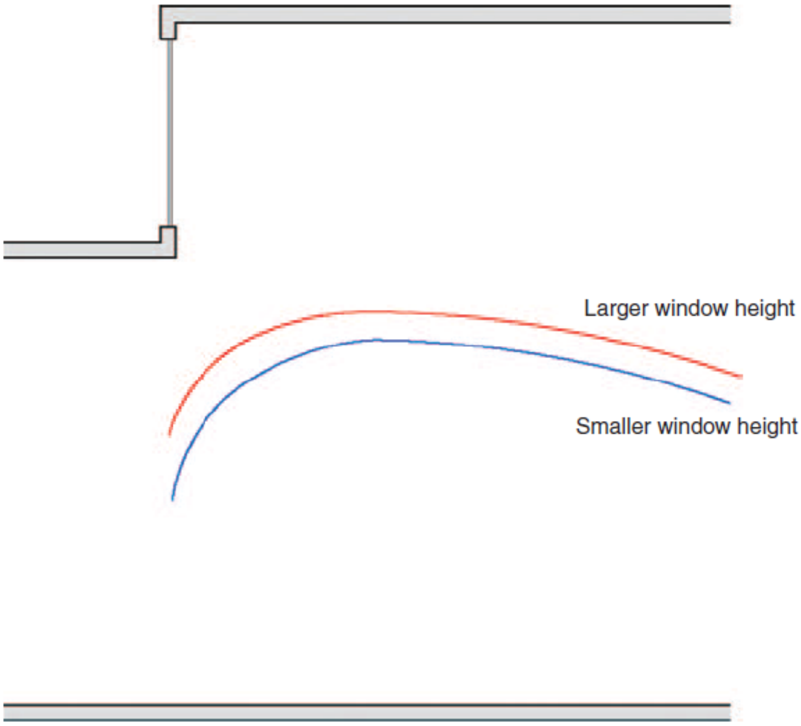



Figure 7: Pattern of Daylight Incidence through Clearstory Window (Retrieved from Mohamed, 2008).

### 2.8.2.3 Combined Side-systems

Combining side window with clearstory can cover wide range of dark zones, reducing glare contrast and increasing lighting balance, *fig.8* and *fig.9* (Mohamed, 2008).

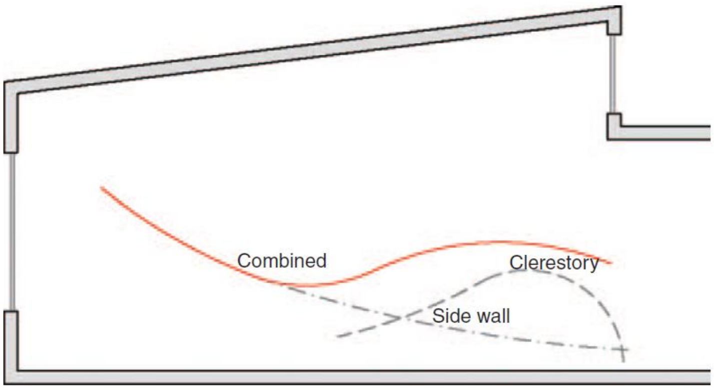



Figure 8: Effective Daylight Distribution by Two Opposite Apertures (Retrieved from Mohamed, 2008).

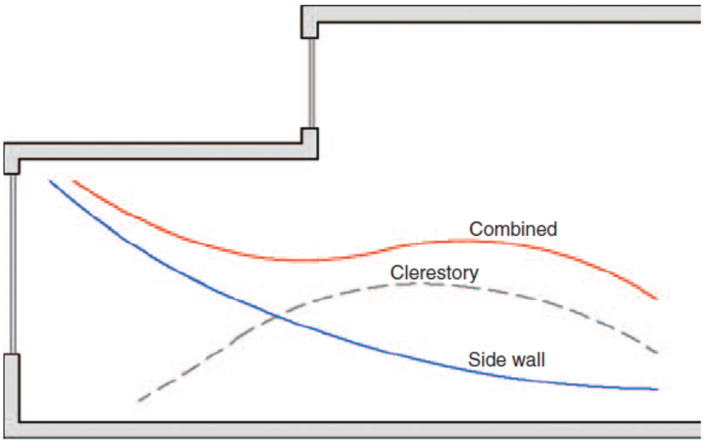


Figure 9: Effect of Two Vertical Openings in One Side (Clearstory and Side Window) (Retrieved from Mohamed, 2008).

### 2.8.2.4 Lightshelf System

Lightshelves are sunlight capturers and redirectors devices. By using the ceiling as extra reflectors, lightshelf dived windows into bottom section provide sunlight and view and top section that provides indirect daylight towards deep part of the space, *fig.10*. Basically, lightshelf works perfectly in sunny days maximizing sunlight reflection by its specular upper surface material. Beside normal considerations, as orientation, size, height, etc., this system should be considered from early design stages for better integration results (Mohamed, 2008).

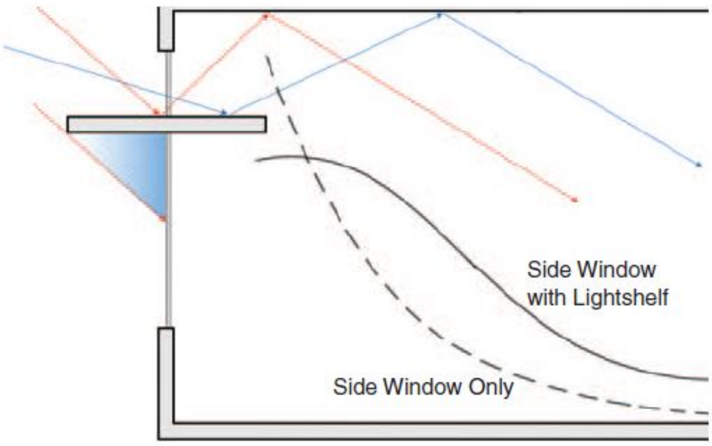


Figure 10: Integration of Lightshelf in A Side Window (Retrieved from Mohamed, 2008).

### 2.8.2.5 Variable Area Lightshelf System

This system is an automated system add dynamic move to the lightshelf system. This allows lightshelf to follow the sunlight on daily and seasonally bases and changes for more efficiency, *fig.11* (Mohamed, 2008).

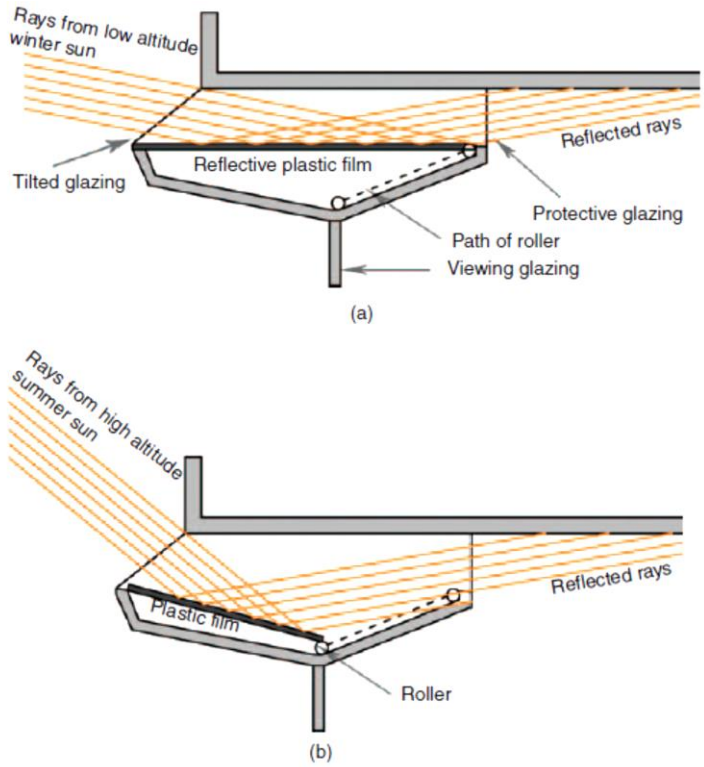



Figure 11: Variable Area Lightshelf Adjusted to Two Spots; (A) Selected Low Sun Angles (B) High Sun Altitudes (Retrieved from Mohamed, 2008).

### 2.8.2.6 Louver Systems

Louver system shares the same concept of other sidelighting systems, provides balanced lighting levels by directing daylight to darker spots of the space and reducing glare near the windows, *fig.12*. Also, it can be fixed or adapted as dynamic system and works optimally in clear daytime (Mohamed, 2008).

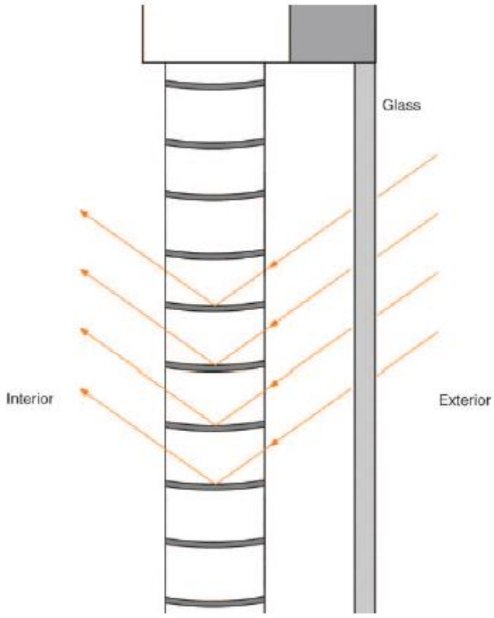



Figure 12: Louver System's Reflective Behaviour (Retrieved from Mohamed, 2008).

### 2.8.2.7 Prismatic Systems

Prismatic is a designed glazing system to orient the beam of light by reflection and refraction ways into the space. This system is classified as a sidelighting strategy as illustrated in *fig.13*. The prism redirect the incoming light by reflection of sunlight upward to the ceiling and onwards the deep area of the space. The combination of prismatic glazing with artificial lighting is not an invention, but it used normally for optimum distribution of light. Although, the utilization of this collecting and controlling system is facing some challenges and limitations in performance. This puts the prismatic system under evaluation and research for further design solutions. The reflection panel is recommended to be customized in the upper portion of the window for better performance. The sandwich position between double or triple glazing windows is most preferable due to cleaning and maintenance issues (Mohamed, 2008).

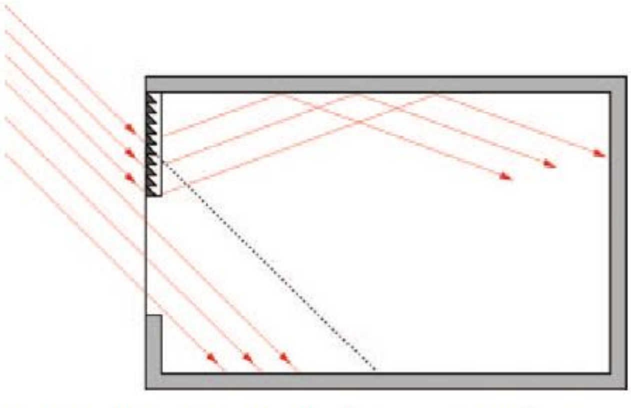


Figure 13: Integration of Prismatic Panel within Side Window (Retrieved from Mohamed, 2008).

### 2.8.2.8 Anidolic Zenithal Collector System

The Anidolic Zenithal system is based on the concept of using two concentrating parabolic mirrors to collect and flux light over wide area inside a space, *fig.14*. The main purpose is to maximize the balanced daylighting distribution throughout the deep areas. The zenithal antidolic system can be combined with inter-reflective duct to interpret light into space in more controlled method (Mohamed, 2008).

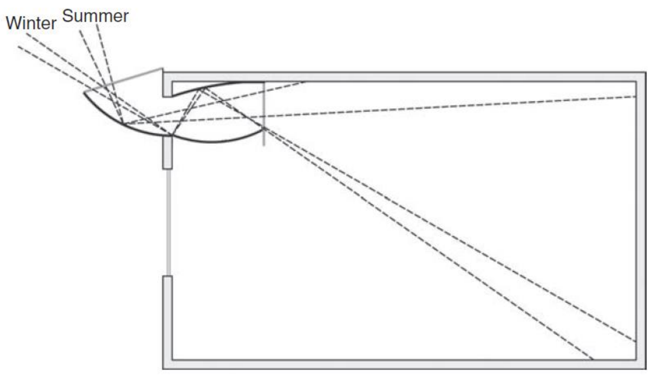



Figure 14: Side Window with Anidolic System (Retrieved from Mohamed, 2008).

### 2.8.3 Toplighting Strategies

#### 2.8.3.1 Skylight System

A skylight system is considered as the most basic toplighting strategy. It is usually designed as horizontal or slanted roof opening to capture daylight. It works either with high levels of sunlight available or excessive defused skylight from zenithal sky vault. The introduced light is distributed into the portion that located directly under the skylight opening and gradually lessens to the faraway areas, *fig.15* (Mohamed, 2008).

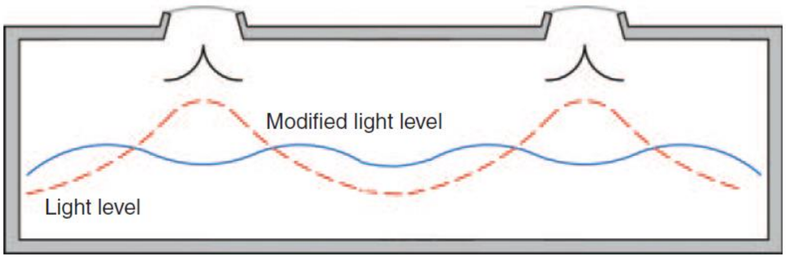



Figure 15: Balance Effect on Daylighting Levels by Deflecting Devices Underneath the Skylight Openings (Retrieved from Mohamed, 2008).

#### 2.8.3.2 Roof Monitor and Sawtooth Systems

The primer difference between roof monitor and sawtooth strategies are their shapes. In principle, these systems capture light through angled or vertical roof openings, *fig.16*. According to daylight demand, apertures are designed and adjusted to capture sunlight throughout daytime or seasons.

Roof monitors could be designed as single-sided or double-sided. Single-Sided and sawtooth systems direct sunlight inside to deep areas, but double-sided distributes light in more uniform levels and less directionally, especially under overcast sky conditions (Mohamed, 2008).

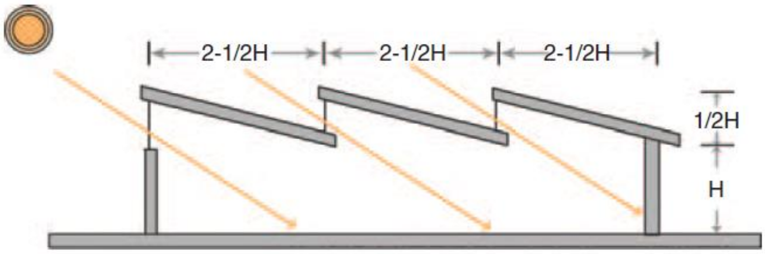


Figure 16: Mono-Side Sawtooth System Orients the Sunlight Inside the Space (Retrieved from Mohamed, 2008).

**2.8.3.3 Light Pipe System**

The light pipe system is a strategy used to interpret light in the multi-story buildings to the lower levels. The application of this method could be very basic or sophisticated and elaborate. The mechanism of this system combines solar collector that assembles solar energy, concentrator surface to focus sunlight, carrier method and distribution system, *fig.17*. A simple fixed mirror can be used as a collector or sophisticated automated heliodon that follow the sun path. As well, a concentrating mirror or lens could work as a solar concentrator in this light pipe system. The carrier method (transport system) could be a simple shaft through several floors or more complicated apparatus like prism or fibre optic system that transports light by inter-reflected within fibre optics walls (Mohamed, 2008).

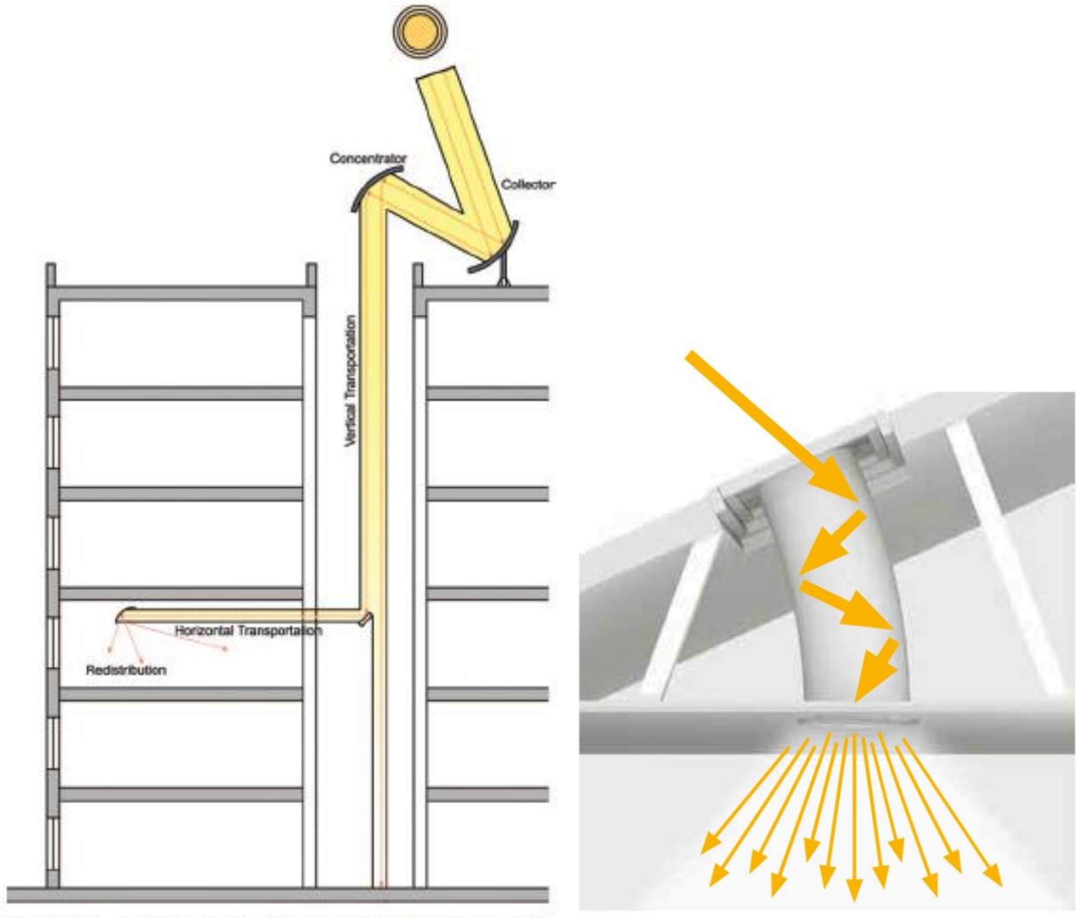



Figure 17: Light Pipe System with Collectors and Transporter Systems (Retrieved from Phillips, 2004 and Mohamed, 2008).

## 2.9 Parameters Influencing Daylighting Performance

### 2.9.1 Site Climate Zone

The dominant climate of the desired site of the building identifies the main potentials of the daylighting and visual comfort. The availability of sunlight is defined by the sky condition in every significant climatic-zone when fluctuating between clear-sky luminous to overcast-sky with different levels of intensity. This variation, as illustrated in *fig.18* and *fig.19* below, is affected by the weather along with the site latitude as it is going on the hemisphere (Andersen & Foldbjerg, 2014).

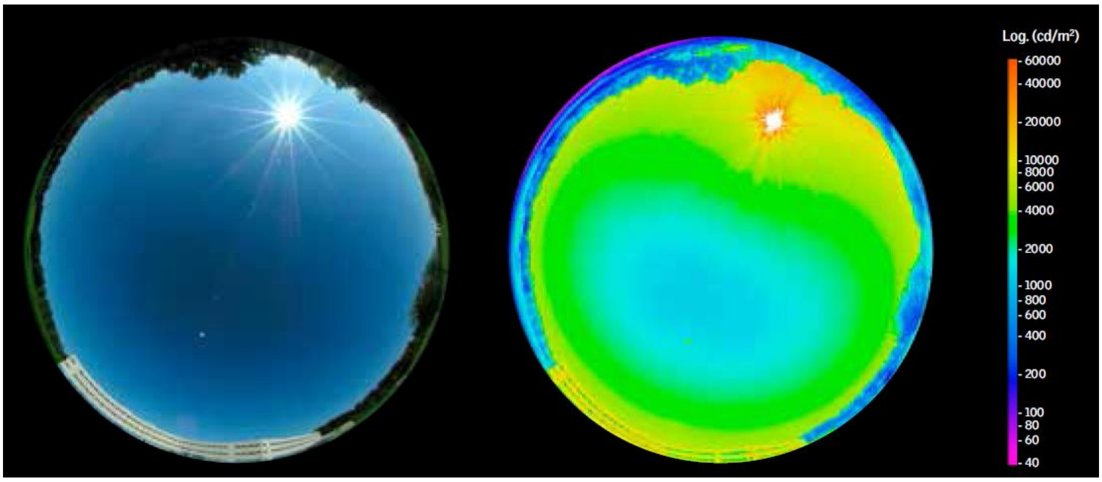


Figure 18: Luminance Map in Clear Sky Condition (Retrieved from Andersen & Foldbjerg, 2014)

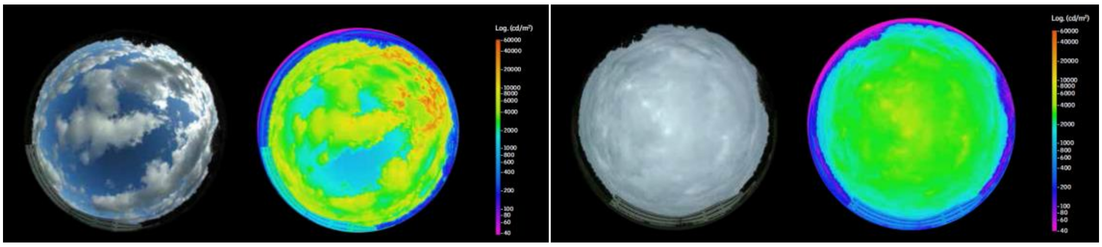


Figure 19: Luminance Map of Intermediate Sky (Left) and Overcast Sky Conditions (Right) (Retrieved from Andersen & Foldbjerg, 2014)

### 2.9.2 Latitude of the Building

Depending on the building location on the earth, every site has its longitude and latitude. A unique solar altitude is determined for each time of day. The parameters given by the solar altitude for a particular location in hemisphere have important impacts in design to regulate the solar radiation. Based on the latitude, the daytime hours are defined alongside the quantities of solar radiation at seasons.

Parallelly, the angle of the sun is directly related to the site location and its latitude, where the difference between winter and summer expands as the location is shifting from equator towards the earth poles. The *fig.20* below is illustrating the low levels of outdoor illuminance in Sweden in Northern Europe compared to Italy in Southern

Europe in the year (Andersen & Foldbjerg, 2014).

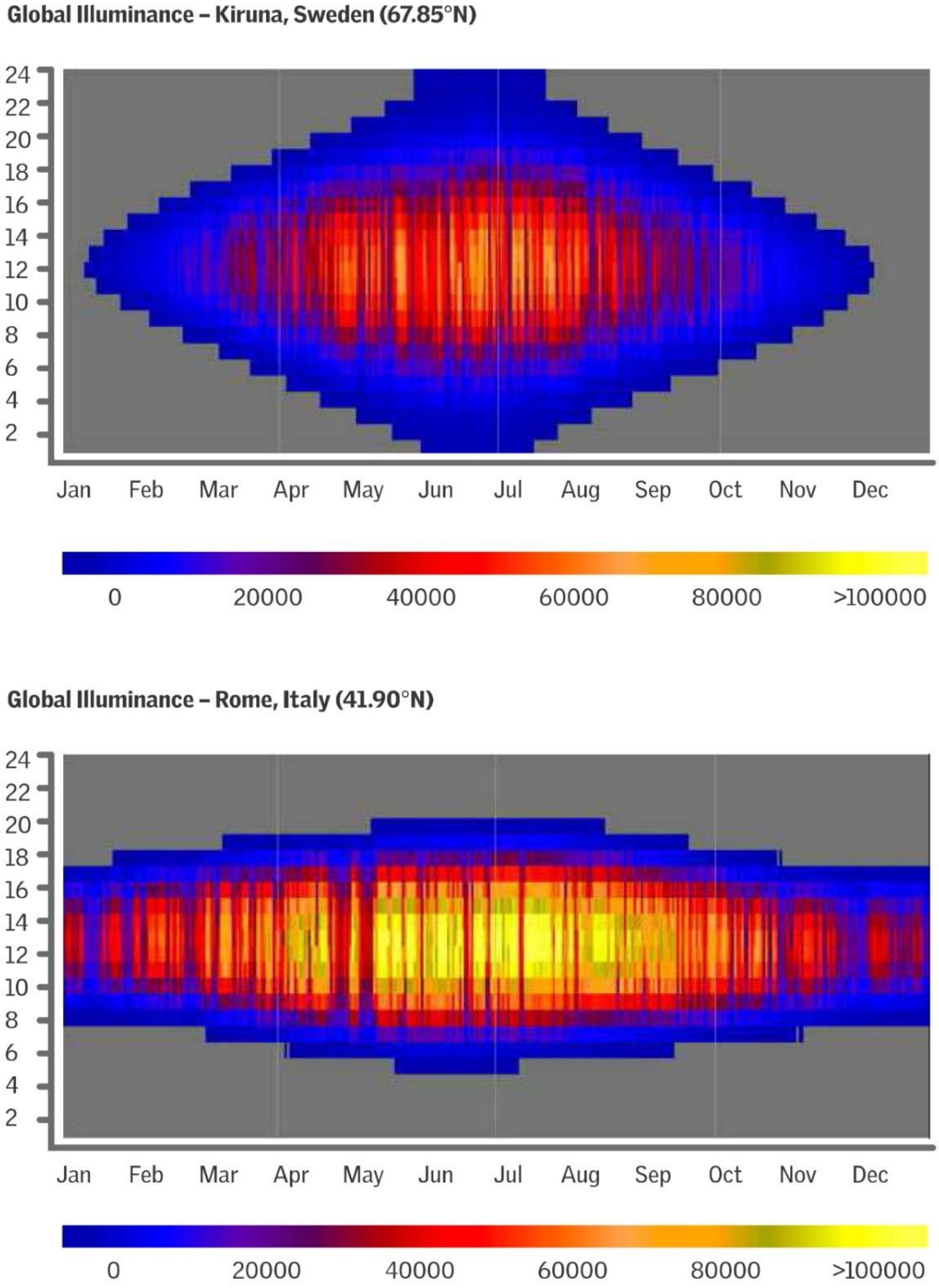



Figure 20: Annual Illuminance in Northern (Sweden) and Southern (Italy) European Locations (Retrieved from Andersen & Foldbjerg, 2014).

### 2.9.3 Surrounding Obstructions and Reflections

All the nearby buildings, vegetation, the nature of the surrounding ground surfaces and other obstructions, have direct influences, in a way or other, on the external reflections toward the designed building, *fig.21*. Rather the skylight and roof apertures have wider view to the sky, it is sometimes suffering from overstocked dust and in some areas that is affected by arid climate and deserts (Andersen & Foldbjerg, 2014).

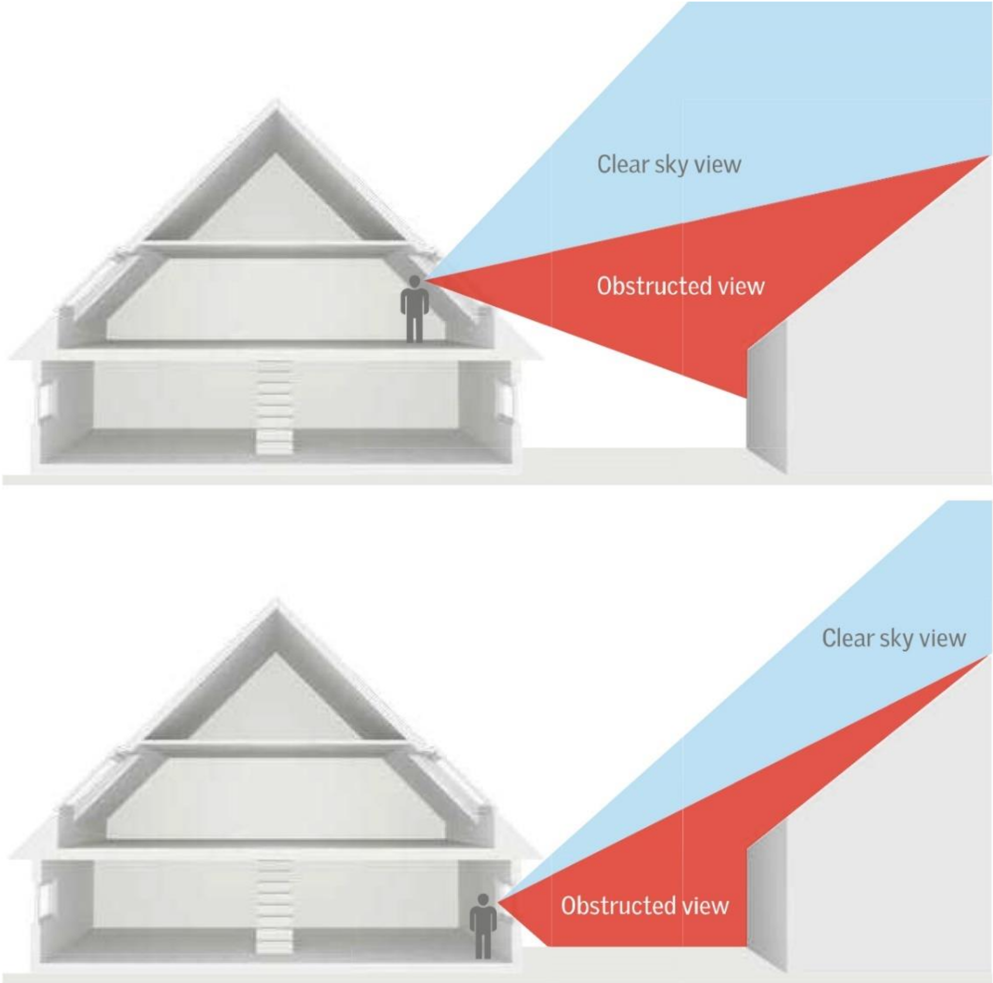



Figure 21: View Components from Roof Window(Up) and Side Window (Bottom) (Retrieved from Phillips, 2004)

Where there is no direct skylight reaching a significant area in the space, then this area is categorised as a range beyond the no-sky line. Therefore, the levels of daylighting will be poor and there is a necessity to utilise the artificial lighting in indoor spaces. An alteration could be happened in the no-sky line by adapting the aperture height or increasing the distance between the façade and the obstructions. The no-sky line is calculated by bounding the lines of the obstruction through the edges of the apertures inside the space, as illustrated in *fig.22* bellow, ensuring that the sky is disappeared behind the no-sky line.

In the case of many widows are in the same space, the final no-sky area is defined by overlapping all the areas where are no capturing of any skylight beyond the windows. A space with two sides windows can provide a good skylight distribution without blind spots far from the sky. Considering the no-sky line from each side of the space will set some limits to the depth of space with sufficient daylight, otherwise roof-lighting and atriums can be optional solutions for the deep spaces if it is required.

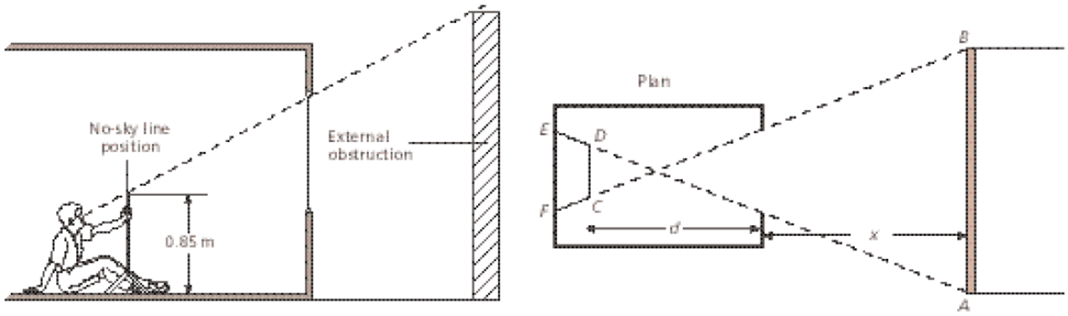



Figure 22: No-Sky Zones Defined by the Distance of the Obstructions and the Size of the Openings (Retrieved from LG10,1999)

### 2.9.4 Aspects Related to Building Design

"Effective daylight design must start at the site layout stage, before windows are considered in detail. This is because large obstructions may have an impact both on the amount of light reaching windows and on the distribution of light within a room. Site layout is also the most important factor affecting the availability of sunlight inside a building. For an effective passive solar design, gaining the most of winter solar gains, it is especially important that the degree of obstruction of the site is considered" (LG10,1999).

### 2.9.5 Geometry

Commonly, the capacity of capturing the daylight and adequately distributed in indoor spaces can be related to the building geometry. In buildings with large spans, daylighting is facing challenges in penetrating deep for covering all the space and windows on facades are limiting this even more.

These limitations are allowing to receive adequate daylight distribution in only few meters nearby the apertures (around DF > 2%). Enlarging the window size could help for deeper distribution with limits related with the visual comfort metrics, otherwise more approaches are required, *fig.23*. Strategies as light shelves and reflective ceiling would provide an enhancement in light distribution within indoor space, yet these solutions are generally associated by discomfort issue which is needed to be considered carefully (Andersen & Foldbjerg, 2014).

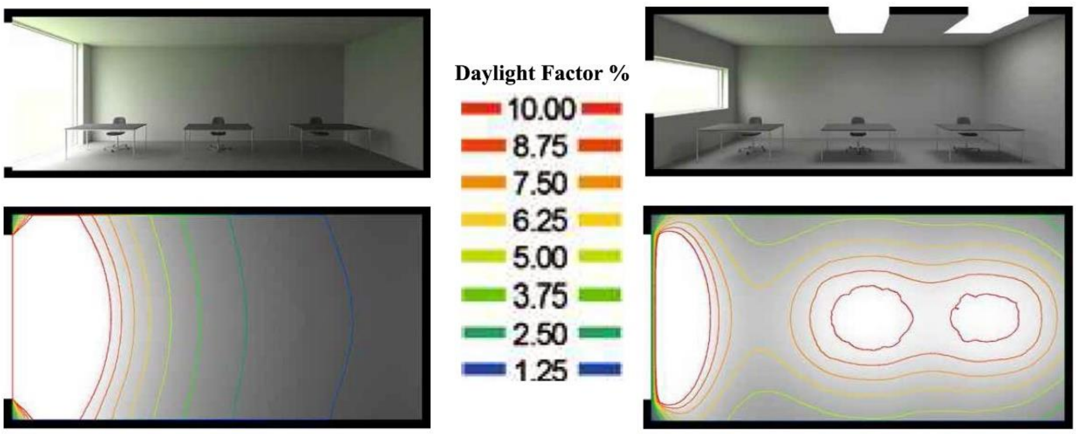



Figure 23: Simulation of Luminance and Daylight Factor with Two Different Scenarios Related to Window Size (Retrieved from Andersen & Foldbjerg, 2014).

### 2.9.6 Material Properties

The reflectance features of the space's inner surfaces and its colours are contributing to the whole lighting system, exemplified in *fig.24* below. For instance, poor lighting levels and insufficient luminous atmosphere can be resulted by dark coloured and non-reflective surfaces which is absorbing the light and reflect minor amounts to the space. Rather it is more desirable to have bright vertical bright in the space, yet the shading system with darker colours is required to control sunlight to prevent the glare effects (Andersen & Foldbjerg, 2014).

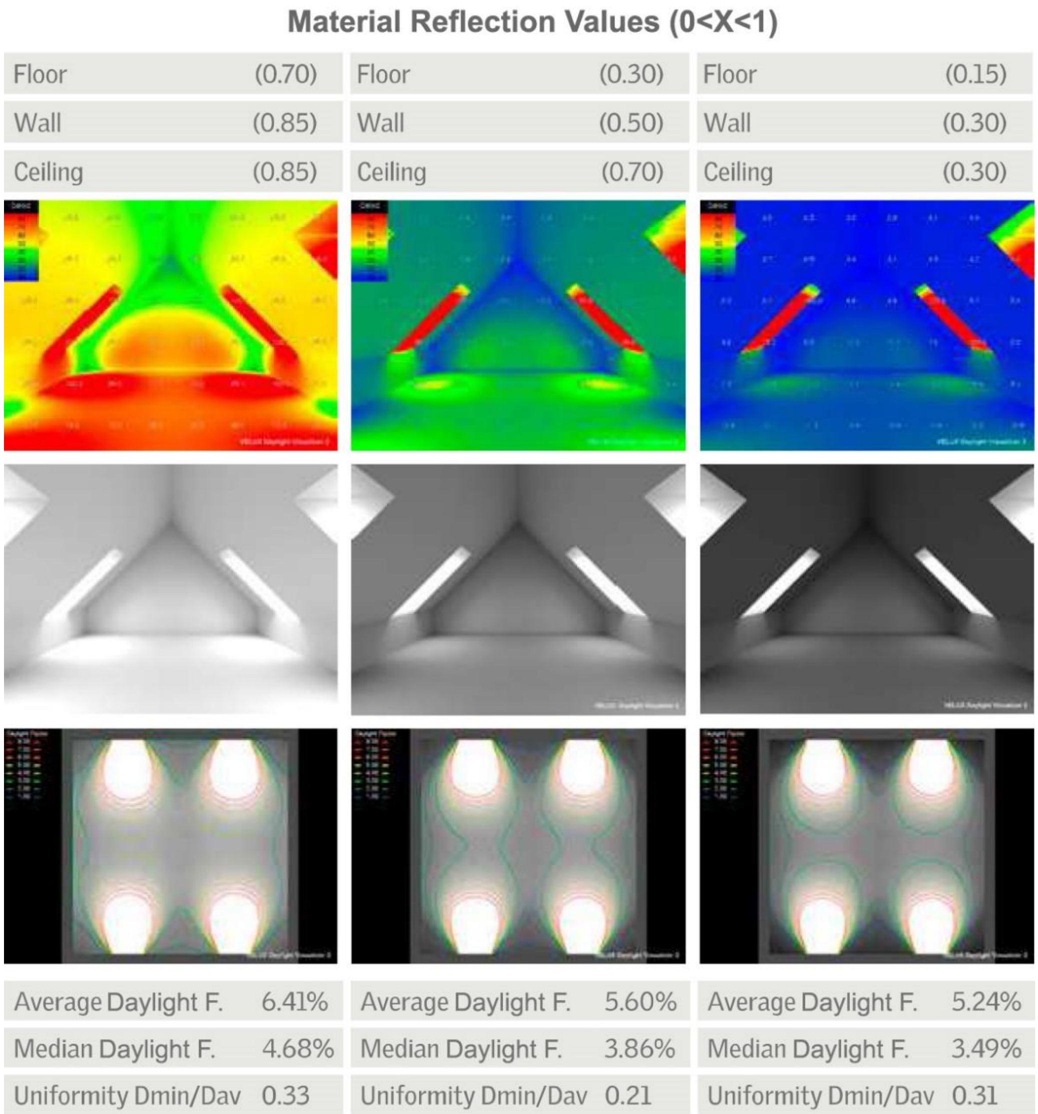



Figure 24: Simulations of Three Different Surface Reflectance on Daylighting Distribution (Retrieved from Andersen & Foldbjerg, 2014).

### 2.9.7 Apertures

#### 2.9.7.1 Orientation

The building position on the site is determining the orientation of the windows and accordingly the quantities and qualities of daylight inside the space. Referring to the Northern Hemisphere, the northern façade of building is mostly exposed to the diffused light coming from the sky with comfortable and desirable qualities throughout the daytime in stable rhythms *(fig.25).*

Meanwhile, all other facades in three directions are receiving direct sunlight with significant varieties of light levels that penetrate the spaces daily as the sun pursues its path around the planet. The roof windows installed in flat or very shallow slope are mostly the same in allowing direct sunlight to enter the space (Andersen & Foldbjerg, 2014).

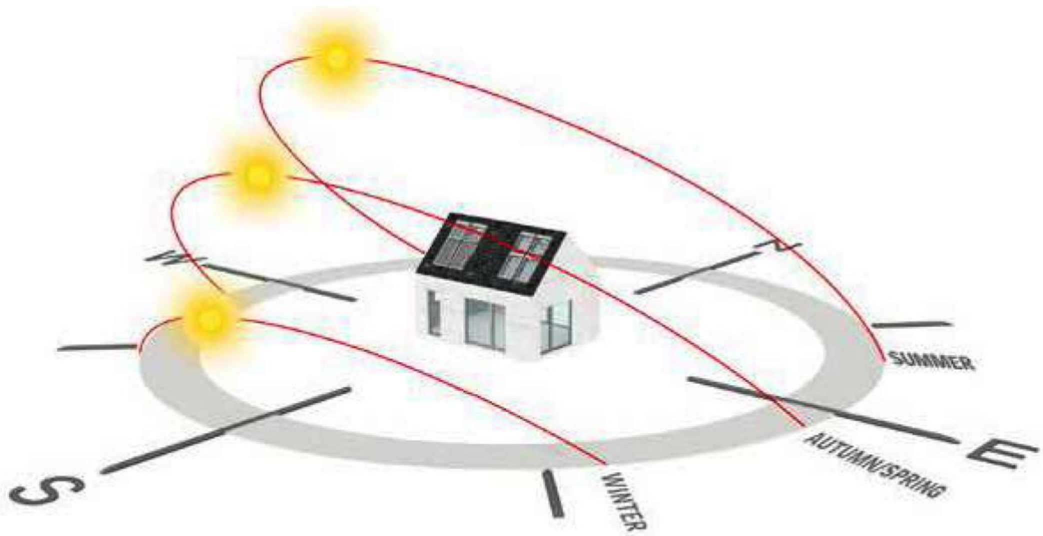



Figure 25: Sun Path Diagram on Equinox and Two Solstices Days (Retrieved from Andersen & Foldbjerg, 2014).

#### 2.9.7.2 Opening Size and Glazing Transmittance

Both daylight qualities and quantities are correlated to the glazing portion of the window area in the space (Andersen & Foldbjerg, 2014). If it is assumed that a multi-story building is totally lighted by natural light, limitations will appear in the issue of spaces deepness. By the following procedure, it is possible to define the limiting space depth when it is lighted by one-side windows;

$$\left(\frac{L}{W} + \frac{L}{H_w}\right) < \left(\frac{2}{(1 - R_b)}\right)$$

Where (L) is the maximum space depth, (W) is the space width, ($H_W$) is the window lintel height from floor surface and ($R_b$) is the average reflectance of surfaces in the distant part of the space from the window opening. In cases where the L value is exceeding this limits in the equation, the space will appear gloomy and extra artificial light sources will be required.

Table 4: Relation between Window Height, Space Width and Surfaces Reflectance (Retrieved from LG10,1999).

| Reflectance $R_b$ | 0.4 | 0.4 | 0.5 | 0.5 | 0.6 | 0.6 |
|---|---|---|---|---|---|---|
| Space width (m) | 3 | 10 | 3 | 10 | 3 | 10 |
| Window top height (m) | The maximum space depth (m) | | | | | |
| 2.5 | 4.5 | 6.7 | 5.7 | 8.0 | 6.8 | 10.0 |
| 3 | 5.0 | 7.7 | 6.0 | 9.2 | 7.5 | 11.5 |
| 3.5 | 5.4 | 8.6 | 6.5 | 10.4 | 8.1 | 13.0 |

The table 4 above shows the effects of reflectance values and the window head height on the space maximum depth when the space has different widths. Generally, surfaces with high reflectance values and higher window head are allowing to design deeper spaces with appropriate light levels. Evidently, wide spaces are allowing to have greater depth. For example, in a 10.0m wide room with 2.5m window head level and 0.4 surfaces reflectance, the maximum depth should be 6.7m. If the reflectances are increased to 0.6, the depth limit increases to 10.0m. The effect of window head height is appearing when it is increased to 3.5, the space depth can be enlarged to 8.6m with 0.4 reflectance and to 13.0m with 0.6 surfaces reflectance. Otherwise, it is obvious that the spaces which are lighted with two opposite sides windows have sufficient light for a deeper length with twice limiting space depth (LG10,1999).

One more factor related with the windows is the transmittance of light through the window layers. As a rule of thumb, in comparison with an open window, the non-coated double glazing window is allowing about 80% of light while the non-coated triple glazing can provide only 70% of the light that falls on its surface. Coating and colouring would reduce these values to very low levels as 20% and expressively adapt the spectral quality of the transmitted light and the behaviour of the coloured surfaces inside the space (Andersen & Foldbjerg, 2014).

### 2.9.8 Shading Strategy

The existence of shading devices is influencing the unwanted solar irradiation and the useful daylight that is needed in indoor space. When the conditions in the space are marginal within the comfort zone, shading controls should be designed to prevent any ingress of solar irradiation. However, placing reflective light-colour as interior shading devices between two glazing may maintain to minimize about 20-30% of amount of transmitted solar radiation or by its thermal mass effect to inner space.

Glazed openings facing south are the easiest to shade, horizontal shading devices work efficiently to pass winter sunlight and protect from summer solar radiation. Whilst vertical devices are more practical to treat east and west windows, but usually it become a challenge be integrated into the building envelop without blocking the visual interaction between indoor and outdoor. Trees can be some suitable protectors for east and west facades from overheating at the summer season in cases of low rise buildings. At the same time, interior shading devices act efficiently at controlling glare and lighting levels (Robertson, et al., 2010).

#### 2.9.8.1 External Shading Control

Exterior shading strategies has direct contribution to the sustainability plans of the building by several compensations obtained. Regarding the discomfort glare issues, external shades are consisted as high efficient method in term of glare controlling and prevention, *fig.26*. It reduces the glare without diminishing the view with internal blinds, tinted glass or individual preferences by space's occupants.

On the other hand, utilizing exterior shadings are reducing the peak electric energy demand and that impacts on the lower peak demands from services, resulting significant reduction in electro-mechanical operations and costs. Likewise, energy savings are affected positively by reducing the direct solar gains by apertures. Initial costs of construction can get beneficial impacts by replacing unshaded high performance glazing surfaces with shaded less-expensive glass with similar efficiency on energy saving issue.

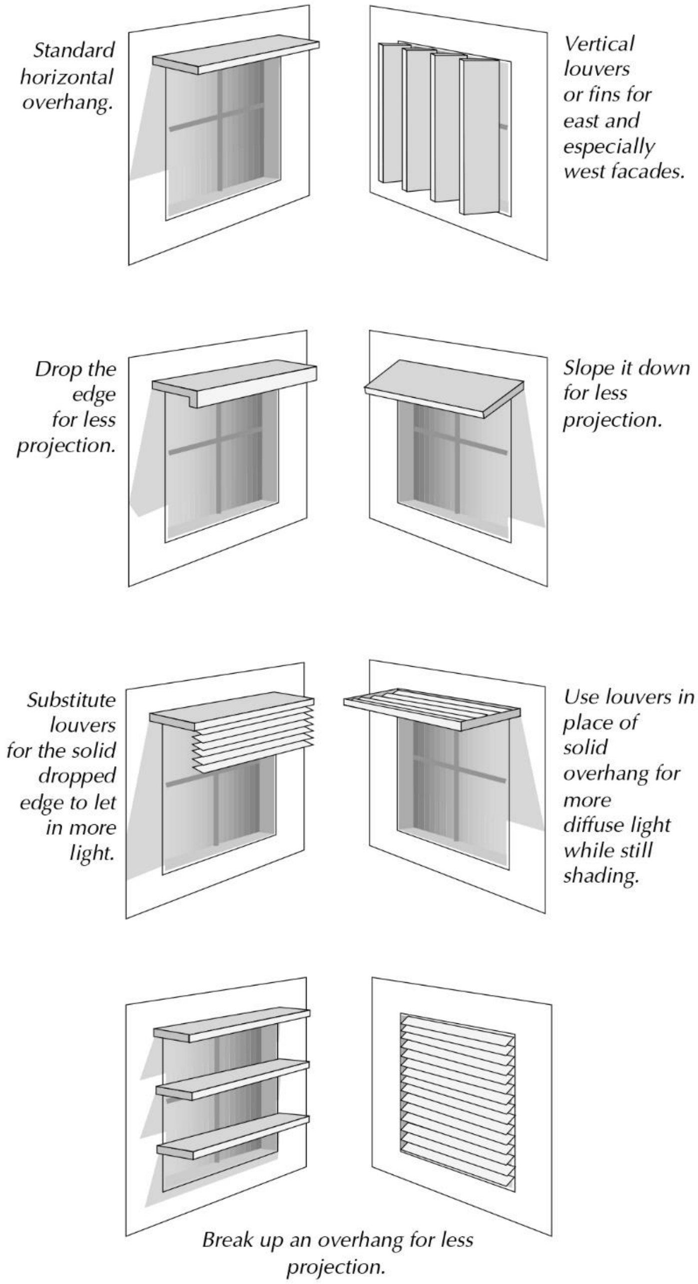



Figure 26: Samples of Basic External Shading Strategies for Side Windows (Retrieved from Robinson, A., & Selkowitz, S., 2013).

### 2.9.8.2 Internal Shading Control

Enhancements where done by internal blinds or sun-screens have its importance as the aperture itself. Different types of internal shading devices as Venetian and Pleated blinds are commonly utilized to control excessive daylighting and discomfort glare.

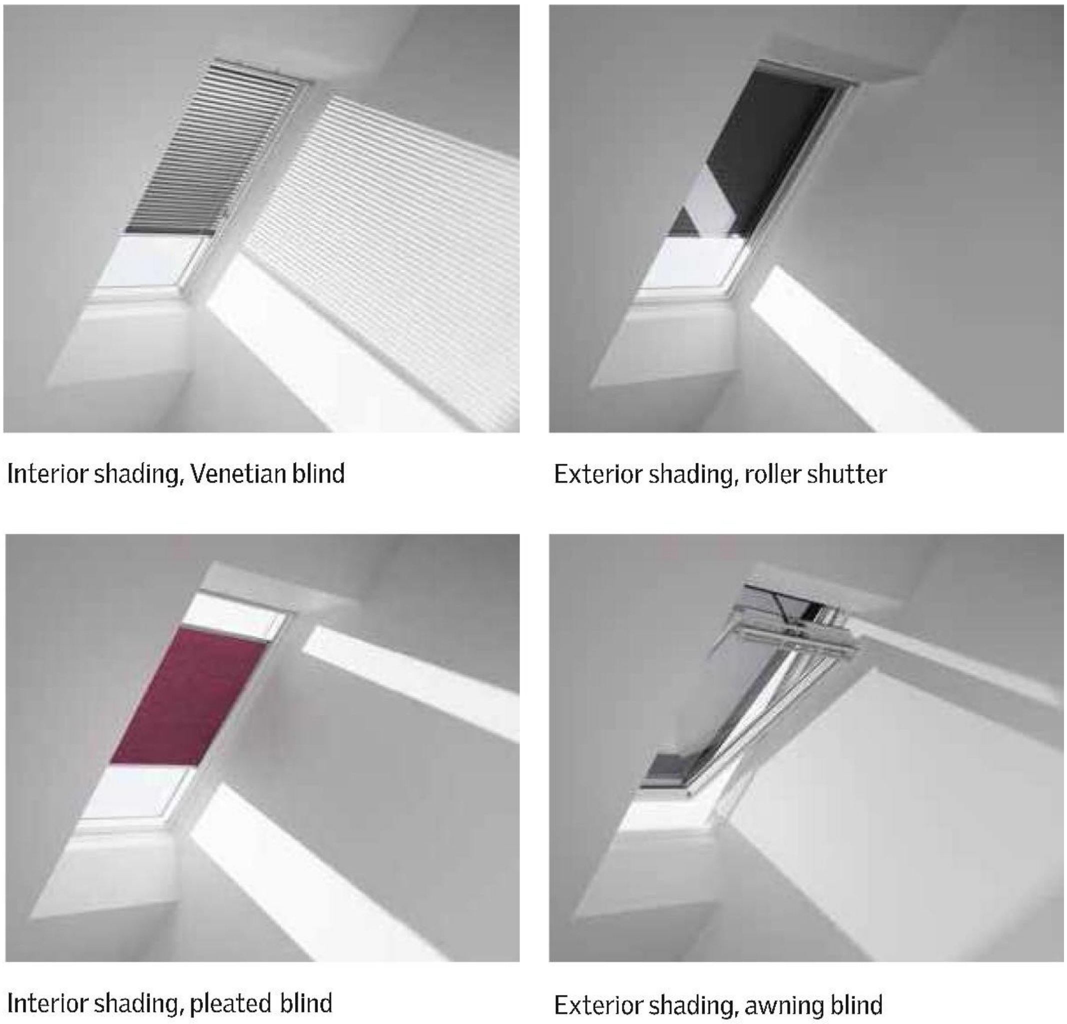



Figure 27: Samples of Internal and External Shading Strategies (Retrieved from Andersen & Foldbjerg, 2014)

The internal shadings have several advantages such as improvements in the occupant's comfort by preventing glare which provides better architectural design opportunities *(fig.27)*. But, it requires some precautions if it is designed against negative effects on the thermal conditions in the space as well as visual metrics such as colour rendering problems.

## 2.10 Libraries Types and Classification

The Whole Building Design Guide by National Institute of Building Science (NIBS) (2013) is classifying the libraries as the following categories:

Academic Libraries (exist in colleges and universities) are usually used by students for research and study purposes. It is requiring comfort, quiet and adequate space for study and material usage. Mainly, academic libraries are relying on paper-based and printed materials. Therefore, reader seating is one of the most important consideration in its design.

Public Libraries: Public libraries can be differentiated from academic, school, and special libraries because they function to serve the needs of a diverse service population including small children, students, professionals, and the elderly. In contrast, academic libraries serve college and university faculty and students; school libraries serve elementary, middle, and high school students and faculty; and special libraries (such as Presidential Libraries) serve scholars and experts within narrowly defined fields.

Public libraries are featured by the served functions to the different public age categories including students, researchers, professional, children and elderlies. Special libraries are libraries focusing in specific field as medical, law, religious, government or army libraries. The design of this type of libraries is exclusively used by specific group of people without expecting fast rhythm of expansion as other types of libraries.

School libraries are highlighted by the expanded space program which includes the media and the printed materials as a must requirement of education process. Therefore, media centers, auditoriums and classrooms can be found in this type. Accordingly, design should support learning process as space expansion, controlled lighting, reading activities and support computer use (Guide, 2013).

## 2.11 Assessment Standards

### 2.11.1 Building Research Establishment (BRE) and Building Research Establishment's Environmental Assessment Method (BREEAM) Ecohomes

The BRE and Ecohomes are relaying on the daylight requirements by the British Standards (BS 8206-2 Lighting for buildings) to achieve a good practice according to the BS code (BS 8206-2,1992). In association with The Chartered Institution of Building Services Engineers (CIBSE) Lighting Guide 10 'Daylighting and window design' states, the sufficient daylight in indoor space should be with maximum limit of 5% daylight factor. The exceptions are taken on over-casted days in early morning hours and late afternoon periods with a minimum limit of 2% daylight factor. Otherwise, this will create a gloomy visual experience in the space and artificial lighting will be needed to support the visual tasks. Beside this code, BRE is recommending the codes related to daylighting that are approved by the British Standard like British Standard BS 8206-2 (2008) *Lighting for Buildings-Part 2: Code of Practice for Daylighting* and CIE, S. 011/E: (2003*) ISO-15469: 2003: Spatial Distribution of Daylight* by CIE Standard General Sky (Guide, 1999; Rao, 2010).

### 2.11.2 The Passive House (Passivhaus) Institute and International Passive House Association

The Building Research Establishment (BRE) is registered with the ‘Passivhaus Institut’ which is working on the passive house design principles and certification criteria. As recommended by both institutions, the building that is located in the Northern part of the earth should be oriented laterally with the east/west axis. Although, the most recommended orientation is when the building’s façades are 30 degrees toward south to maximize the benefits from solar gains. With this principle, the southern façade is predominantly facing the winter’s sun which supposed to has impacts on the internal environment and space organization. Yet, it is possible to achieve a passive building (Passivhaus) without orienting the building to the optimum southern angle regarding the 30-40% increases in heating/cooling demands (McLeod, et al., 2010).

The most significant step to achieve the energy efficiency in the Passivhaus building is with intelligent usage of daylight with optimized windows. The shadows and dim ceiling (cave effect) that is caused by the unplanned over-hanged shading devices should be prevented indeed. Therefore, the shading strategy should be able to redirect the daylight into further spaces as well as the bright and reflective surfaces. On the other hand, glare reduction should be taken on concern as in reduction of east/west facing window which is an aspect that highly required in non-residential buildings design in this code (Feist, 2014).

As solution strategy proposed by both institutions, the glazing ratios should be optimized on the southern façades and reduced on the northern façades. Factually in the late past, the south glazing surfaces are exceeding 50% in continental Europe according to Passivhaus surveys which is recommended to be adopted to 25-35% in southern façade with a need of good space planning (McLeod, et al., 2010).

To sum up, these codes of the both institutions are focusing on the energy demand of the building as an evaluation criteria. By considering the visual comfort metrics, these recommendations are might exposing the interior spaces to massive amounts of solar irradiations especially during the winter that might cause some visual difficulties in the building. Rather that, the required orientation is giving the opportunity to provide natural light in wide areas in indoor spaces with a need of daylight controlling strategy.

### 2.11.3 US Green Building Council (USGBC) LEED™

The code constituted for the "Green Building" is standardised by The Leadership in Energy and Environmental Design (LEED™) in order to provide a Green Building Rating System that represents the U.S. Green Building Council. Early proceedings of the USGBC, LEED required 2% daylight factor for 75% of the floor area used for critical visual tasks should be achieved in interior environment. It is following the British Standard Institution, BS 8206-2 that required 2%-5% DF conditional to electrical support in indoor spaces (Council, U. G. B., 2003; National Renewable Energy Laboratory, 2012).

For the **daylight** manner, there are two main aspects should be measured for the LEED Rating System, the view and the daylight. There is a high intention to the daylight penetration into the space and to connect the space occupants with outdoors. Firstly, the view aspect is mainly demanded in buildings (especially the healthcare buildings) where 90% of the regularly occupied floor should have direct line of sight to vision glazing to outdoors (Council, U. G. B., 2003).

Secondly, for the daylight assessment, there are three options for the evaluation:

**Option 1 – Simulation-based (spatial daylight autonomy):** by computer simulation the spatial daylight autonomy$_{300/50\%}$ (sDA$_{300/50\%}$), about 55%,75% or 90% of the regularly used space should be covered with minimum 300 lux in minimally 50% of the year (excluding the direct sunlight penetration), *see table 5*. Additionally, annual sunlight exposure with 1000 lux (ASE$_{1000,250}$) should not exceed 10% of the regularly occupied floor area that has daylight per the sDA$_{300/50\%}$ simulations (Council, U. G. B., 2003).

Table 5: The LEED Requirements of Spatial Daylight Autonomy (Retrieved from Council, U. G. B., 2003).

| Building type | Spatial Daylight Autonomy ($sDA_{300/50\%}$) |
| --- | --- |
| New Construction, Core and Shell, Schools, Retail, Data Centers, Warehouses & Distribution Centers, CI, Hospitality | 55%-75% |
| Healthcare | 75%-90% |

**Option 2 – Simulation-based (illuminance calculation):** under the conditions of clear-sky day at the equinox for 9am and 3pm, the required illuminance levels are between 300-3000 lux in the regularly occupied floor area. The calculations should include the sun and sky components with the typical meteorological year data for the building location. One day should be selected within 15 days of 21 September and 21 March. The average of hourly value for the two days, is used for evaluation. Moreover, all the blinds, movable furniture and partitions should be excluded and exterior obstructions should be included in the simulations to achieve 75%-90% coverage (Council, U. G. B., 2003), *see table 6*.

Table 6: The LEED Requirements of 300-3000 Lux Illuminance Coverage (Retrieved from Council, U. G. B., 2003).

| Building type | Percentage of regularly occupied floor area |
| --- | --- |
| New Construction, Core and Shell, Schools, Retail, Data Centers, Warehouses & Distribution Centers, CI, Hospitality | 75%-90% |

**Option 3 – Measurement-based method:** by taking similar process as option 2 with real measures from the floor. The measured illuminance should meet the required 75%-90% for floor areas covered with 300-3000 lux.

Thus, LEED has recommended several technologies and strategies to achieve the code requirements and building orientation, exterior/interior strategies and daylight predictions throughout physical and computer models. Furthermore, the provision of glare and/or daylight control system to prevent high-contrast conditions must considered for visual tasks (Council, U. G. B., 2003).

### 2.11.4 European Committee for Standardization (CEN)

EN 12464 standard (12464-1: 2011 Light and lighting–Lighting of work places–Part 1: indoor work places) (EN, 2011), is providing a clear definition for each visual task in relation to the lighting design which offers new approaches of design. Both lighting quality and quantity can now be described precisely for every induvial task (CEN, 2011).

Table 7: Standard Values for Lighting of Indoor Spaces (Retrieved from CEN, 2011).

| **Type of Interior** | **Task or Activity** | **$\bar{E}_m$(lux)** | **$UGR_L$** | **$U_O$** |
|---|---|---|---|---|
| Libraries | Bookshelves | 200 | 19 | 0.40 |
| | Reading areas | 500 | 19 | 0.60 |
| | Counters | 500 | 19 | 0.60 |
| Educational Buildings | Entrance hall | 200 | 22 | 0.40 |
| | Stairs | 150 | 25 | 0.40 |
| | Computer practice rooms (menu driven) | 300 | 19 | 0.60 |
| | Demonstration tables | 500 | 19 | 0.70 |
| | Preparation rooms and workshops | 500 | 22 | 0.60 |
| | Stock room for teaching materials | 100 | 25 | 0.40 |
| | Circulation areas, corridors | 100 | 25 | 0.40 |

Retrieved from the European standards, “Lighting of indoor workplaces” EN 12464-1 (June 2011), the values in table 7 are demonstrating the lighting qualities that is needed for each task. Where $\bar{E}_m$(lux) is the minimum illuminance required on the visual task area. In the case of the reading activity, the task area is the surface of the reading desk which is set to 500 lux. $UGR_L$ values are the maximum limit of direct glare on the visual field and glare measure should not exceed it. Though, $U_O$ is the ratio between the $\bar{E}_m$ and the mean level of illuminance on evaluated surface $\bar{E}$ (CEN, 2011).

EU Standard Visual Comfort: uniformed brightness is considered as a basic need for the space perceptions which shares the same importance with the light needed for specific visual task. To achieve this visual comfort metrics several factors can be controlled as:

− Balanced brightness distribution

− Varying luminance levels

− Plasticity/modelling

− Discomfort glare

− Uniform illuminance in area around visual task

− Sense of security

− Artificial lighting complemented by daylight

− Use of flicker-free ballasts (CEN, 2011).

The lighting for indoor tasks can be evaluated psychologically by the uniformed glare rating method ($UGR_L$) as regulated in European Standard EN 12464 (Light and lighting. Lighting of work places Part, 1) which specified the ($UGR_L$) maximum limits as follow:

$\leq 16$ Technical drawing

$\leq 19$ Reading, writing, training, meetings, computer-based work

≤ 22 Craft and light industries

≤ 25 Heavy industry

≤ 28 Railway platforms, foyers

The CEN provided concepts of lighting that correlates additional options to customize in lighting design. The financial scope is adding concepts as visual function (glare and contrast control), emotional and biological effects (as exciting lighting accents) and optimum energy efficiency (CEN, 2011).

**2.11.5 ASHRAE Standard**

American standards as ASHRAE/IES 90.1-2010, ASHRAE 189.1 (green building standard) started to regulate the standard illuminance for specific task along with the EU standards of 500 lux and suggested the concept of daylighting harvesting in the building design by the American Society of Heating, Refrigerating and Air-Conditioning Engineers along with other standards like International Energy Conservation Code (IECC) 2009 and Title 24-2008 (California's unique energy code). These codes are describing the requirement for daylight zone by the area next to the side opening or underneath the top aperture which is relaying on the opening size and the existence of any obstructions blocking the daylight (Standard, A. S. H. R. A. E., 2016).

The International Energy Conservation Code (IECC) 2009 code provided simple approach to employ the daylight harvesting system. It stated that the main daylight source in the space should be separately controlled without and specification for the controlling system in a way to give the freedom to designers to choose between dimming or switching (Standard, A. S. H. R. A. E., 2016). ASHRAE/IES 90.1-2010 presented more details about the approach to achieve that in its code:

Sidelighted spaces: for spaces larger than 23.23 $m^2$, the controlling system should be automated either with continuous dimming, offering one move between 50% and 70% of powered lighting and another move between OFF and 35%. The ASHRAE/IES 90.1-2010 is highly recommended the application of daylighting harvesting through sidelight sources in offices, classrooms, public spaces and commercial to reduces the energy consumption for lighting (Standard, A. S. H. R. A. E., 2016).

Toplighted spaces: If the overall area underneath the skylight aperture and covered by daylighting is exceeding 83.6 $m^2$, the general lighting should be completely independent with one of the strategies (stepped-automated or continuous dimming) (Standard, A. S. H. R. A. E., 2016).

# Chapter 3

# EMU MAIN LIBRARY: FIELD STUDY EVALUATION

## 3.1 The Method of Data Collection

The research arguing the validity of daylighting optimisation to achieve sufficient visual comfort metrics in EMU Main Library. To obtain the accurate data needed, many data sources will be consulted and measured.

1. Primary Data sources obtained through: observations, questioners, schedules, surveying and computer simulations.
2. Secondary Data sources will be used as referenced these includes: books, e-books, scientific journals, maps, organizational records, case studies.
3. Third Data sources considered such as literature reviews, proceedings, media promotions and internet.

### 3.1.1 Data Evaluation Method

The data evaluation of this research would be based on several parameters, which are considered as basic elements of visual comfort metrics and daylight controlling systems correlating aspects as site location, orientation, building form, building envelope, openings and shading treatments. The evaluation would be conducted through a field study to the case study area, EMU Main Library, the building would be surveyed, observed, photos pictures, computer simulated and measurement would be taken where is necessary also, and the questionnaire would be administered to the building occupants and users.

## 3.2 Case Study (EMU Main Library)

### 3.2.1 Location Data Findings

Eastern Mediterranean University (EMU) Main Library, Ozay Library, can represent a major facility in educational sector with direct contact with high priority of visual tasks. The central library has been designed in Turkey and built in Famagusta, North Cyprus. Due to the importance of optimum designed atmosphere in the university libraries to meet the challenge of both environmental conditions and the occupant's needs and comfortable usage of the space, the library has been selected to be tested how far its design responses to these challenges. The building is located in hot-humid climate zone with moderate humidity with mild winters, in Latitude: +35.11 (35°06'36"N) and Longitude: +33.94 (33°56'24"E) (*fig.28)*.

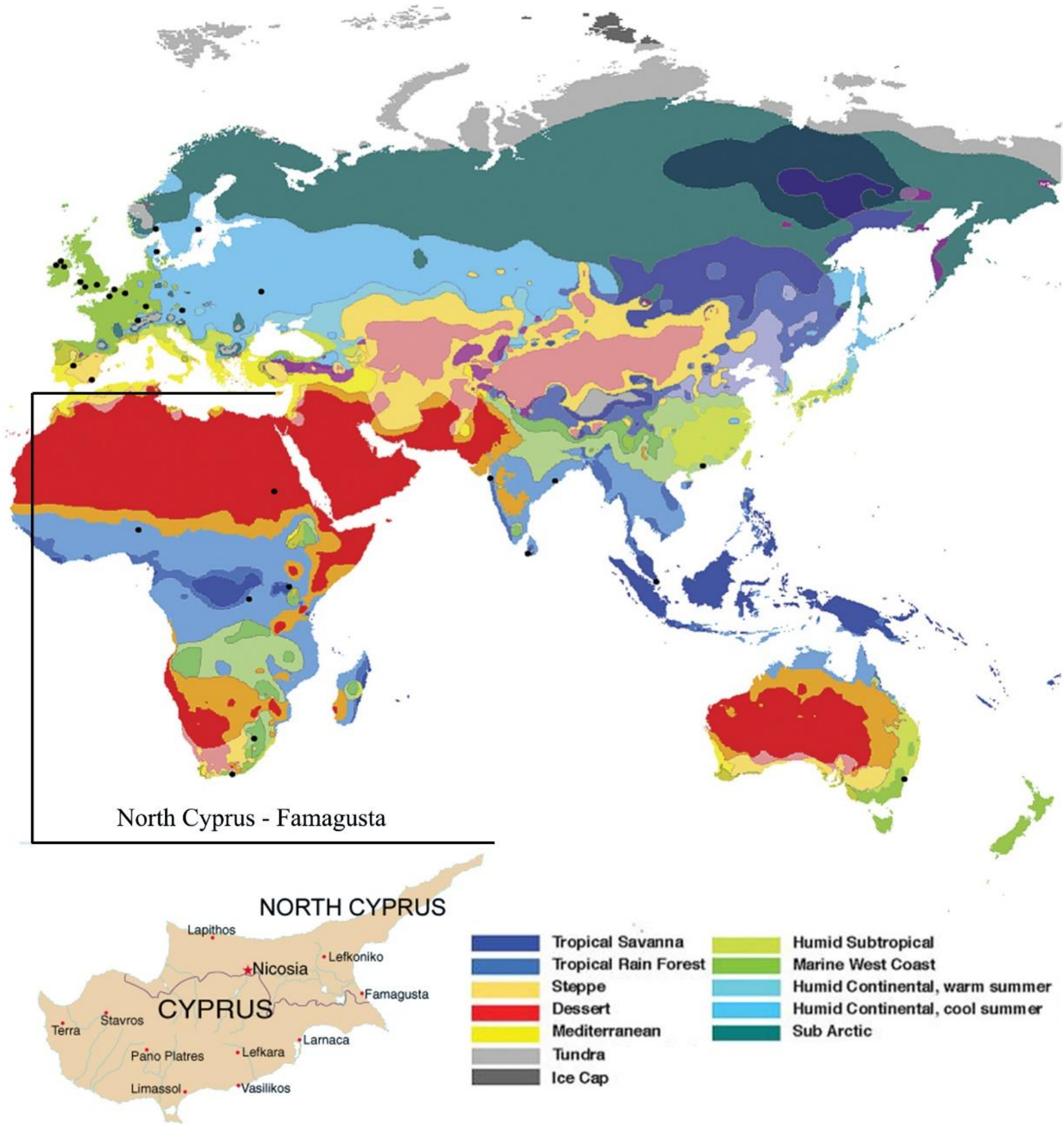



Figure 28: Cyprus Climate Map in Koppen Classification - Case Study Location (Retrieved from Guenther, Et Al, 2013 - Edited by Author)

### 3.2.2 Annual Sun Path

Since the library is suited in hot-humid zone, the preference of the sunlight is quite varied between seasons, especially winter and summer. It is more preferable in winter due the slight angle it takes and the warm feeling it provides. As seen in *fig.29* below, the sunlight hits the building directly on two facades in the southern portion of the block. Apparently, the summer slice of sun path, 21$^{st}$ June, took a place toward the north with a difference of 45$^{o}$ from the winter slice in 21$^{st}$ December of each year.

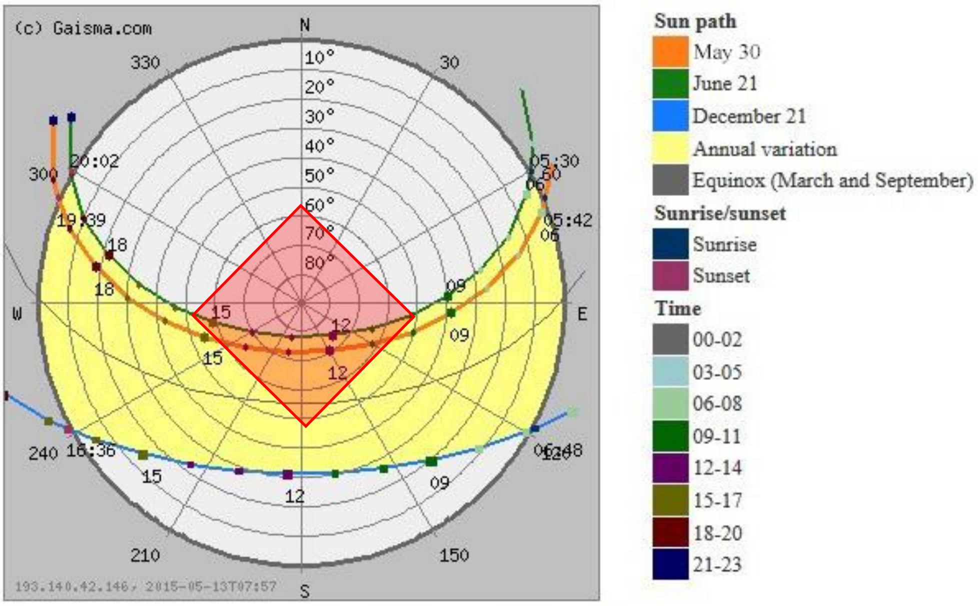



Figure 29: Famagusta Sun Path Diagram (Retrieved From www.gaisma.com)

In view of the sun altitude and azimuth, the sun movement is representing an environmental aspect that should be considered during the design. In the case of EMU Main Library, this movement will shape the reaction to these environmental aspects and the selection of the solutions for different faced challenges.

Table 8: Famagusta's Sun Locations throughout the Year (Retrieved from URL3)

| **Season** | **Altitude (degree)** | **Azimuth (degree)** |
|---|---:|---:|
| Summer (21/Jun.) | 74.60 | 43.65 |
| Spring (21/Mar) | 53.16 | 21.83 |
| Autumn (21/Sep) | 54.4 | 16.24 |
| Winter (21/Dec.) | 30.57 | 11.30 |

Annually, the sun is taking a place of 74.60º vertically in summer sky and drops to 30.57º in winter altitude. Simultaneously, it is moving from 43.65º due of the eastern south to 11.30º due of the western south azimuth, summarised in table 8.

### 3.2.3 Insolation Energy

It's found that Famagusta has above average solar energy and surface meteorology energy throughout the year (around 5.13 kWh/m²/day), (*fig.30)*. These rates raised to 8 kWh/m²/day during summer season. Correspondingly, balanced levels of sky clearance is noticed during daytime most of the year.

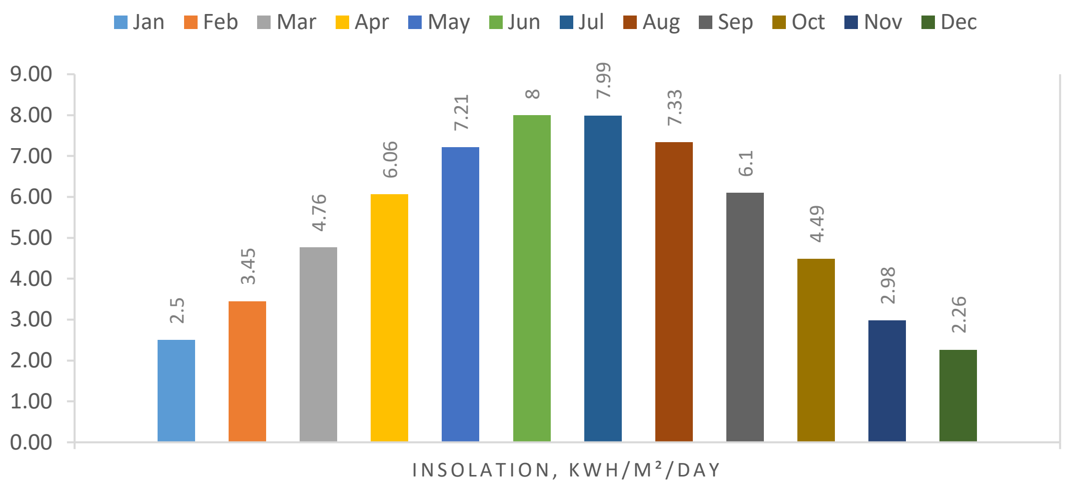



Figure 30: Famagusta Annual Insolation Energy (Retrieved From www.gaisma.com)

### 3.2.4 EMU Library

Location: (35.141386º, 33.911950º) degrees.

It is found that the Library building is oriented to (55°) South direction and (35°) East. The four-story building is built on a plot of 1600 m$^2$ (40x40m) with a total of 6600 m$^2$ built-up area and capacity of 710 occupants (*fig.31)*. The library block designed in half cubic geometry with four typical facades and almost similar space organisations, especially in the study areas in second and third floors. The building has 54 m$^2$ skylight aperture in the centre of the roof, affecting the second and the third floors, the study areas. The third floor is setting back from the corners to create galleries with large vertical windows all around except the entrances pays.

Figure 31: Case Study Location Map (Retrieved from maps.googl.com)

## 3.3 Observation Findings

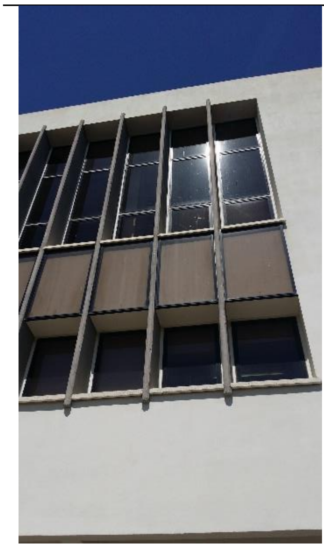
Observations had been done during several visits to the main library of Eastern Mediterranean University and many findings related to daylight utilisation are concluded as following:

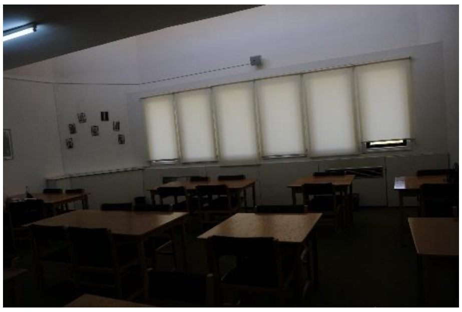
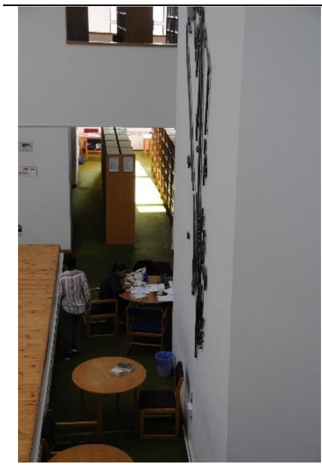
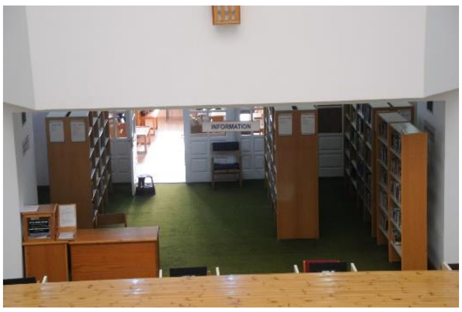
Figure 32: EMU Main Library (by Author).

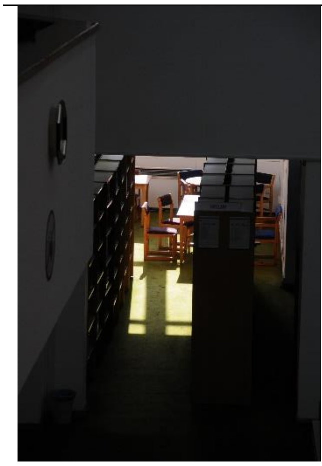
- All the elevations have the same concepts and treatments facing all directions.

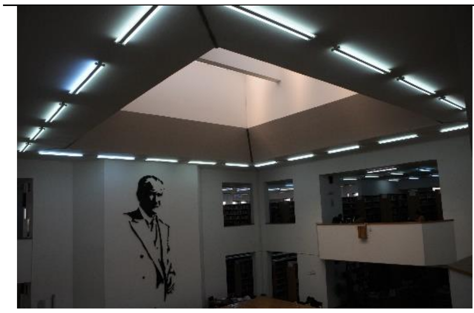
- The entrances are defined in the middle parts of the facade which are created by different building volumes. These entrance parts have horizontal openings which are usually used for darker study rooms *(fig. 32)*.

Table 9: Data Collected by Observation from Field Study (EMU Main Library)

| **EMU Library** | **Field of Study Observation Photos** | **Observation Facts** | **Indicators / Notes** |
|---|---|---|---|
| Exterior observations |  | The building is taking a square shape with unified elevation designs in all directions<br><br>Glazing ratio is 51% of the façade surface area. | It can be predicted that the interior spaces are suffering from inefficient shading devices |
| |  | At certain periods during the day, sunlight is directly penetrating into interior spaces passing through inefficient shading devices. | Mono-sized for external shading devices<br><br>Single layer glazing window |

| | | | |
|---|---|---|---|
| Enterior observations |  | Study Tables are under direct sunlight.<br><br>Normally, these areas are unoccupied by users during periods when covered by direct sunlight. | Study areas are distributed next to external windows<br><br>Very high vertical windows are revealing the space to direct sunlight |
| |  | Low levels of lighting are existed in the small study room due the use of internal blinds.<br><br>Electrical lighting covers insufficient natural light levels.<br><br>Laptops users mostly occupy these rooms. | Basically, this is the silent zone<br><br>Gloomy atmosphere during daytime with electrical lights and blinds |
| |  | Clear difference in lighting distribution on one level.<br><br>High contrast between dark and over-bright spaces.<br><br>At certain periods, there is adequate levels of light in the centre of the building underneath the skylight opening but supported by artificial lighting. | Users distribution pattern is moving wherever adequate light is available |
| |  | Internal partitioning system is creating gloomy atmospheres in spaces behind it in the shelves zone.<br><br>The excessive bright light from background has harden the computer's screens experience (glare). | Lack of transparency in partitioning system is causing dimness in transitional zones to the central void between floors |

| | | | |
|---|---|---|---|
| Enterior observations |  | Very high lighting contrast in the same space. | Artificial lighting system and shading devices are insufficient to provide balanced levels of lighting |
| |  | Large number of electrical lighting fixtures are used during the daytime to stabilise the lighting levels in the performance spaces, especially in the book shelves zone due its location far from the natural light apertures. | High energy consumption is in use where it could be preserved with better lighting strategies and techniques |
| |  | Excessive use of artificial light to stabilise lighting levels even in areas near the windows where there is no direct sunlight. | There is a need to enhance the diffused natural light in interior areas |
| |  | When there is no direct light striking the skylight window, commonly during morning and late afternoon hours, adequate light levels are distributed underneath. | Skylight need to be protected from direct sun |

| | | | |
|---|---|---|---|
| Enterior observations |  | Skylight is providing insufficient light along the daytime periods.<br><br>Skylight is supported by large number of lighting fixtures, regarding reasonable coverage from 10 meters high. | |
| |  | With all excessive natural light in some side parts and is existence in the heart of the building through the skylight, yet there are gloomy areas covered by artificial lighting. | Skylight is a major source of light in both levels but it could be source of disturbance with glare effect during mid-day hours when it is exposed to direct sunlight |
| |  | Area provided for computer use are not in use due the excessive light levels from background. | |
| |  | | The orientation of the building and the unprotected vertical windows are exposing the interior space to excessive exposure of light for deep distances |
| |  | Users are eschewing the areas near to windows and they prefer deeper spaces with adequate light levels. | High light contrasts might cause feeling of discomfort in the space |

| | | | |
|---|---|---|---|
| Enterior observations |  | Areas under shadow with an opportunity to have a view to exterior space are mostly preferred and occupied. | There is a good potential to provide visual comfort zones if daylight is optimised |
| |  | Bright colours in the walls and book shelves are causing unwanted reflections and glare what makes the space visually uncomfortable. | Direct and indirect sources of glare are existing in the study areas |

### 3.3.1 Observation Summary

Regarding the observations in table 9, the study areas are in high demand to solve the direct excessive light which is penetrating through the windows. Meanwhile, the flooring is acting in a prover way to prevent unwanted reflections. Parallelly, the centred skylight aperture in the library roof is to provide more daylighting inside deep spaces. While, direct sunlight dropped directly on the study desks through this skylight opening. For warming issue, it is noticed that some students prefer to sit under direct sunlight for a while with no reading activity. Otherwise, study places located directly under skylight are rarely used during mid-day throughout the cooling season. Offices and computers cannot be used properly without using the blinds to reduce direct sun light, glare, and solar irradiation.

Observations showed the importance of blinds to do visual tasks because it is obvious that appropriate external shading devices are needed. Therefore, there are various essentials which demanded to be implemented as proper controlling strategies, responsive electrical lighting systems and well-studied space utilisation plan.

## 3.4 Questionnaire Survey Findings

The tested sample (281 respondents) of library occupants were asked to respond to several questions to test their comfort in the study areas and satisfaction level correlated to lighting levels. Firstly, survey results are presented graphically and discussed to analyse design indicators and other factors could affect its reliability. All the 12 questions are close-ended and fluctuates between scaled and direct response types. Thus, questions did not consist of any scientific terminologies that might confuse the respondents. Moreover, collecting information about different periods during the day time was considered in the design of questions to assure clear responses.

### 3.4.1 Lighting Availability at Study Area: Brightness

In terms of brightness, the percentage of people agreeing with brightness increases during the daytime. Along the daytime, it is claimed that levels of lighting are adequate during the day with respectable percentage which is gradually increases from bright to over-bright especially after 12:30pm (*fig.33)*. Yet, about 15% of the sample are complaining of dimness in some parts during the same daytime, mainly at morning time (10am-11am) and late afternoon time (3pm-4pm).

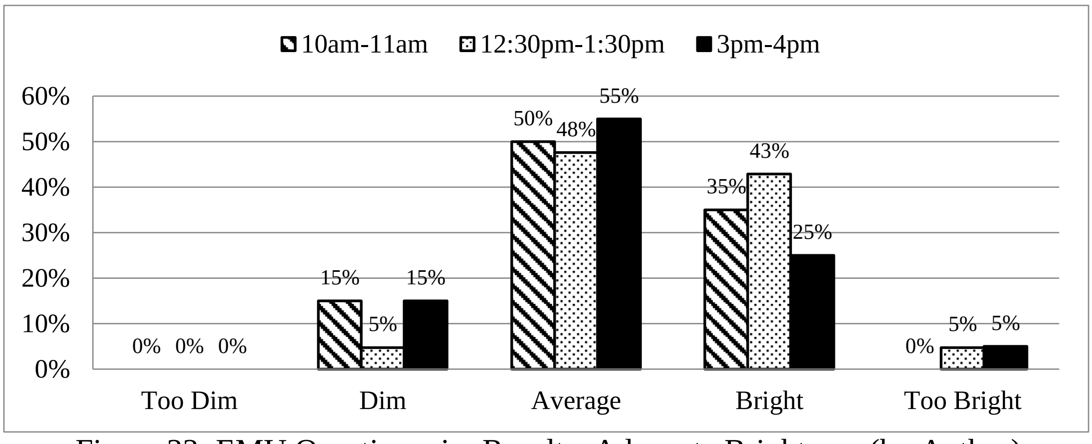



Figure 33: EMU Questionnaire Results: Adequate Brightness (by Author).

On average, 48~55% of the respondents are believing that daylighting is in average levels during the day. Whilst there are around 25~43% seeing the daylighting is bright, especially at noon time when 43% are experiencing brightness in the spaces. Furthermore, about 5% are suffering from over-brightness in both periods (12:30pm to 1:30pm) and (3pm to 4pm).

On the other hand, none of the respondents is complaining about being in gloomy or dark spaces in the library during the day. Thus, there is an indication of unbalanced-distribution of daylighting pattern in indoor spaces of the library.

### 3.4.2 Lighting Affects Amount of Time Spent in Library

Responsively, the effect of these levels of brightness on duration of using the study areas in library was asked to respondents to find out exactly the amount of time spent on library. As seen in *fig.34*, around 40~53% are agreed that daylight levels have influences on their time in the library, especially in the morning hours which recorded 53% agreement of total occupants. Although, the other questioned-sample are almost distributed in similar time periods between other responses.

It is found that 15~20% of the respondents neither disagree nor agree with the statement that daylight affects the amount of the time spent in the library. While 18~20% of the respondents disagree that the lighting levels affects their time in the building. Subsequently, since 40~53% of users agreed and 10~18% are strongly agreed with it in all the daytime, this proves that the amount of time spent has been affected by daylighting,

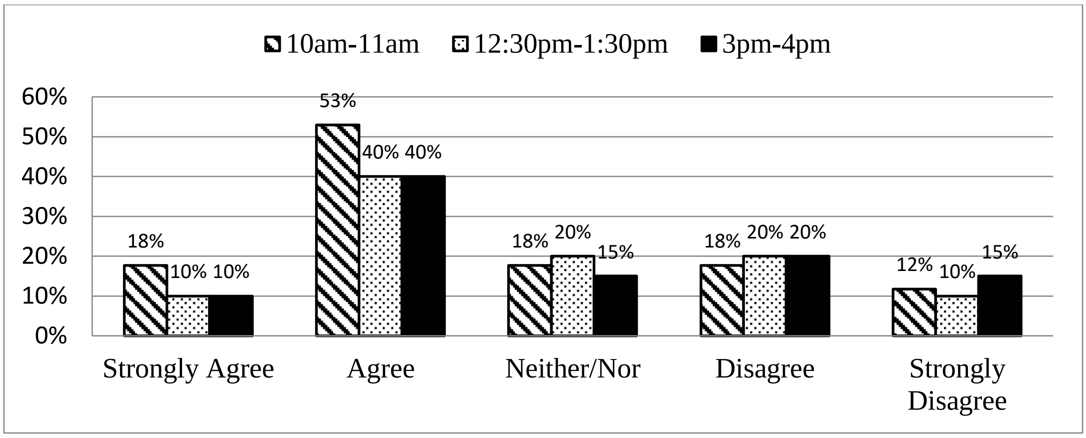



Figure 34: EMU Questionnaire: Effect on Time Spent (by Author).

### 3.4.3 Design of the Seating Layout and Effects on Seating Selection Preference

Related to the previous questions, the benefits of daylighting on seating areas throughout the day is interrogated. On average, around 33% of the respondents could not decide about the issue, but averagely 49% showed agreement responses with the question's statement as 40~62% of the respondents chose to agree and 5% strongly agreed with it in noon and afternoon periods. The results were that the layout design of seating needs to be optimized more efficiently to daylight as shown in *fig.35*. Distinguishable 10% are totally disagree with question's statement which highlights the seating layout concern related to daylight optimisation.

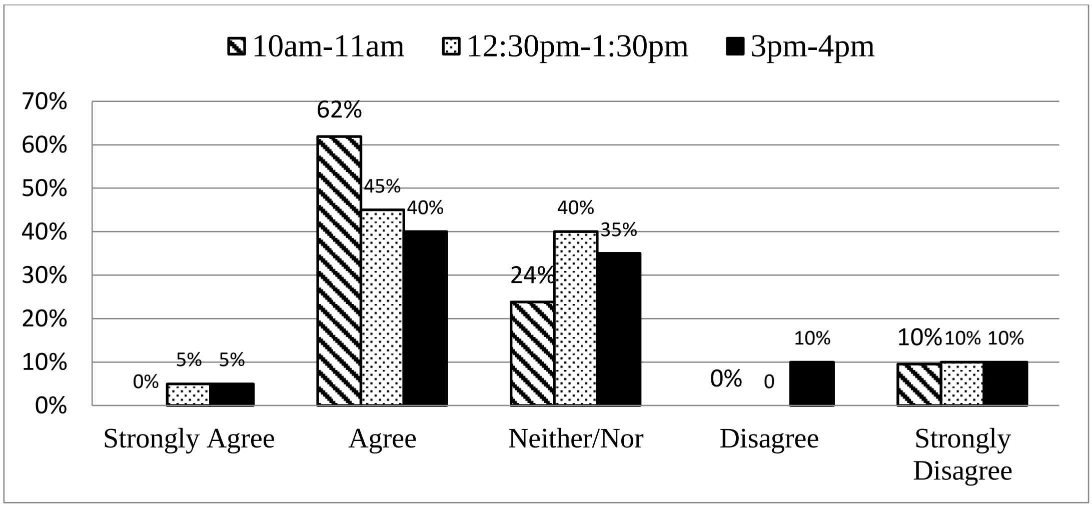



Figure 35: EMU Questionnaire: Seating Layout Response to Daylight (by Author).

From the questionnaire results, it was found that lighting affects the seating preference of the users in *fig.36*. Around 40~65% of the respondents agreed that lighting affects their seating preference especially in morning hours and 15~30% of them strongly agreed with it. Therefore, it was more than half of the respondents, where averagely more than 53% of them agreed that their seating preference affected by the lighting especially in morning hours (65% agreed and 15% strongly agreed) and late afternoon periods (55% and 25% are agreed and strongly agreed respectively). Rather the agreement on the effect of daylighting on place selection, noon time is showing balanced levels of agreement without radical fluctuation in percentages. Yet, selection decisions of 10% of users are not affected on early and late hours of the day.

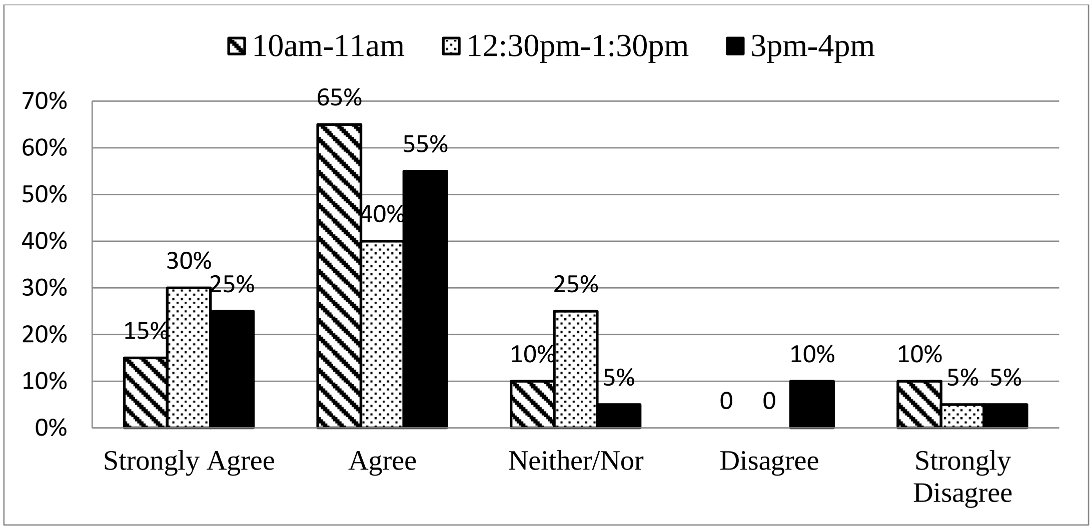



Figure 36: EMU Questionnaire: Lighting Affects Seating Preference (by Author).

### 3.4.4 Glare Through Windows

Since glare is a scientific terminology, the question about this issue was modulated in the preference of being near to the windows. Due to the different conditions of each floor that might affect the responses to this question, the results are illustrated separately in *fig.37* and *fig.38*.

Thus, in level 3 as seen in *fig.37*, most respondents preferred to keep themselves either far or at least in average distance from the windows. Remarkably, about 38% are preferring to sit far away from the window in morning time. This is increased to 44% to be in average distances from daylight sources in the space and none of the respondents wanted to sit very near or very far from the window in morning hours. Furthermore, around 14% is occurred by the users who like to take a seat just nearby the window in the middle of the day which can be related to the solar latitude in this period.

These results are showing the occupant's reaction to over-brightness or glare possibility in the space that made the users to desire keeping a distance from floor's windows.

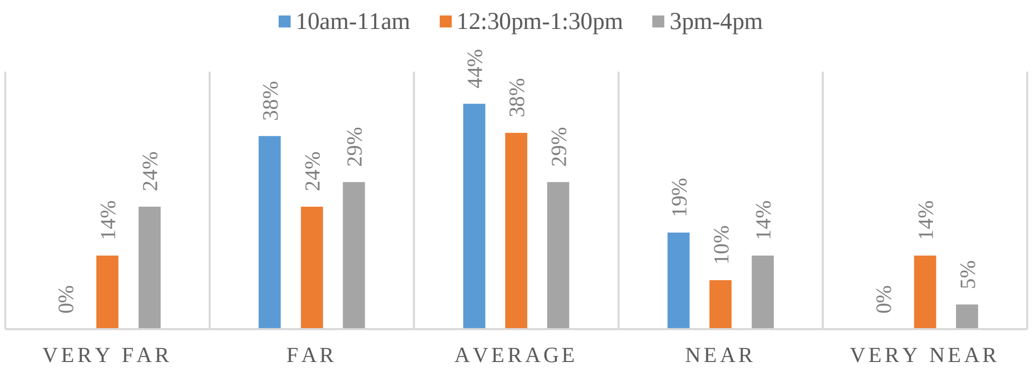


Figure 37: EMU Questionnaire: Glare Effect (Level 3) (by Author).

Whereas in *fig.38*, most of level 4 users are preferring to be in reasonable distance far from the apertures. Most of the records are moving to be near the windows in this floor. About 44% are choosing seats near to windows or in average distance during morning time but still there is no preference to be neither very close nor very far from the windows in these hours. Noteworthy records are shown in 12:30pm to 1:30 period when 10% selected seat near to windows and 14% are even choosing to be closer.

Hence it is found that glare is not much high throughout daytime duration in the upper floor (level 4). But, since the highest average percentage among the day sectors is 48% recorded in 12:30pm to1:30pm period and the lesser potentials of glare due the floor setback, this is indicating daylight overexposure near to windows in this floor. This excessive light can be related to opening’s size and the sunlight diffuses from external surfaces.

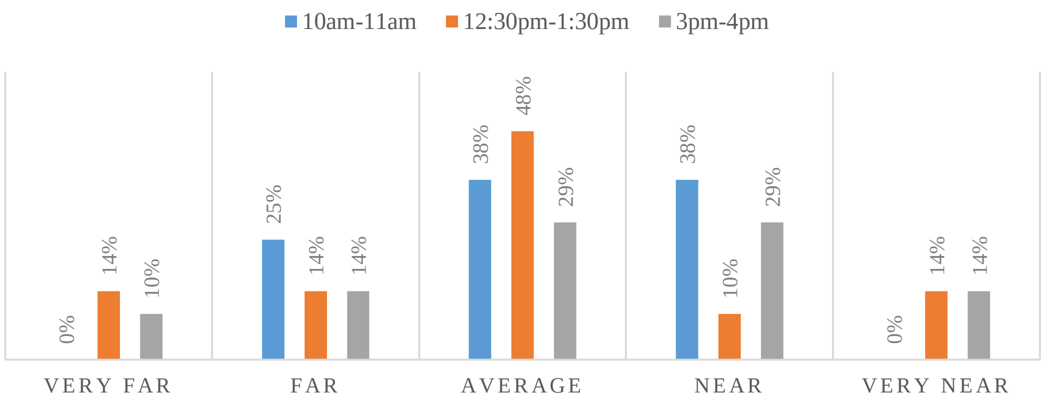


Figure 38: EMU Questionnaire: Glare Effect (Level 4) (by Author).

### 3.4.5 Internal and External Shading Devices Efficiency

Noticeably as schemed below in *fig.39*, near to 65% of the users agree for the need and efficiency of internal blinds. Mostly, the internal curtains found in the separated and small study rooms, where the windows took the normal sizes with 130x100 cm. The need to use computer devices which require low levels of lighting is the explanation for the occupancy by computer users in smaller rooms. The importance of internal curtains usage is appeared to provide adequate levels of light. Therefore, the external controlling system’s role is questioned to identify how efficient it is.

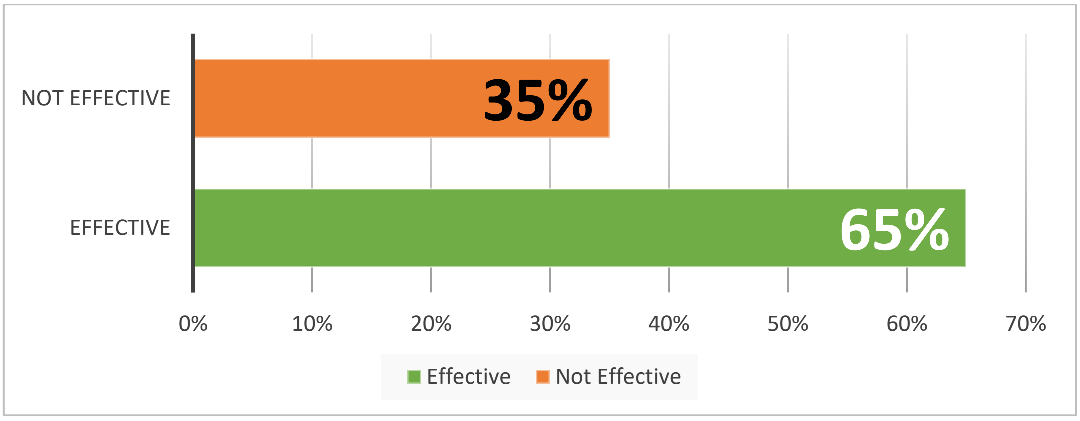


Figure 39: EMU Questionnaire: Internal Shading Devices (by Author).

Understandable conflicts in percentages came about external shading devices. Whilst 80% of investigated-users on the upper floor thought devices are effective, about 60% of the lower users are disagreeing with that fact, (*fig.40)*. The reason is probably that there is less opportunity to be near to windows in level 4 due the setback of the floor from façade walls. Thus, the failure effects of the external shading devices are more noticeable in level 3 due the bigger chances to experience the spaces directly next to the apertures. These levels of dissatisfaction with the role of the shading devices can directly related to the lack of protection from excessive daylighting and glare during the daytime.

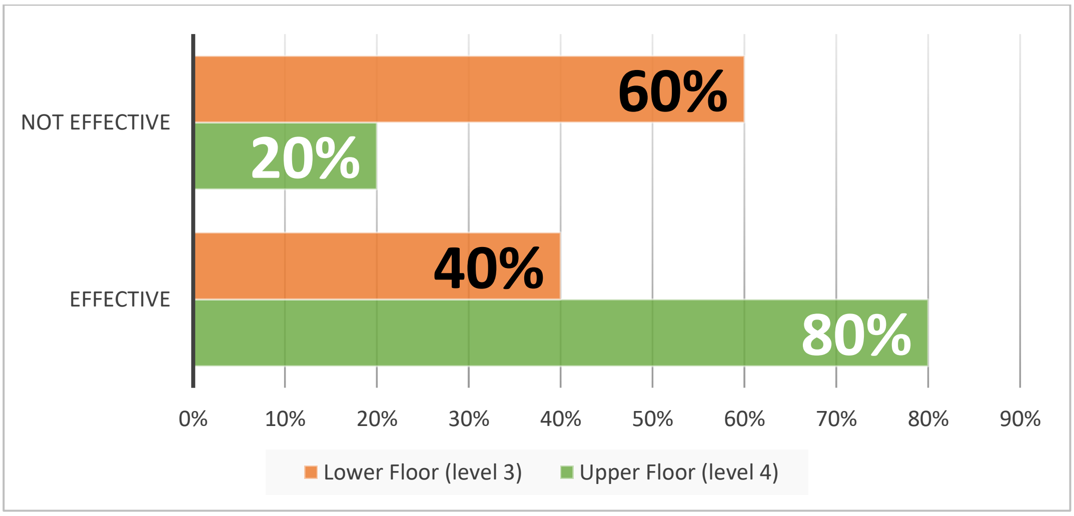


Figure 40: EMU Questionnaire: External Shading Devices Effectiveness (by Author).

### 3.4.6 Visual Comfort

At last but not the least, one of the most important question is about visual comfort while using the study areas in the library. Approximately 75% of overall tested samples found that interior space of the library has visually comfort spaces, (*fig.41*). This is indicating several average subjective ratings of comfort for each individual but mainly related to visual comfort issue.

Obviously, it can be very subjective response due many factors may contribute to this results, but mainly it is related to natural colours in the space and the availability of preferred seating locations since the library is not fully occupied. Rather than the subjectivity in these results, this is indicating the absence of unwanted visual effects that might be produced by the internal surfaces as diffused glare or specular reflections.

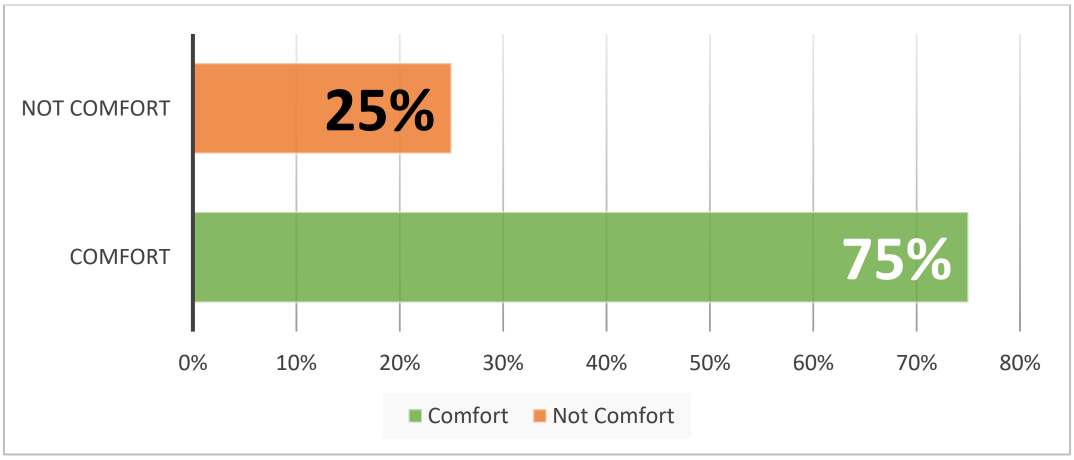



Figure 41: EMU Questionnaire: Library Visual Comfort (by Author).

### 3.4.7 Questionnaire Survey Results Summary

Regarding the response of the questionnaire participants, there are indicators of discomfort in study areas. By assuming that library's indoor environment was thermally well controlled by air-conditioning system, direct sunlight and glare can be the main annoying factors since most of the users are using electronic devices and laptop screens. Thus, they had to move their eyes between paper documents and the reflective screens, resulting hard experiences of high contrast and glare discomfort probability.

User's responses are indicating several problems as disturbing daylight pattern distribution, the need to move between the spaces to find adequate light levels and high influence of this on their time in the library. There are influences of over brightness in level 4 but in addition to this there is a disturbing glare next to the windows in level 3. The occupant's evaluation of controlling system showed that they are unpleasant with the external shading devices and they are suffering because of its inefficiency. Otherwise, they perceived visual comfort by the finishes of all the internal surfaces and its colours and materials without negative effects.

## 3.5 Computer Simulation Programs and Tools Employed

The building of EMU Main Library has been modelled in the software (Autodesk Ecotect® and Revit®) and allocated in Famagusta weather condition with its orientation. However, the program imitates accurate virtual solar path, describing the sun movement in Famagusta hemisphere. By defining material type's parameters and glazing transparency, the software can analyse the inputs, providing analytical data for daylighting effect, glare, shading effect and other date related to context of building envelope. In consideration of orientation, the building is suited in the EMU complex and oriented 55$^{o}$ to the north.

Autodesk Ecotect® Analysis is a software that performs calculations of yearly daylighting by using weather data of the particular location of desired design. Commonly, it can visualise the results of daylight factor, internal reflectance, insolation, shading effect and many other analytical representations. Meanwhile, Autodesk Revit® BIM offers similar opportunity to perform lighting analysis under the LEED standards for green buildings (Analysis for illuminance and validation for LEED v3 IEQc8.1 and LEED v4 IEQ Daylight Credit), providing complete energy brake down study with tables and charts. Other advantage of Revit® is the possibility to adapt and test the selected shading strategy with architectural visualisation of design and analysis.

The exchange of data between the two software is achieved by 'Green Building' file format (.gbxml) that ease the data transfer with same accuracy and in a continuous flow towards persistent analysis and conclusion.

### 3.5.1 Field Study's Current Condition by Simulation-based Evaluation

#### 3.5.1.1 Daylight Levels Analysis

Essentially, the field of study model has been exposed to evaluation process in Autodesk Ecotect® to estimate the current situation of daylighting, denying any other artificial sources of light. Accordingly, evaluation illustrations show the red-to-yellow range coloured areas which have high levels of daylighting. It has been measured much more than 750 lux (approximately +2400 lux) near all apertures which provides more than three times what is needed for visual tasking in the library as shown in *fig.42*. In level 3, average illuminance values recorded are around 928 lux. Excessive daylighting effects a wide range near the windows which is occupied by study desks. Although, the affected zone has been moved to the centre, near to the skylight in the upper floor. Based on evaluations of existing conditions related to occupant's seating layout as illustrated in *fig.42*, the zones with suitable levels of lighting are used for book shelves and circulation corridors. Yet, there are about 10.3% of the floor area is below the 300 lux (areas are clipped out of colour among level 3) which needed to perform visual tasks in libraries. In level 4, the average values are decreasing to approximate 324 lux which is within the required range of light illuminance.

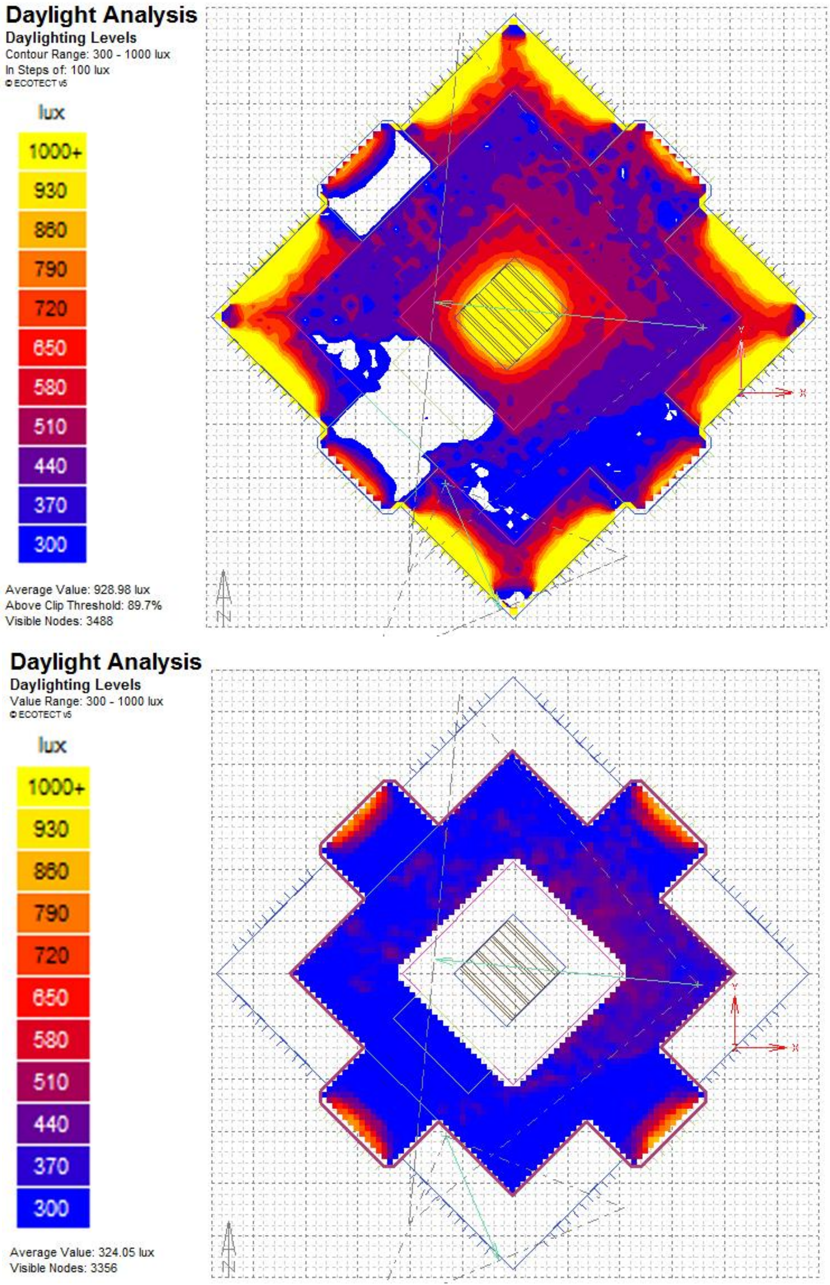



Figure 42: Daylight Levels Analysis of Level 3 (Top) and Level 4 (Bottom) of EMU Library (by Author).

### 3.5.1.2 Internal Reflections Analysis

Calculations of internal reflection would be helpful to measure the effect of interior surface which correspondently influence on the occupant visual comfort and satisfaction. On average 3.62% of the sunlight is reflected toward the deep areas in level 3 while 2.83% is average internal reflections in level 4, (*fig.43)*.

According to the space organisation, colour selection and used materials, the diffused daylight is distributed moderately throughout both floors. Mostly, the average levels of internal reflections are found out, which seems that the carpet flooring is absorbing unnecessary light levels without creating disturbing reflections.

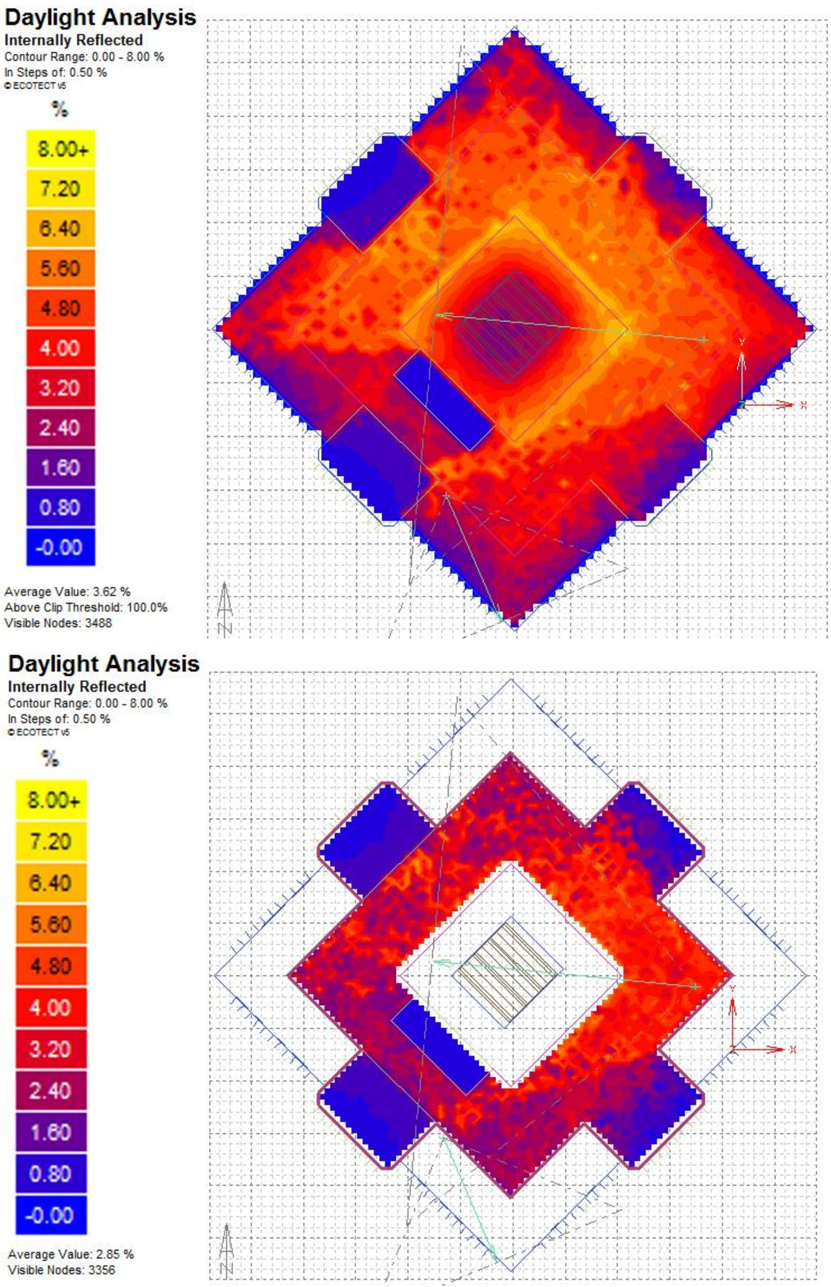



Figure 43: Internal Reflections Analysis of Level 3 (Top) and Level 4 (Bottom) of EMU Library (by Author).

### 3.5.1.3 Existing Shading Devices Evaluation

The illustration *fig.44* shows areas affected by direct light through windows. Regarding the unified shading strategy in correlation to building orientation, the simulations exposed the weakness of shading devices to prevent overexposure and direct daylight penetrates through tall windows. In level 3, the zones along the southern portion of the building, near the windows, suffer from direct sunlight and glare prevention cannot be achieved by the existing shading devices. This effect is decreasing in level 4 due the setback distance from the exterior walls. The insufficiency of shading strategy could be linked to apertures vertical length ratio to its depth, especially that its mainly facing south. The hatched areas next to south-east and south-west façades are showing the effect of direct sunlight pattern in indoor spaces in both floors.

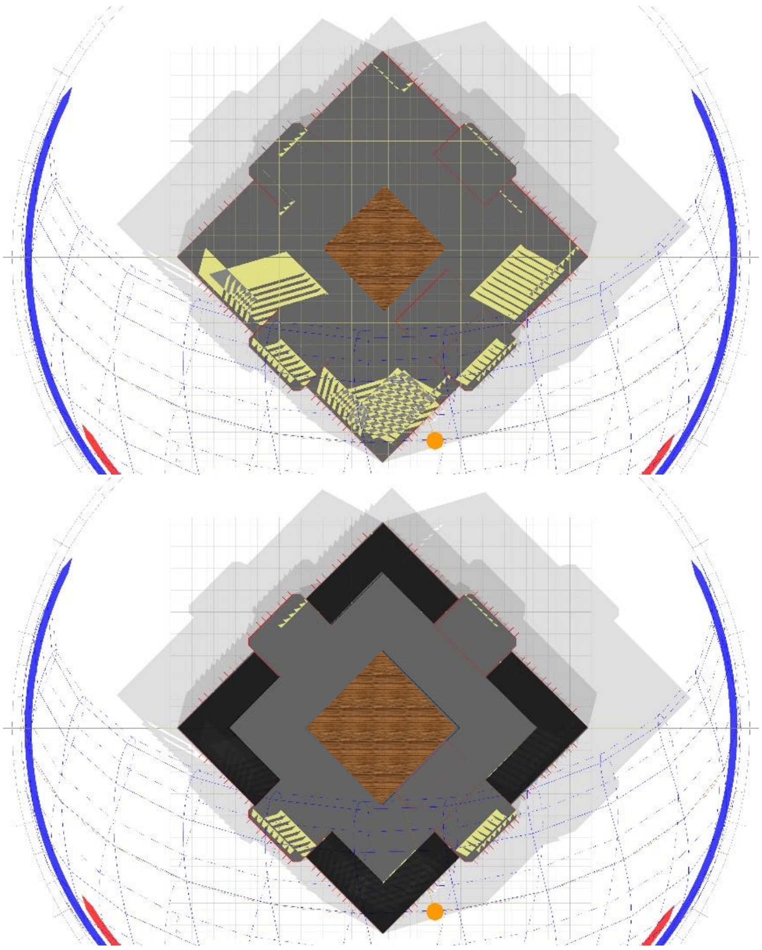


Figure 44: Illustration of Incidence Pattern of Direct Sunlight in Level 3 (Top) and Level 4 (Bottom) of EMU Library (by Author).

Wide floor areas along the inner space behind the facades are exposed to solar irradiations that would certainly affects the occupant’s performance in these areas, (*fig.45*). As shown below, red-to-yellow range of coloured areas are affected by high levels of insolation radiations. The high rates of insolation are not just because of the direct sunlight, but also the reflected radiations by the vertical shading devices has influences on the interior spaces. As it is shown in the top northern portion of the building. Although, according to the software calculations, the exposure exceeds 20% in some parts of the building along the south-east and south-west façades where covered with yellow colour as in the scale.

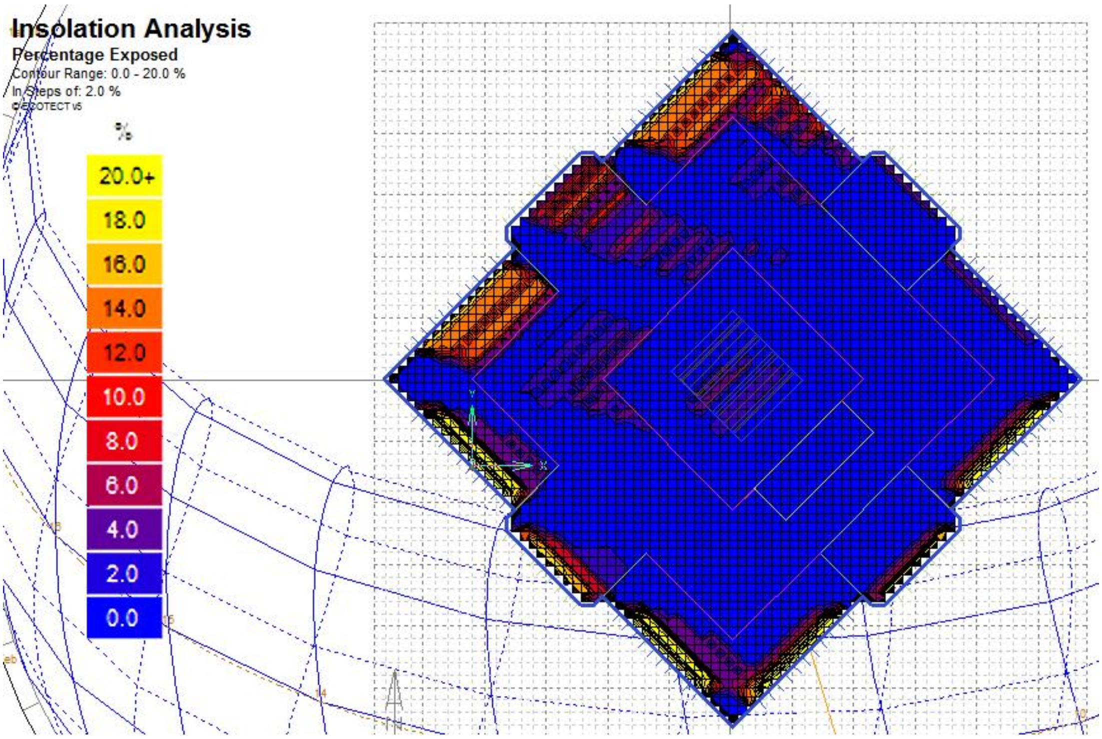



Figure 45: Insolation Analysis in the Lower Floor (Level 3) of EMU Library (by Author).

### 3.5.1.4 Computer Simulations Evaluation Summary

To some extend the building is too deep to be covered totally by daylight where there is an excessive light in all the perimeter zones by the windows, otherwise the light levels are slightly low for visual tasks underneath the upper floor's slab. Regarding the skylight opening in the centre of the roof's building, it is providing natural light but it needs to be controlled during noon time along the year.

Solar irradiation is covering a respective portion of the library floors which has both advantages and disadvantages correlated to visual performance and comfort in the space. Whilst direct sunlight is distracting the occupant’s eyes in the southern part of the building.

# Chapter 4

# DAYLIGHTING SIMULATION-BASED OPTIMISATION AND RE-EVALUATIONS

## 4.1 Discussion

Towards having a solid-grounded methodology for evaluations in this study, it is adapting several recommendations retrieved from recognized standards and institutions codes and guides as follow (see *fig.46*):

- Building orientation and fenestration ratios followed the recommendations of The Passive House (Passivhaus) Institute and International Passive House Association.
- Visual task illuminance (modified by author) and Glare metrics based on European Committee for Standardization (CEN) recommendations.
- Threshold area coverage relies on the methodology retrieved from the simulation-based (illuminance calculation) by US Green Building Council (USGBC) LEED™ (modified by author).
- Automated system behaviour in response to integrate ASHRAE 90.1 recommendations.

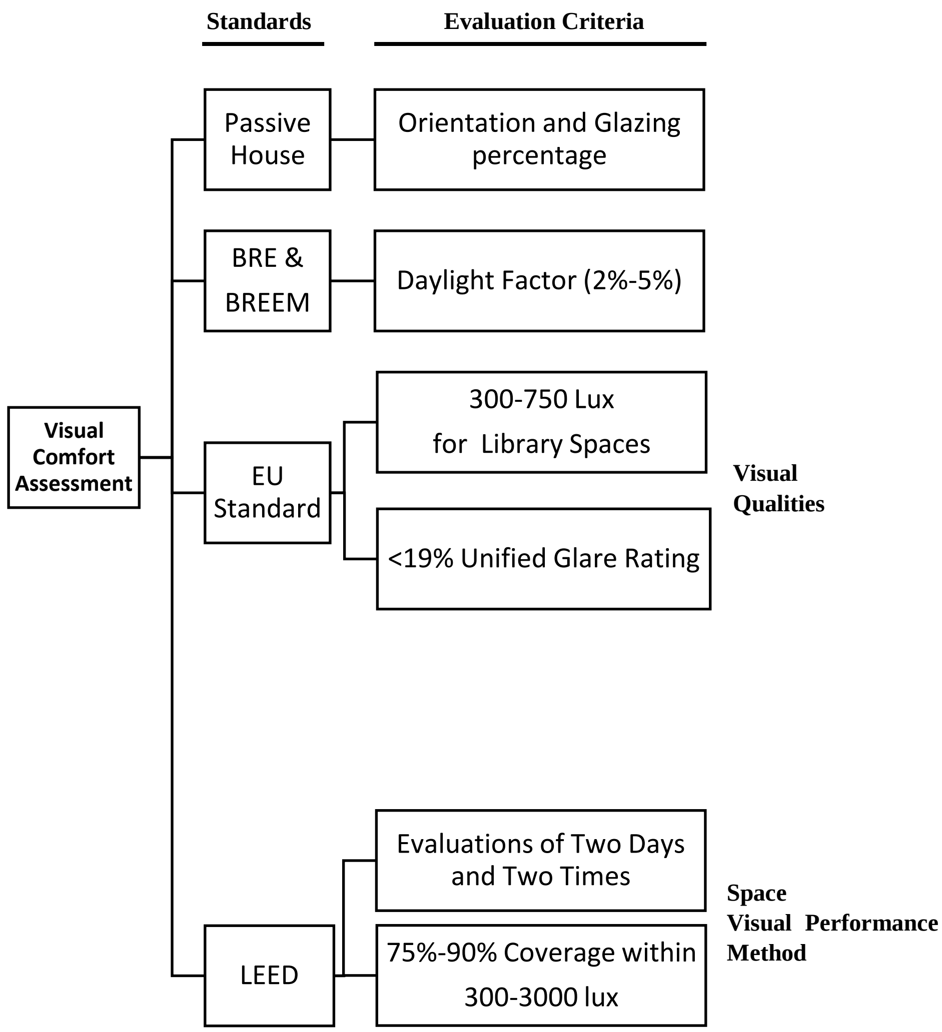



Figure 46: Selected Standard Methods and Requirements for Visual Comfort Assessment (by Author)

Among infinite design possibilities, many strategies can be adapted and integrated in the building to optimise the daylighting in a way to coup the challenges presented in the library building. Suggested strategies should be oriented by the evaluation indicators which have found during the data collection, analysis and evaluations have done for the current situation in the building. Regarding these aspects, the indicators can be summarised as follow:

- The building orientation is exceeding the 30 degrees preferred angle due to South proposed by The Passive House (Passivhaus) Institute which exposed the indoor space to unwanted sunlight.

- The 51% glazing ratio to the façade surface in far beyond the recommendation on 25-35% recommended by the Passivhaus.
- Since all the shading devices are vertical towards all direction, a prima facie observation is the lack of responsive shading toward the south direction or automated system. This is very noticeable regarding the building orientation on the site.
- The areas near the external windows are requiring protections from solar irradiation preventing high exposures during summer and direct glare from sun in winter season.
- The high vertical windows and its ratio to façade surfaces are representing the biggest challenge to control daylighting utilisation.
- The small study areas showed the potential of using the internal blinds as controlling strategy since it has normal window opening with acceptable ratio to space depth.
- The façade design unity is calming a responsive strategy in all facades equally due to the behaviour of the natural lighting during the day throughout the year as shown in *fig.47* and *fig.48*. Incident solar irradiation is invading very wide areas from sunrise to sunset time.

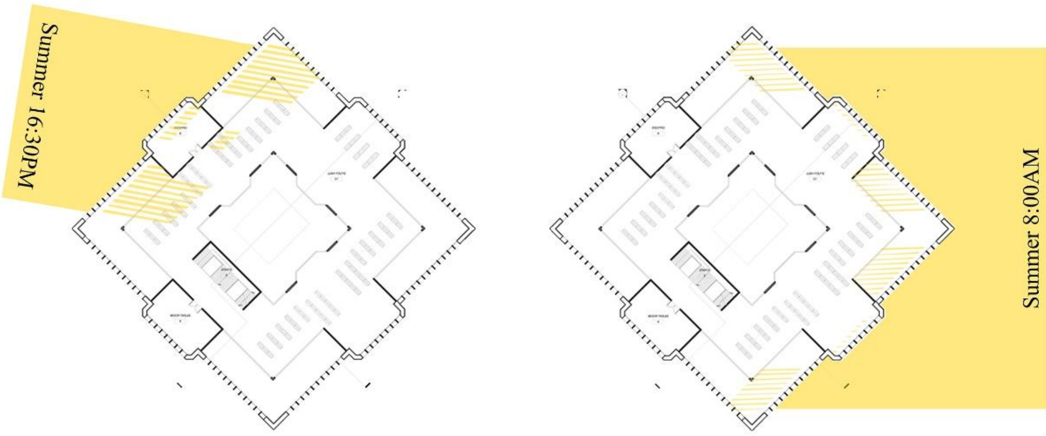



Figure 47: Illustration of Solar Radiation on Building Façades throughout Summer Season with 43.63$^{o}$ Latitude and 30.57$^{o}$altitude When Causing Marginal Glare (by Author).

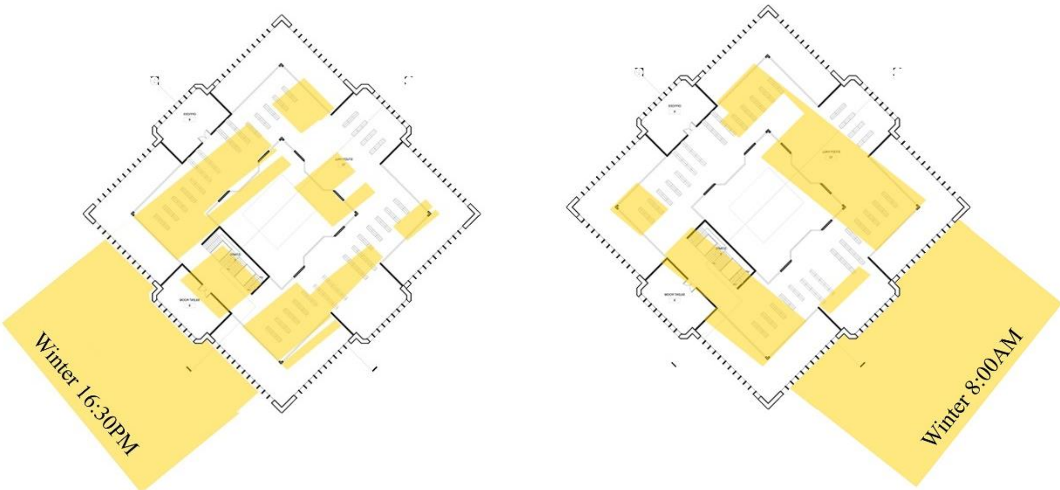



Figure 48: Illustration of Solar Radiation on Building Façades throughout Winter Season with 11.30$^{o}$ Latitude and 74.60$^{o}$ Altitude When Causing Marginal Glare (by Author).

- There is a high contrast in lighting qualities in difference zones among the floors area which indicate the need to enhance the quantities of diffused light in the indoor space.
- Visual connectivity with outdoor spaces around the building should have a major consideration during strategy proposition due its importance to the user's health and preferences.

- The presence of adequate light qualities is available among the mid-distanced zones between the exterior windows and the central area underneath skylight, but there is an absence of equal distribution of adequate levels of light for visual performances in the library.

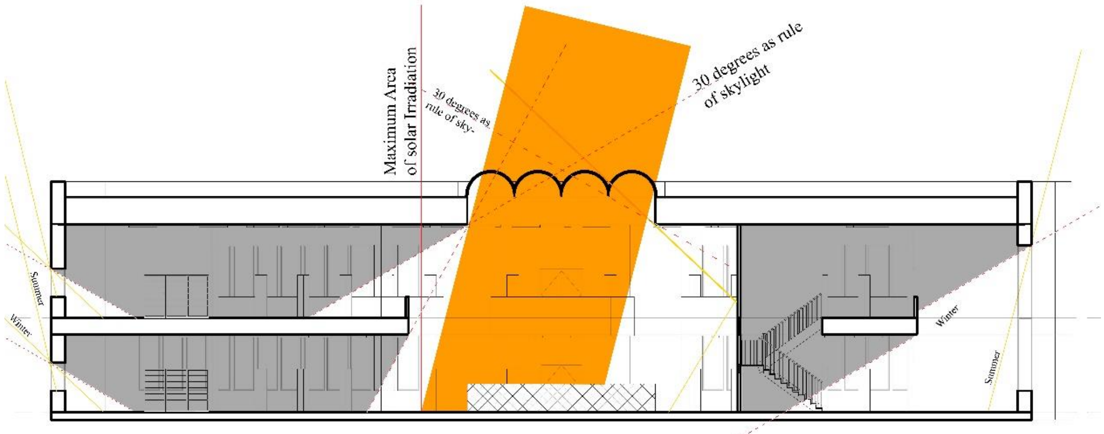



Figure 49: Section Illustrate the Incident Solar Irradiation through the Roof Opening with Altitude of Summer Sun on 21 June Noon Incidence Angle 74.60$^o$ (by Author).

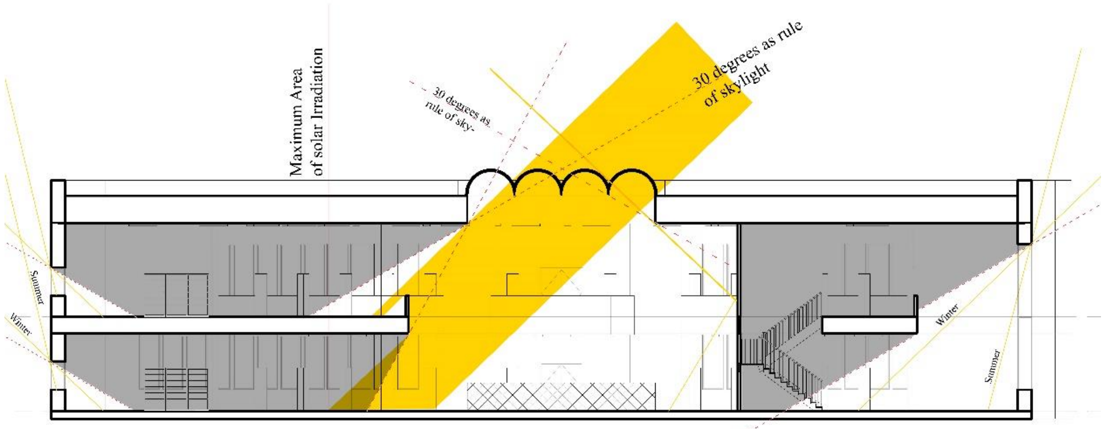



Figure 50: Section Illustrate the Incident Solar Irradiation through the Roof Opening with Altitude of Winter Sun on 21 December Noon Incidence Angle 30.57$^o$ (by Author).

- The main function of the skylight is to provide natural light in the deep spaces but according to evaluations it needs to controlled during mid-day time when it allows excessive light levels to penetrate the building, as illustrated in *fig.49* and *fig.50*, which shows uncomforted space with high exposures and glare effects.

- Rather than the carpet flooring, most of the internal surfaces are showing potentials to be sources of indirect glare which is disturbing the users under certain circumstances.

Regarding these indicators, there are supplementary considerations during proposition strategy as sun movement between seasons where the sun altitude is determining the amounts of incident solar irradiations through apertures. The winter sunlight is more preferred in the space with high cautions due to glare potentials, while the summer sunlight has high exposure intensity with annoying reflections. Therefore, opening ratio at each certain façade is influencing the quantities of light in the indoor space beside the qualities of natural light distribution patterns if the diffused skylight is added into concerns. Thus, additional aspects should be considered such as the space depth and floors height behind these windows and roof apertures as it is significantly defining the natural light coverage in the deep spaces.

Visual contact with outdoor space has its own importance due the human psychological needs. In spite the fact that it will create voids in strategy coverage, the range of view is considered as a basic requirement for space quality of the library interior spaces.

As a minor concern, surrounding obstructions are considered due the studied levels are the third and fourth levels of the building and there are not obstructions in short distances from building façades.

All these concerns are illustrated in *fig.51* with taking Famagusta's summer and winter altitudes as (74.60°) and (30.57°) respectively. Additionally, since the lowest altitude of the sun is in winter (21st December), the rule of overcast skylight is occurred as (30.57°) and applied in the building 3D model with its real dimensions.

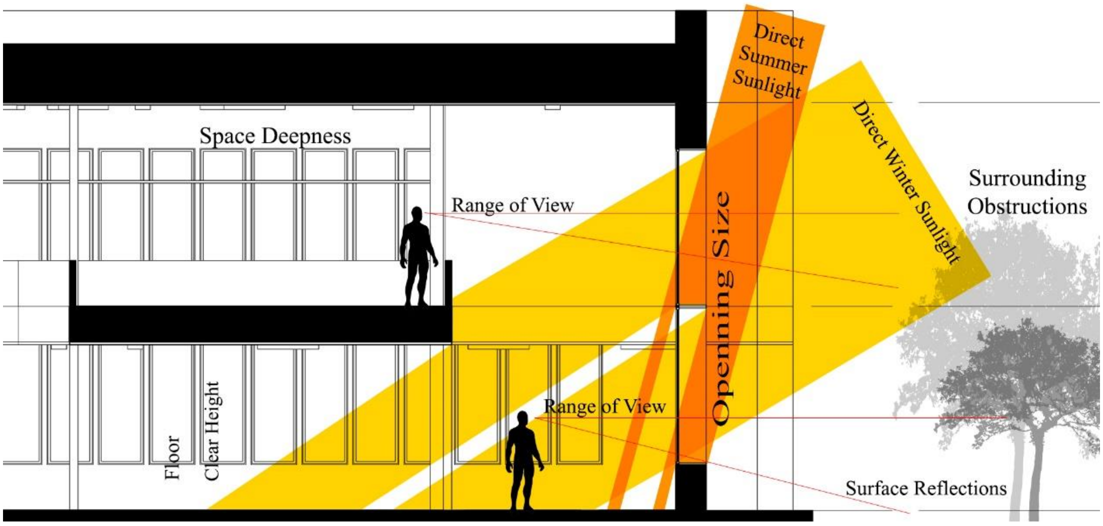



Figure 51: Illustration of Considerations for Suggested Strategies Design (by Author).

### 4.1.1 Finding Alternative Strategies

Aiming to create a clear responsive methodology from the numerous alternatives and possibilities such as material variations and different shading strategies that varies between fixed, automated and mixed systems, this study is proposing some suggestions for side windows and roof skylight.

**Side-window shading strategy** selection criteria is based on the building orientation and solar latitude. Since the existing vertical devices are not providing sufficient daylight control due building angle which exposing the windows to south direction, the horizontal shading strategies can offer better controlling qualities. To check the validity of this proposed strategy, one window in south western façade was selected to generate a conceptual optimised shading device. The simulation results confirmed that horizontal shading devices for optimisation, as seen in *fig.52*.

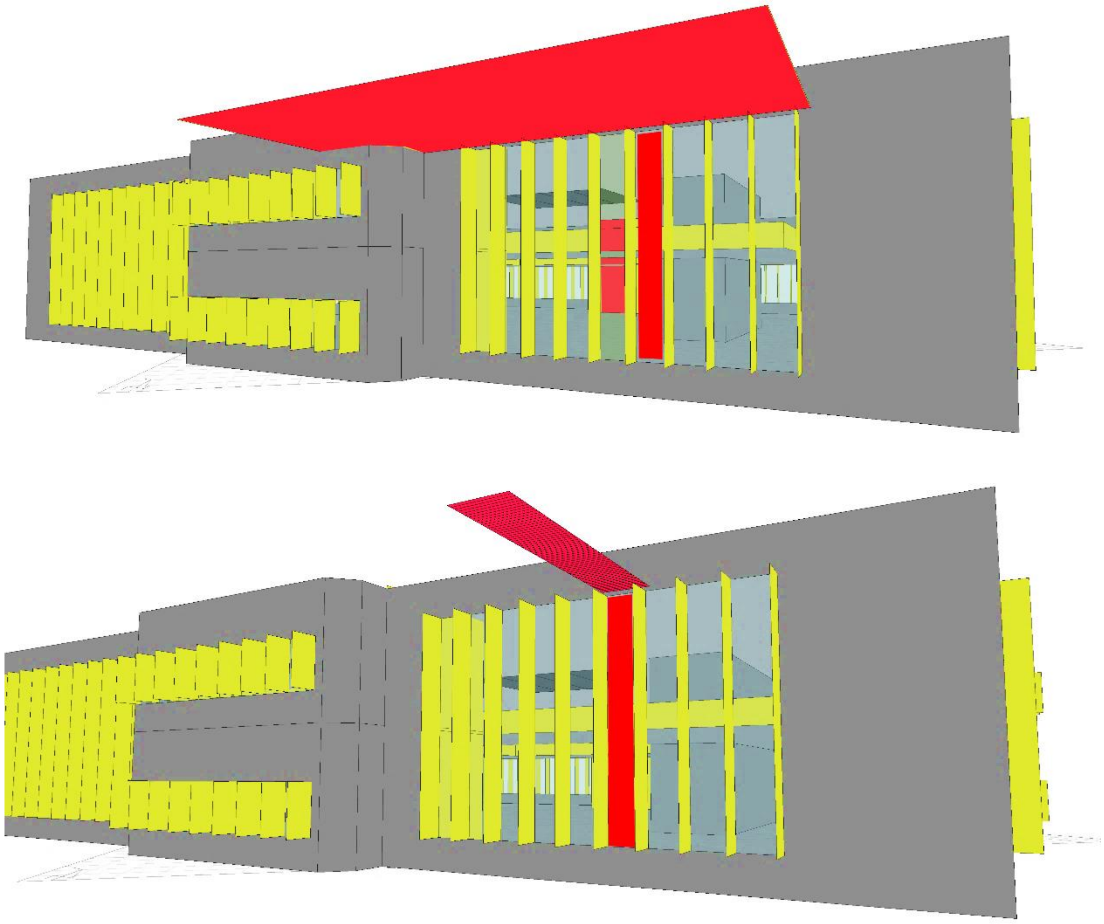
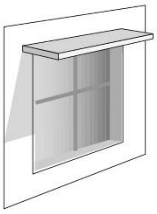
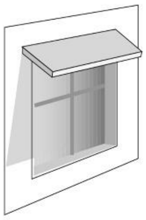
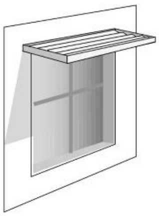
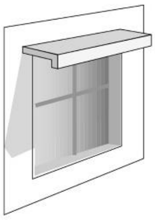
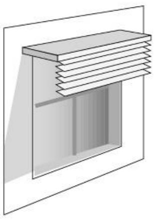
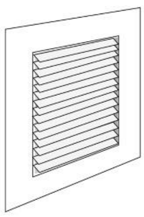
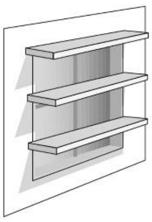


Figure 52: Optimised Shading Device Generated in Ecotect® for One Window (Top: Solid Over-hanged Shading, Bottom: Louvered Over-hanged Shading) (by Author).

Subsequently, several horizontal shading devices are evaluated to check the potentials of each strategy and it compatibility with the library's condition. To limit the number of the valid options, visual connection with outdoor space and the practical length of the shading members are added to considerations in table 10 below.

Table 10: Samples of Horizontal Shading Strategies Evaluations (by Author).

| Type | | Evaluation | |
|---|---|---|---|
| | | Advantages | Disadvantages |
| Over-hanged shading |  | - Protection from direct sunlight<br>-Open view to exterior spaces<br>-No distractions in the field of view | -Long projection to cover high windows<br>-Visible additions are expected to support it<br>-Diffused light is not controlled |
| Slope over-hanged shading |  | - Protection from direct sunlight<br>-Open view to exterior spaces in the lower portion<br>-No distractions in the field of view | -Medium projection to cover high windows<br>-Blocking the views from upper floor<br>-Diffused light is not controlled |
| Louvered over-hanged shading |  | - Protection from direct sunlight<br>-Open view to exterior spaces in the lower portion | -Long projection to cover high windows<br>-Visible additions are expected to support it<br>-Annoying shadow patterns<br>-Diffused light is not controlled |
| Drop edge over-hanged shading |  | - Protection from direct sunlight<br>-Open view to exterior spaces<br>-No distractions in the field of view | -Medium projection to cover high windows<br>-Visible additions are expected to support<br>-Diffused light is not controlled |
| Substitute drop edge over-hanged shading |  | - Protection from direct sunlight<br>-Open view to exterior spaces in the lower portion<br>-No distractions in the field of view | -Medium projection to cover high windows<br>-Blocking the views from upper floor<br>- Diffused light is not controlled |
| Louvers shading |  | - Protection from direct sunlight and diffuses<br>-No projection from the facade | - Blocking the views totally<br>-Can create gloomy spaces in the deep areas |
| Break up and over-hanged Shading |  | - Protection from direct sunlight and diffuses<br>-Open view to exterior spaces | -Annoying shadow patterns<br>-Possible projections off the facade |

Due to the importance of visual contact with outdoor spaces, substitute drop edge over-hanged and louvers shadings are eliminated. Long spans are not practical, therefore over-hanged and louvered over-hanged are not reliable in this case. As presented from questionnaire results, the diffused light from the sky component and external surfaces is playing a key role for user's satisfaction. Thus, slope over-hanged and drop edge over-hanged shadings cannot optimize daylighting to achieve user's visual comfort. Accordingly, it is found that break-up shading devices are the most potential shading strategy between the suggested samples.

As seen from questionnaire results and computer simulations, there are spaces with low daylighting levels in floor 4 and there is not direct sunlight harming this floor area. Therefore, after adopting shading strategy which is controlling the diffused light, a need for diffused light enhancements is expected in level 4.

**Daylight strategies** that reviewed in chapter 2 are offering several alternatives to improve the daylighting qualities in deep spaces. Between Light-shelf, Louvers Prismatic and Anidolic Zenithal controlling systems, it is found that the light-shelf system is offering the simplest system with the required capacities. The light-shelves can be part of a fixed optimization strategy and its properties are matching with the selected shading system in a harmonic design.

The window strategy is consisted of two major parts. The opening height is divided to four sectors; convex light-shelf is in the upper portion with dual mission of protecting from direct sunlight and reflect solar irradiation towards the ceiling surface, enhancing the diffused light in the upper floor (level 4).

Within the original depth of the window in the external walls, angular louvers developed with (35º) from horizon and (65cm) length in the effective height as shown in *fig.53*. The remaining two sectors of the window's height were left clear to have the visual contact with outdoor space.

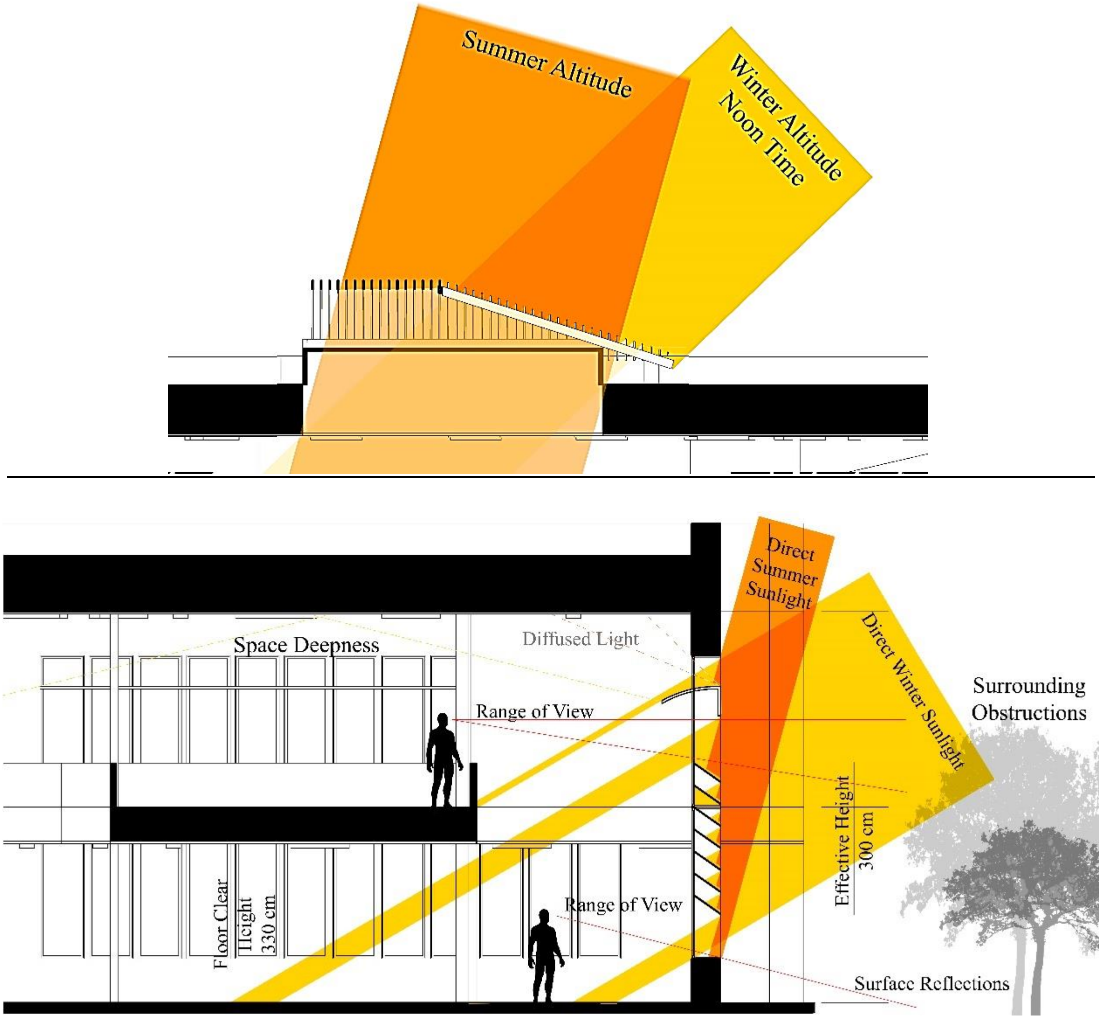


Figure 53: Optimised System Details Illustrate the Considerations and Responses Have Been Taken in Strategy's Design (by Author).

The **skylight aperture** is also requiring a responsive daylight controlling system. Due to the building location, it is measured that the central areas are suffering from excessive sunlight during noon hours. Rather that, it is playing a critical role by providing daylight in the deep spaces in the centre of the building.

Therefore, there is a need for a shading system to reduce the amount of sunlight without blocking it totally. The penetrating sunlight will be transmitted as diffused light when it passes through the existing translucent panels of the skylight.

Consequently, the roof skylight opening is suggested to be covered by hyperbolic-shape roof shading (*fig.54)*, but due the translucent fiberglass panels used, the hyperbolic-shed was segmented into louvers members with (15cm) depth for purpose of providing more incident solar irradiation through, (*fig.54* and *fig.55)*. The louvers orientation and inclined angle are allowing the system's members to face the east and west vertically. Whilst, the same members react in horizontal manner during the sun's slight movement towards the south direction along the daytime. Accordingly, this strategy is supposed to reduce the incident sunlight in several hours daily and block particularly the noon time direct sunlight.

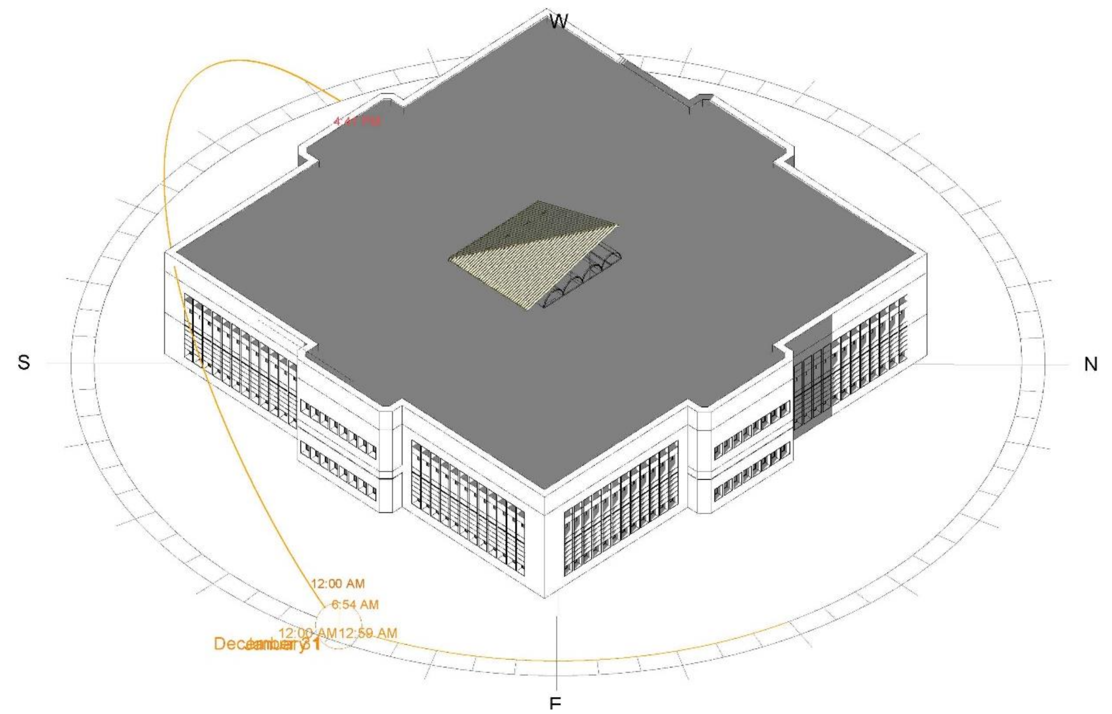



Figure 54: The Library Building 3D Model with Additional Shading Strategies (by Author).


Figure 55: Proposed Strategy Illustration on Real Building's Photo (Edited by Author)

This study is suggesting a fixed horizontal break-up system with light convex light-shelf for windows and diagonal louver system for roof aperture as solutions which are meeting the existing challenges in library, illustrated in *fig.56*.

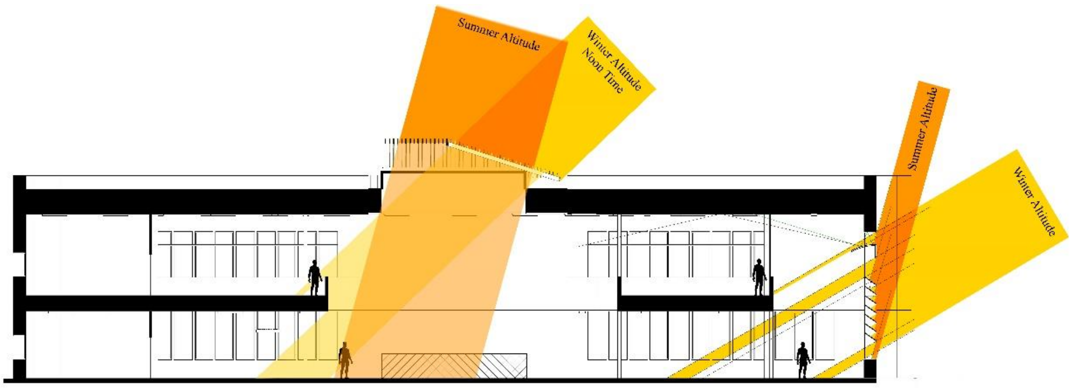



Figure 56: Building Cross Section Illustrate the Predicted Behaviour of Shading Strategies (by Author).

#### 4.1.2 Re-evaluations: Simulations and Assessments

Evaluations of the proposed system have been through different stages consisted of lighting levels and qualities, testing glare probability and estimated electricity consumption rates.

Is the automated shading system offering a better solution? This question will be presented and answered during evaluation process. This study will evaluate the potentials of each system, solo-performance and combination of both.

**4.1.3 Daylighting Levels Re-Evaluations**

The evaluation stages are taking in concern the CEN, LEED recommendations, offering clear data platform to apply the advices by ASHRAE for farther studies. The simulations had been processed under several controlled circumstances as standard (CIE Clear Sky for annual simulations and CIE Overcast Sky for equinox- solstices simulations) with regular working hours from 9:00am to 3:00pm in daily base. For comparison purpose, equinoxes and solstices dates on earth were selected to predict and monitor the changes between seasons, and to define the effects of additional shading devices on light distribution pattern. Two models were created for the library building: one with the original condition and the other with proposed fixed strategy. During further discussions, the focus has engaged on the fixed strategies which will be stated as suggested strategy unless the automated systems are mentioned.

Since the optimum conditions of lighting levels for reading and other visual tasks are placed in the rage of 300-750 lux to provide averagely 500lux by (CEN, 2011) and evidently, the threshold was set within this limits to clearly measure the performance of the suggested shading strategy. Furthermore, the study focused on two particular points in day time (9:00am and 3:00pm) due the sun angle and it is predicted to have significant direct glare problem.

The most significant differences found in the selected periods are in level 3 as seen in table 11. The existing level 3, particularly on 21 June, is suffering from excessive daylight levels in the northern and western parts with more than 3000 lux which considered harmful to perform visual tasks. As illustrated in *fig.57*, most of the floor area is covered with illuminances of 1000~3000 lux that is clearly above the required levels. These light levels are generally optimised to be within the range of 300~1000 lux when the shading strategy is implemented in the building model. This improvement is appeared in calculations as increases from 16~18% to 57~59% within the limits of 300~750 lux in this day.

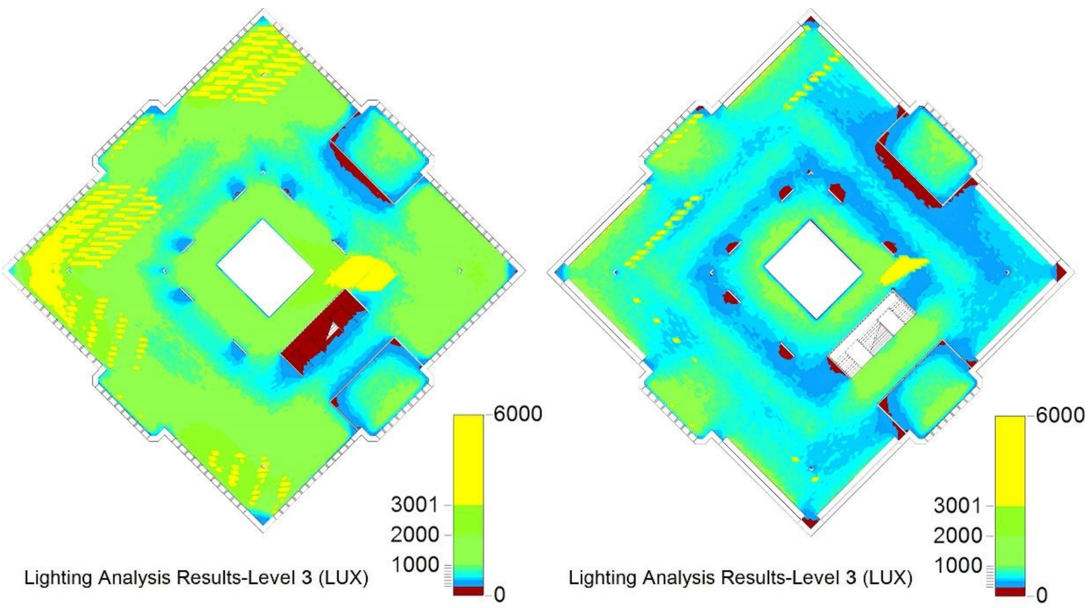



Figure 57: Improvements by Suggested Fixed Shading Strategy on Daylight Qualities in Level 3 on 21 June (Existing in Left and Optimised in Right) (by Author).

Unfortunately, negative impacts of the additive strategy are appearing on 21 December in the same level (*fig.58*). Despite all the improvements those are measured in other periods of the year, the optimisation shading strategy is decreasing the lighting levels to below the 300 lux which is indicated the potentials of creating gloomy spaces in this floor in this particular day.

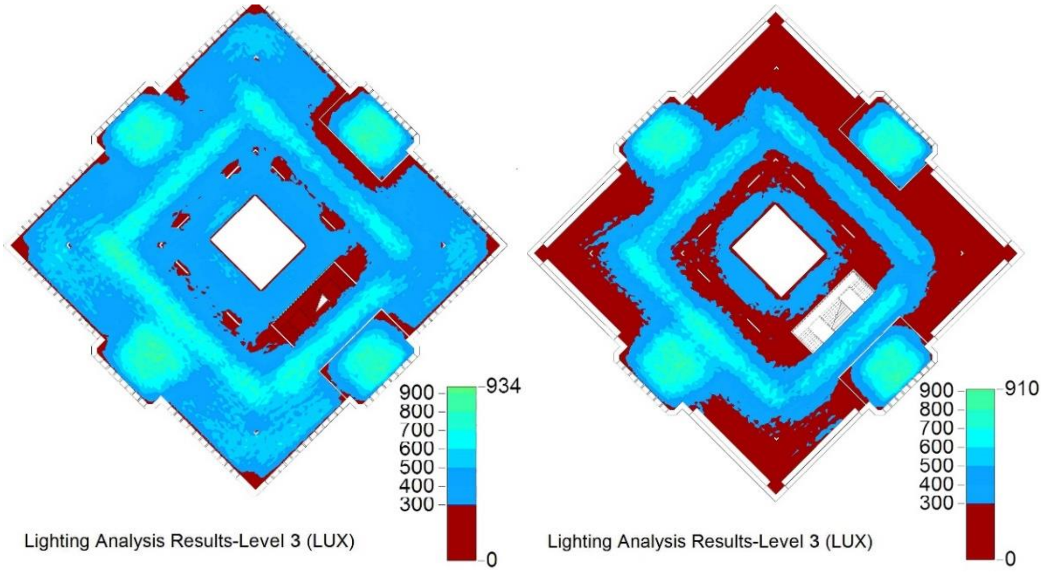
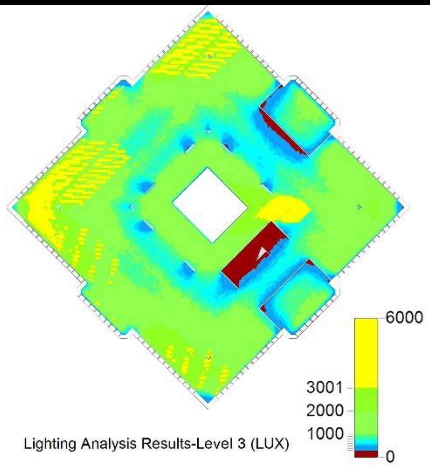
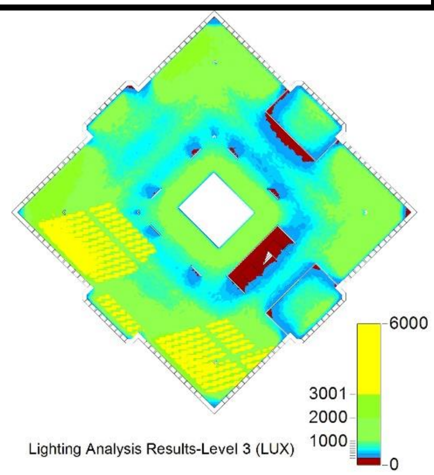
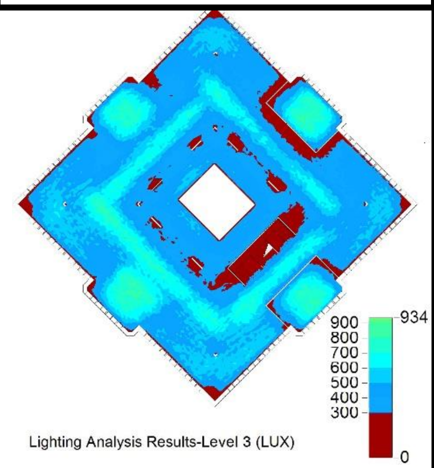
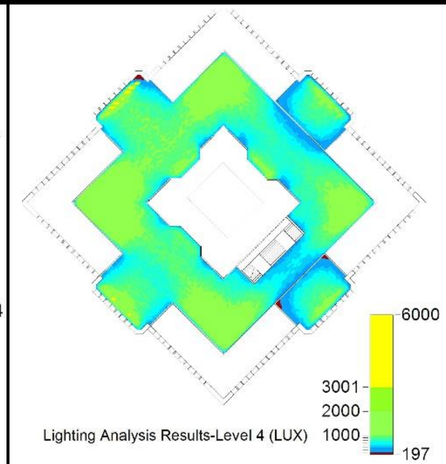
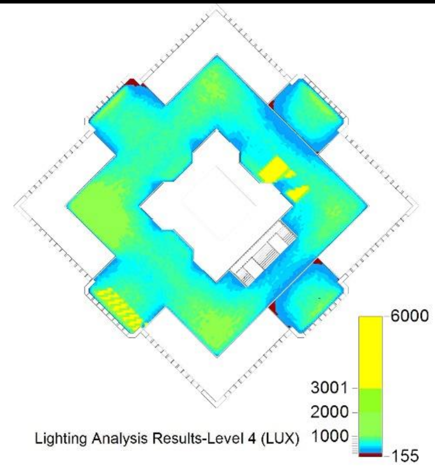
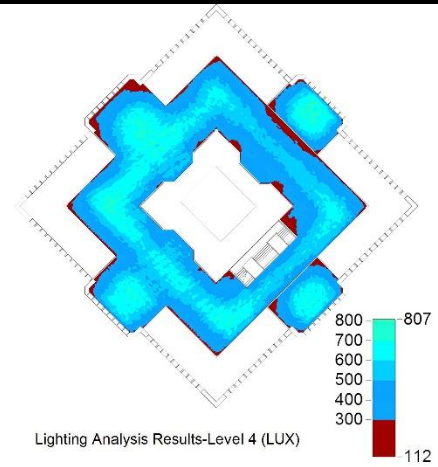
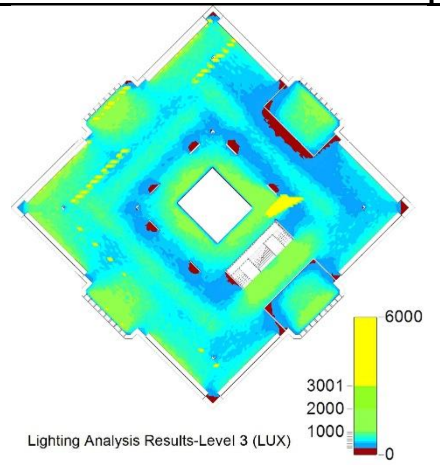
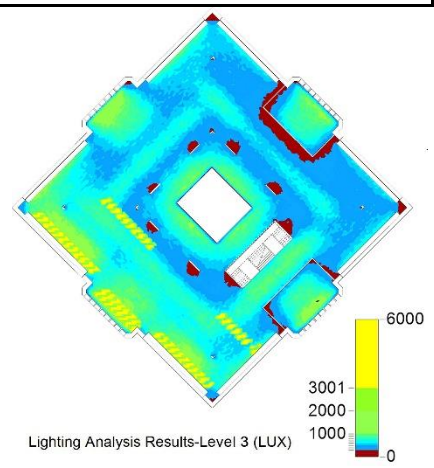
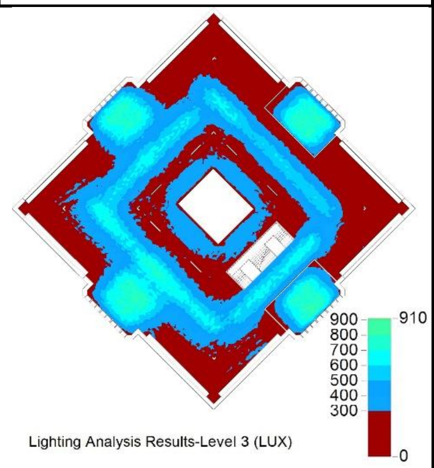
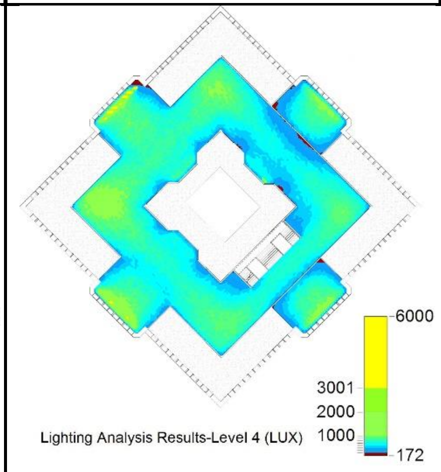
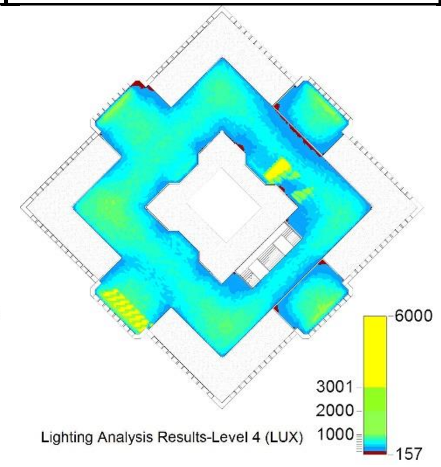
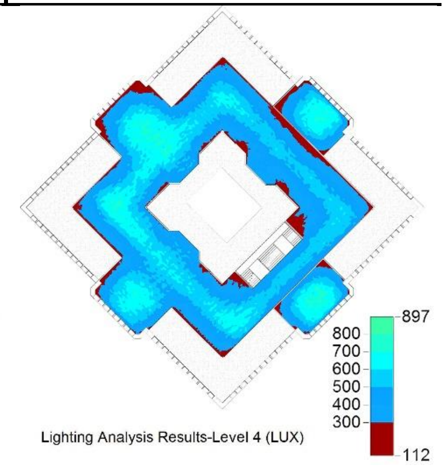



Figure 58: Negative Impacts of Suggested Fixed Shading Strategy on Daylight Qualities in Level 3 on 21 December (Existing in Left and Optimised in Right) (by Author)

Daylighting distribution pattern is showing more stable dispersal with prediction of solving the problem of high contrast shadows between indoor spaces. This is offering more comfort visual experience for the library users. Otherwise, direct sunlight is blocked to far extend by shading strategy but replaced by diffused light which can enhance the space usage during same periods under original conditions. Moreover, the roof's ribbed hyperbolic-shaped shading is exceedingly controlling the excessive lighting during mid-day time and refine it in suitable way.

Despite the early morning hours' measurements on 21 December in level 3, the suggested shading strategy is acting positively to natural light both qualities and quantities in all measured periods. The question now is switched to the glare prospects inside the library spaces which will be discussed in the section.

Table 11: Visualisation of Daylighting Optimisation Impacts on Level 3 and Level 4 Lighting Distribution Patterns with Proposed Fixed Strategy (by Autor).

| | **LEVEL 3** | | | **LEVEL 4** | | |
|---|---|---|---|---|---|---|
| | 21 June | 21 March/September | 21 December | 21 June | 21 March/September | 21 December |
| Existing |  |  |  |  |  |  |
| | 9am: 18%<br>3pm: 16% | 9am: 25%<br>3pm: 23% | 9am: 82%<br>3pm: 83% | 9am: 27%<br>3pm: 28% | 9am: 47%<br>3pm: 44% | 9am: 92%<br>3pm: 93% |
| Optimised |  |  |  |  |  |  |
| | 9am: 59%<br>3pm: 57% | 9am: 66%<br>3pm: 64% | 9am: 53%<br>3pm: 51% | 9am: 54%<br>3pm: 52% | 9am: 70%<br>3pm: 68% | 9am: 91%<br>3pm: 92% |

*Optimised by fixed strategies.

### 4.1.4 Evaluation of Glare Metrics: Simulation-based Analysis

Afterward analysing the rhythmic solar irradiation patterns, two areas were selected to identify the predicted changes in glare sources and potentials in indoor spaces of the library (*Fig.59*). The first location is positioned in level 3 facing to the south direction, this allows to observe and measure differences that happens precisely in areas attached to eastern and southern windows. Moreover, the clipped view is within the double height zone providing a clear view to the level 3 ceiling, roof's ceiling, level 4 handrail's edge surface, and the floor surface. The simulations took more explained-routine on three different times across the day in each season. Table 12 is illustrating simulations in comparative method which are rendered in false-view with luminance measures of scaled-lighting between (0.0-2000.0 lux).

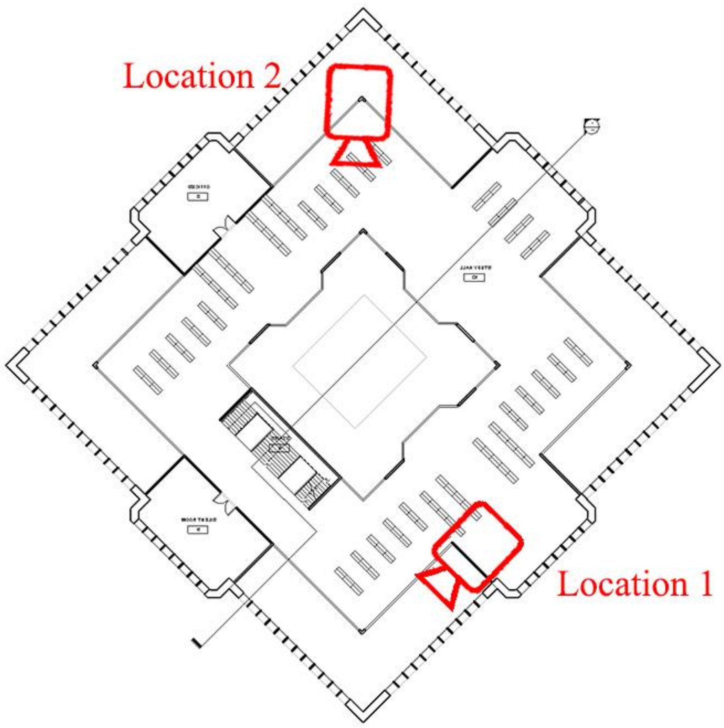



Figure 59: Camera Locations for Illuminance False-Coloured Renders (by Author).

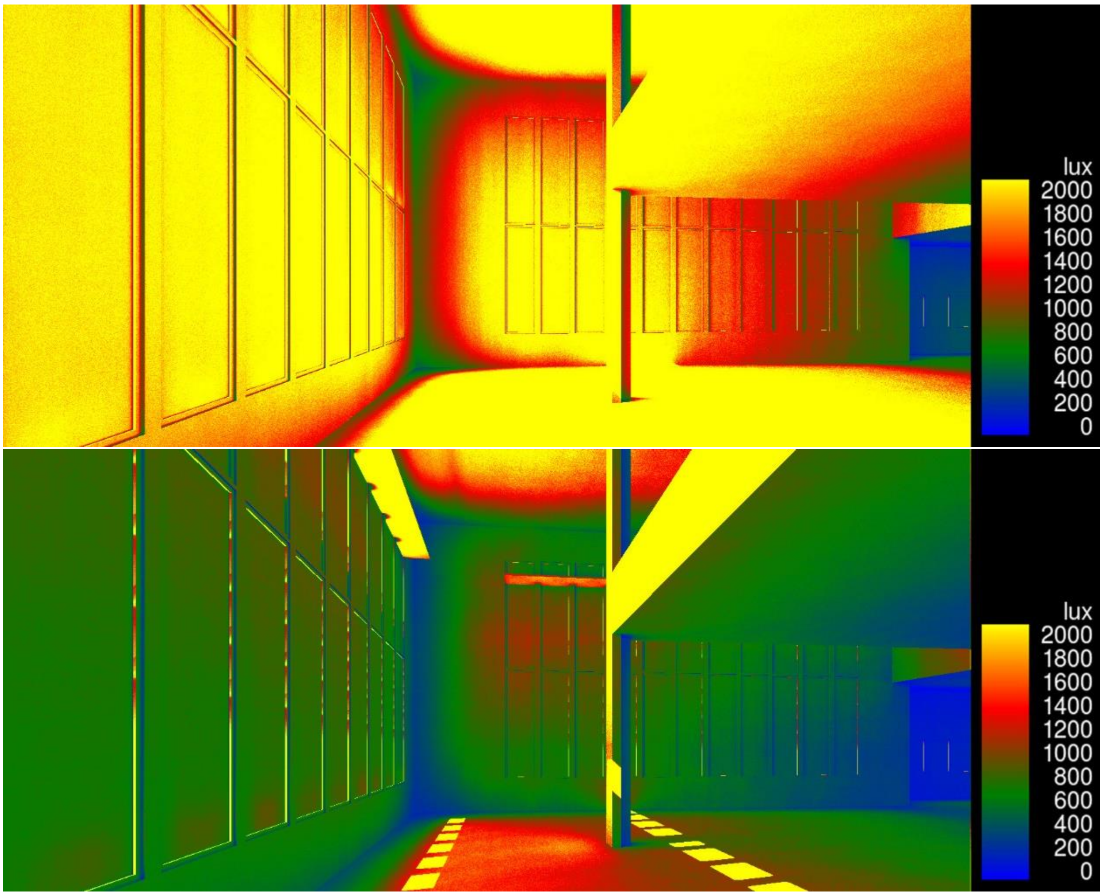


Figure 60: Optimisation Effect on Light Levels of First Location Level 3 on 21 Dec. at 9am (Top: Existing, Bottom: Optimised) (by Author).

Massive changes in level 3 are noticed related to daylighting qualities. The illustrations in *fig.60* are taken as an example to demonstrate the effects of suggested shading strategy on 21 December at 9 am. If a simple rule to understand these false-coloured renders is taken that green is presenting the best levels of lighting level required in the space (generally 500-750 lux). Although, royal blue colour is quite fine for visual tasks (300-500 lux), the difference will be clear. The shading strategy has significant role on stabilising the lighting levels along the daytime inside the library's atmosphere as well as preventing direct incidence of solar irradiation in morning and afternoon time. Moreover, there is a reduction in number of potential surfaces that might act as discomfort glare sources if stroke by direct sunlight as seen in roof and level 4's edge surface. Commonly, the lighting levels between 300 to 750 lux are covering level 3's mainstream, increasing simultaneously the potentials of visual comfort metrics on glare metrics bases.

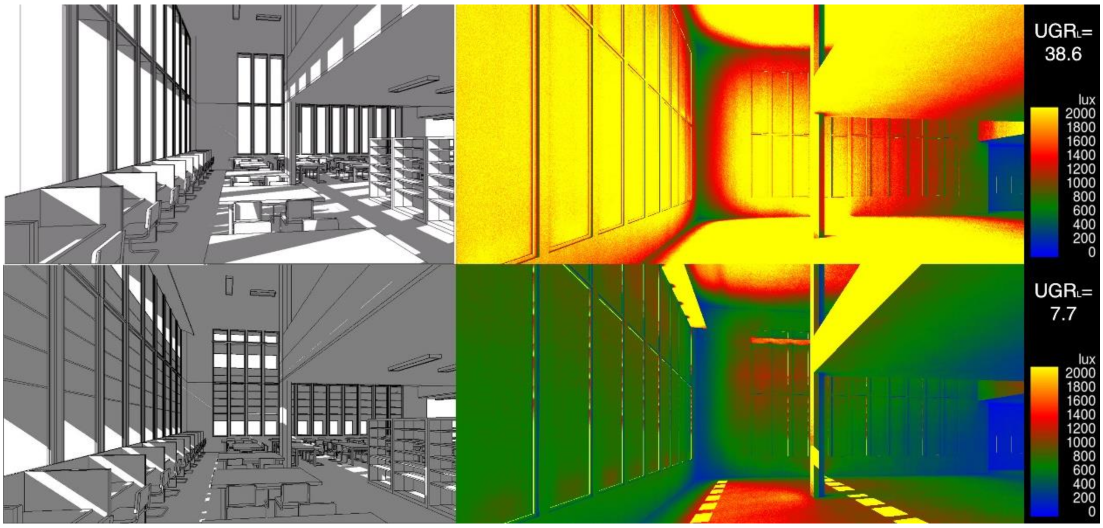


Figure 61: Unified Glare Rating ($UGR_L$) Evaluation in Location 1 on 21 December at 9:00 Am (Top: Existing, Bottom: Optimized) (by Author)

As a sample of improvements in glare manner (*fig.61*), the tested sample on 21 December at 9:00 am showed significant reduction on $UGR_L$ value from 38.6% in the existing building compared to 7.7% with the integration of the fixed glare control strategy. The optimized $UGR_L$ value is optimally meets the European Standard EN 12464 which required 19% as the maximum obtained levels in the space (CEN, 2011).

The second selected position for evaluation was totally oriented toward the centre of the building where the skylight opening is located (*fig.62*). Yet, the south-western portion of the building allows to measure the daylighting qualities in level 4 which are affected by shading strategy. The main problematic issue in these areas are direct sunlight from skylight aperture, high glare potentials from same source and the expansion of negative effects from façade's windows when sun is in low solar altitude in daily bases, see table 13.

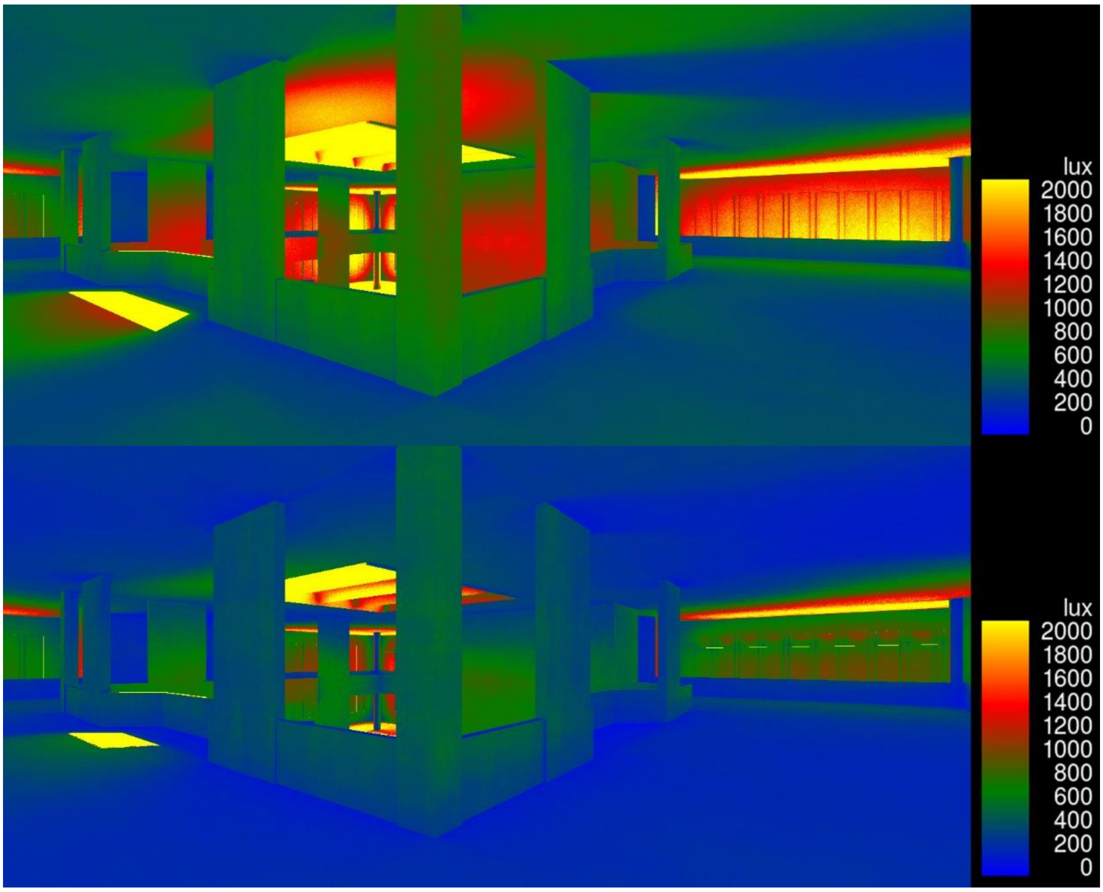
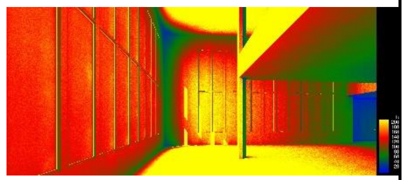
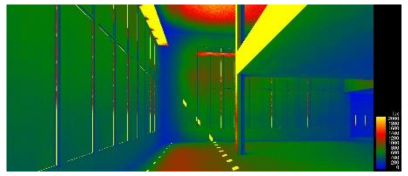
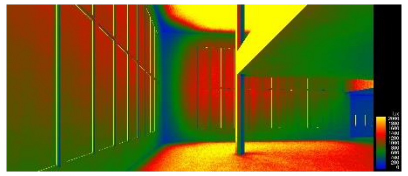
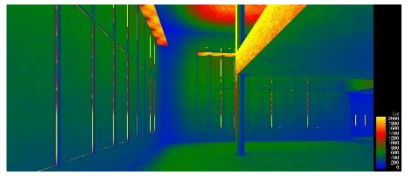
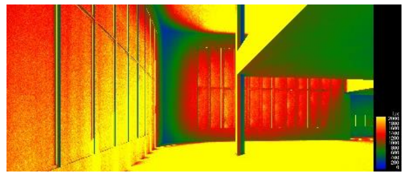
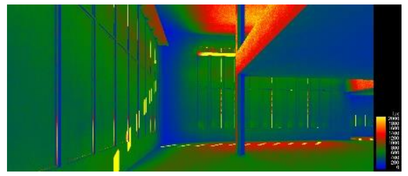
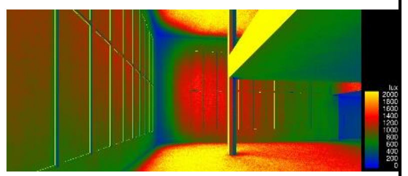
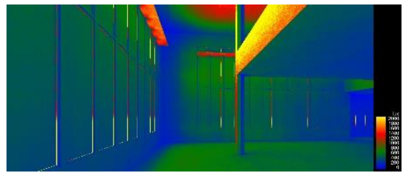
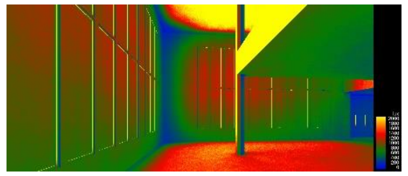
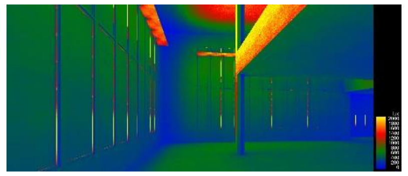
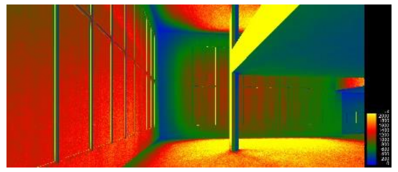
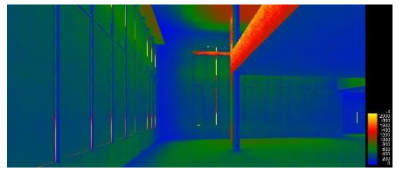
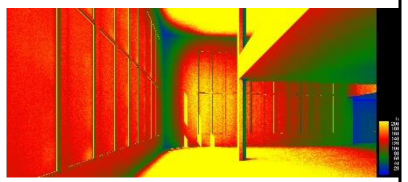
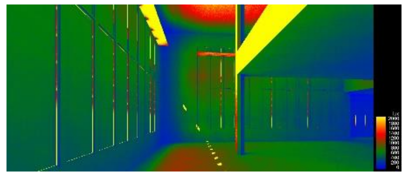
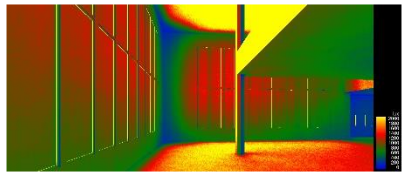
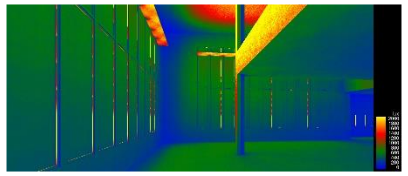
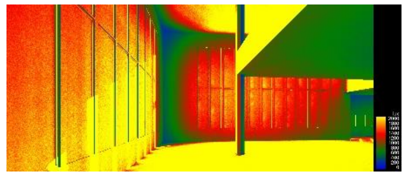
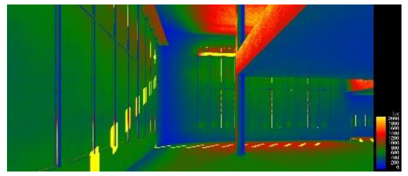
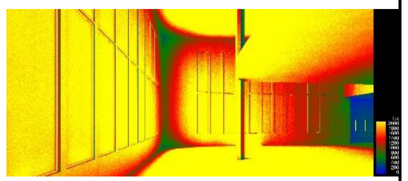
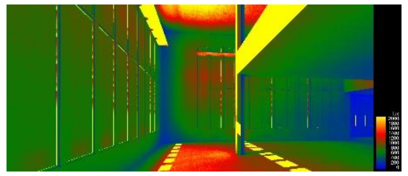
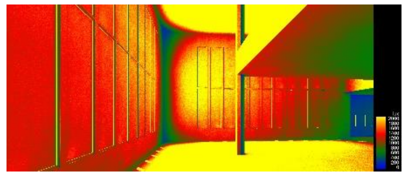
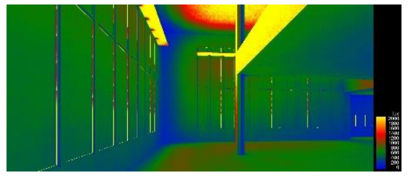
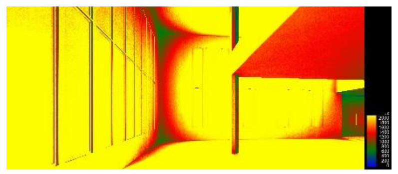
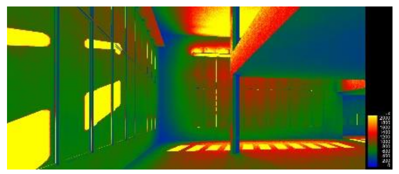


Figure 62: Optimisation Effect on Light Levels of Second Location Level 4 on 21 Dec. at 9 Am (Left: Existing, Right: Optimised) (by Author).

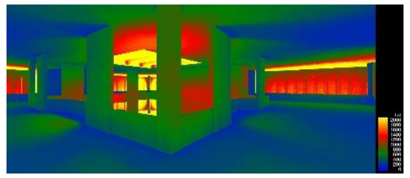
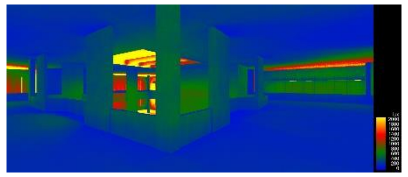
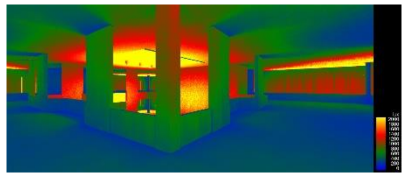
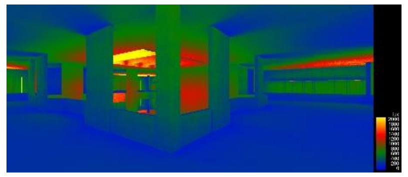
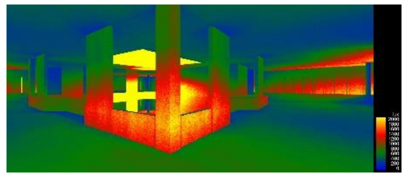
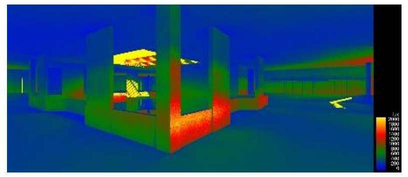
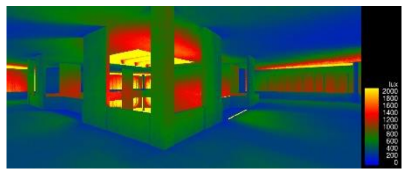
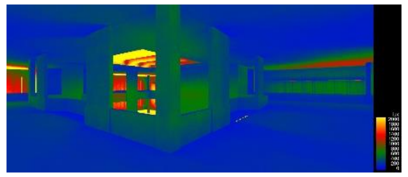
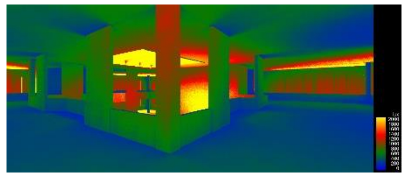
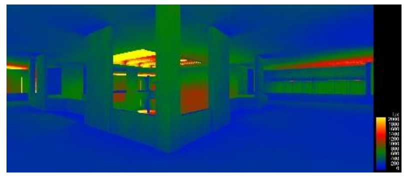
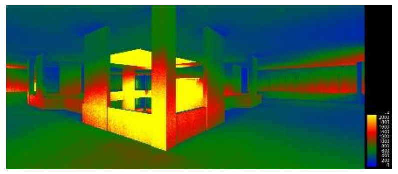
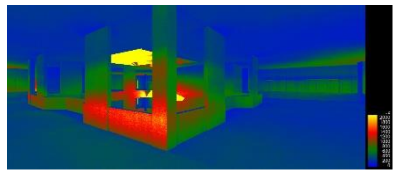
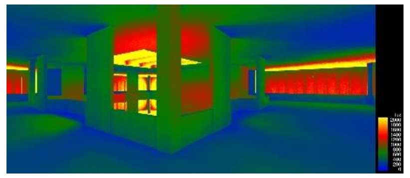
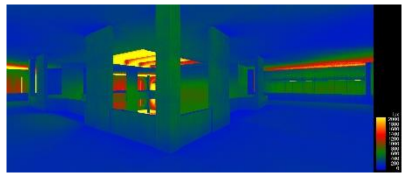
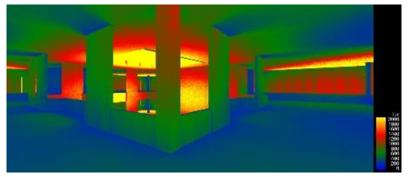
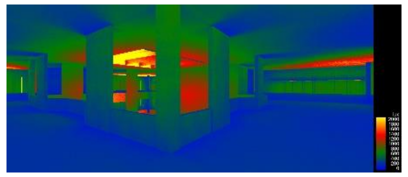
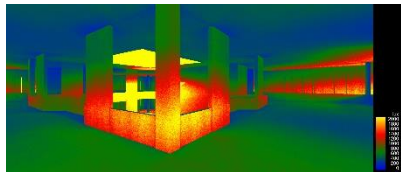
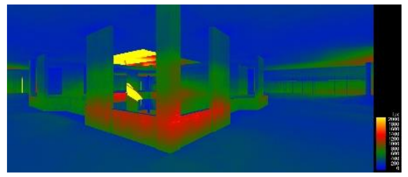
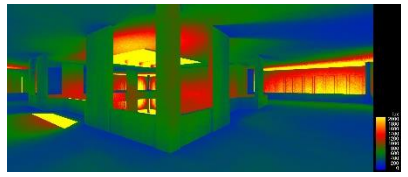
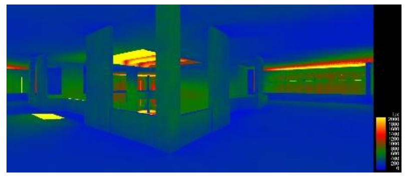
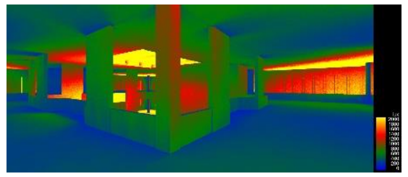
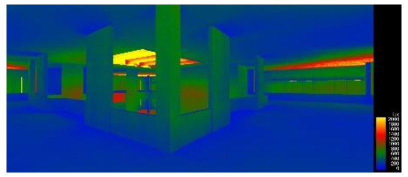
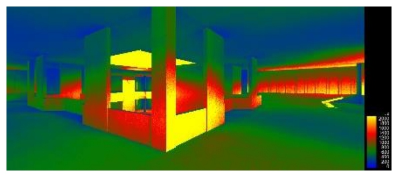
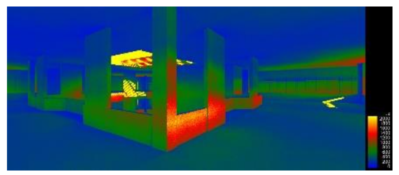
Unlike level 3, the effects of the strategy are slightly noticeable due the floor's setback from main façades. Adaptations are limited to the central part of the building where noticeable reduction is found in glare potentials and excessive light is properly treated without causing gloomy atmosphere in deep spaces. Otherwise, additive shadings are showing the required behaviour against excessive irradiations perceived through different manners.

Table 12: Comparatives of Illuminance Images for Selected View in Level 3 (Threshold Range 0-2000 Lux) (by Author)

| Time | 9:00 | | 12:00 | | 16:30 | |
|---|---|---|---|---|---|---|
| Condition | Existing | Optimised | Existing | Optimised | Existing | Optimised |
| 21 March |  |  |  |  |  |  |
| 21 June |  |  |  |  |  |  |
| 21 September |  |  |  |  |  |  |
| 21 December |  |  |  |  |  |  |

*Optimised by fixed strategies.

Table 13: Comparatives of Illuminance Images for Selected View in Level 4 (Threshold Range 0-2000 Lux) (by Author)

| Time | 9:00 | | 12:00 | | 16:30 | |
|---|---|---|---|---|---|---|
| Condition | Existing | Optimised | Existing | Optimised | Existing | Optimised |
| 21 March |  |  |  |  |  |  |
| 21 June |  |  |  |  |  |  |
| 21 September |  |  |  |  |  |  |
| 21 December |  |  |  |  |  |  |

*Optimised by fixed strategies.

### 4.1.5 Analysis of Optimisation Impacts on Annual Thresholds

Firstly, the building was exposed to all the conditions that is required by the LEED for the illuminance calculation method in order to obtain results that can be evaluated according to LEED code as the clear-sky conditions with the external obstructions. The movable furniture and partitions were excluded. One exception had made by reducing the threshold limits to 300-750lux due to correlating the reading and visual tasks particularly in libraries. Therefore, the discussion will be focusing in percentages within this threshold limit (300-750 lux) unless it is mentioned. Thus, it is predicted not to meet the exact required percentages needed for the code. Additionally, the study has expanded the number of simulated dates as an attempt to get accurate readings for the visual conditions throughout the year. The analysis will be taken on seasons to monitor the changes and the challenges facing the visual tasks in the library.

**Winter season** analysis is taken two days (1$^{st}$ and 15$^{th}$) of December, January and February at 9am and 3pm. For the record in this season, the highest optimum coverage (300-750lux) recorded is 82% on 1$^{st}$ January at 3pm by the optimised strategy (table 14).

In December, there is a slight improvement in the morning hours when the areas covered with 300-750 lux showed an increase from 38.8% in existing building to 43.0% by the optimisation on the month average at 9am. While, that carried along with an inconsiderable average-reduction from 55% to 52% in afternoon hours. Noticeably, the proposed strategy is showing very strange behaviour on 15$^{th}$ December. Significant drop in optimum coverage in the 4$^{th}$ floor during the day from 54% to 13% at 9am and from 74% to 15% at 3pm which is can be accounted to the effect of the light-shelf convexity in response to the sun altitude in that day since this behaviour is limited to the 4th floor.

In January, the optimisation is showing a balanced improvement along the month. On morning hours, the strategy is averagely adding 21% to the 47.8% in the existing building to achieve 68.8% within the illuminance range of 300-750 lux. At the same time, similar increases are recorded at 3pm by 16.2% on average from 56.8% to 73%. These values are representing the **peak monthly performance** measured along the year. Yet, there is a reduction in coverage as the moth goes without any sudden actions.

In February, the improvements by the optimisation strategy continues throughout the month. Average increases of 23.3% (34%-57.3%) in morning hours in both floors and 20.3% (41%-61.3%) in afternoon time are added to 300-750lux coverage.

Overall, the optimisation is increasing the average coverages within the required illuminance (300-750 lux) in both selected periods of the day. At 9am, winter averages within the threshold are upsurge from 40.2% to 56.3% with 16.1% and similar raises are recorded at 3pm with 11.2% growths (from 50.9% to 62.1%). On exception of this rule, it is seen with proposed strategy on 15th December when it fails to maintain the improvement behaviour.

Table 14: Average Daylight Coverage During Winter (by Author)

| Season | Floor | Month | Day | EXITING 9am <300lx | EXITING 9am 300~750 | EXITING 9am >750lx | EXITING 3pm <300lx | EXITING 3pm 300~750 | EXITING 3pm >750lx | OPTIMISED 9am <300lx | OPTIMISED 9am 300~750 | OPTIMISED 9am >750lx | OPTIMISED 3pm <300lx | OPTIMISED 3pm 300~750 | OPTIMISED 3pm >750lx |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WINTER | 3rd Floor | December | 01-Dec | 6% | 26% | 68% | 7% | 36% | 57% | 6% | 59% | 35% | 9% | 67% | 24% |
| | | | 15-Dec | 6% | 28% | 66% | 7% | 36% | 57% | 4% | 38% | 58% | 5% | 47% | 48% |
| | | | Average | 6.0% | 27.0% | 67.0% | 7.0% | 36.0% | 57.0% | 5.0% | 48.5% | 46.5% | 7.0% | 57.0% | 36.0% |
| | 4th Floor | December | 01-Dec | 1% | 47% | 52% | 3% | 74% | 23% | 2% | 62% | 37% | 3% | 79% | 18% |
| | | | 15-Dec | 1% | 54% | 46% | 3% | 74% | 23% | 0% | 13% | 87% | 0% | 15% | 85% |
| | | | Average | 1.0% | 50.5% | 49.0% | 3.0% | 74.0% | 23.0% | 1.0% | 37.5% | 62.0% | 1.5% | 47.0% | 51.5% |
| | December Total Average | | | **3.5%** | **38.8%** | **58.0%** | **5.0%** | **55.0%** | **40.0%** | **3.0%** | **43.0%** | **54.3%** | **4.3%** | **52.0%** | **43.8%** |
| | 3rd Floor | January | 01-Jan | 7% | 35% | 58% | 8% | 45% | 48% | 8% | 67% | 25% | 12% | 70% | 18% |
| | | | 15-Jan | 6% | 29% | 65% | 7% | 33% | 61% | 7% | 63% | 30% | 8% | 65% | 27% |
| | | | Average | 6.5% | 32.0% | 61.5% | 7.5% | 39.0% | 54.5% | 7.5% | 65.0% | 27.5% | 10.0% | 67.5% | 22.5% |
| | 4th Floor | January | 01-Jan | 2% | 68% | 31% | 4% | 80% | 17% | 3% | 76% | 22% | 4% | 82% | 13% |
| | | | 15-Jan | 1% | 59% | 40% | 2% | 69% | 29% | 2% | 68% | 30% | 2% | 75% | 22% |
| | | | Average | 1.5% | 63.5% | 35.5% | 3.0% | 74.5% | 23.0% | 2.5% | 72.0% | 26.0% | 3.0% | 78.5% | 17.5% |
| | January Total Average | | | **4.0%** | **47.8%** | **48.5%** | **5.3%** | **56.8%** | **38.8%** | **5.0%** | **68.5%** | **26.8%** | **6.5%** | **73.0%** | **20.0%** |
| | 3rd Floor | February | 01-Feb | 6% | 27% | 67% | 7% | 33% | 61% | 6% | 59% | 35% | 7% | 64% | 29% |
| | | | 15-Feb | 6% | 23% | 71% | 6% | 24% | 70% | 6% | 55% | 39% | 6% | 54% | 40% |
| | | | Average | 6.0% | 25.0% | 69.0% | 6.5% | 28.5% | 65.5% | 6.0% | 57.0% | 37.0% | 6.5% | 59.0% | 34.5% |
| | 4th Floor | February | 01-Feb | 1% | 48% | 51% | 1% | 65% | 34% | 1% | 62% | 37% | 2% | 73% | 25% |
| | | | 15-Feb | 1% | 38% | 62% | 1% | 42% | 58% | 1% | 53% | 47% | 1% | 54% | 45% |
| | | | Average | 1.0% | 43.0% | 56.5% | 1.0% | 53.5% | 46.0% | 1.0% | 57.5% | 42.0% | 1.5% | 63.5% | 35.0% |
| | February Total Average | | | **3.5%** | **34.0%** | **62.8%** | **3.8%** | **41.0%** | **55.8%** | **3.5%** | **57.3%** | **39.5%** | **4.0%** | **61.3%** | **34.8%** |
| | Winter Average | | | **3.7%** | **40.2%** | **56.4%** | **4.7%** | **50.9%** | **44.8%** | **3.8%** | **56.3%** | **40.2%** | **4.9%** | **62.1%** | **32.8%** |

**Spring season** analysis is included March, April, and May with spring equinox (21st March) as an addition in calculations (table 15). For the sake of more accuracy in measurements, the equinoxes are added to season tables and they will be discussed in detail in upcoming sections. Again, the highest record within (300-750 lux) threshold is displayed by the optimisation system on March 1st at 3pm (51%).

From March records, on average, significant increases are measured on morning hours from 27.3% in existing building to 51.8% with fixed strategy. Along with that, recorders at 3pm showed less raises from 35% to 46.2% but still considered as an improvement. Spring equinox (March 21st) is noticeably recording the highest percentages within the (300-750 lux) threshold in both floors and both simulated times.

As seen in April, optimisation is keeping the same improvement attitude along the month with 19.8% (17%-36.8%) raises in morning hours and 22.5% (19%-41.5%) in afternoon hours. Regarding the high increase percentages of areas above threshold (>750 lux) in this month by achieving 80% (see 3rd floor 3pm), the strategy managed to slightly decrease this excessive light measures of illuminances to record averagely 61% and 55.8% at 9am and 3pm respectively.

In May, the 3rd floor in existing building is showing very low average of cover within the threshold at 9am with 13.5% but this value upsurge to achieve 43% with the strategy in the same time. Otherwise, May's records are showing 20% average increases in average totals of the month in both simulated times.

Spring averages are also presenting significant raises found by the optimisation strategy throughout the season. Significant increases in coverage within the limits of

300-750 lux on average of 21.1% (41.5%-20.4%) at 9am and 18.3% (43.1%-24.8%) at 3pm in both floors. This is companied with optimisation of levels above the threshold (>750 lux) when it is reduced from 76.8% to 55.9% in mornings and from 72.5% to 54% in afternoons. In this season 0% appeared for the first time in the records of areas below the illuminance limit of 300 lux as it represents the excessive daylight in these months.

Table 15: Average Daylight Coverage During Spring (by Author)

| Season | Floor | Month | Day | EXITING | | | | | | OPTIMISED | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 9am | | | 3pm | | | 9am | | | 3pm | | |
| | | | | <300lx | 300~750 | >750lx | <300lx | 300~750 | >750lx | <300lx | 300~750 | >750lx | <300lx | 300~750 | >750lx |
| SPRING | 3rd Floor | March | 01-Mar | 6% | 20% | 75% | 7% | 33% | 61% | 5% | 50% | 45% | 5% | 51% | 44% |
| | | | 15-Mar | 6% | 17% | 77% | 6% | 18% | 77% | 5% | 46% | 50% | 5% | 47% | 48% |
| | | | 21-Mar | 6% | 25% | 69% | 7% | 23% | 70% | 6% | 66% | 27% | 7% | 23% | 70% |
| | | | Average | 6.0% | 20.7% | 73.7% | 6.7% | 24.7% | 69.3% | 5.3% | 54.0% | 40.7% | 5.7% | 40.3% | 54.0% |
| | 4th Floor | March | 01-Mar | 1% | 30% | 69% | 2% | 64% | 34% | 1% | 43% | 57% | 1% | 46% | 53% |
| | | | 15-Mar | 0% | 25% | 74% | 1% | 28% | 71% | 1% | 36% | 63% | 1% | 42% | 58% |
| | | | 21-Mar | 1% | 47% | 53% | 1% | 44% | 55% | 1% | 70% | 29% | 2% | 68% | 31% |
| | | | Average | 0.7% | 34.0% | 65.3% | 1.3% | 45.3% | 53.3% | 1.0% | 49.7% | 49.7% | 1.3% | 52.0% | 47.3% |
| | March Total Average | | | **3.3%** | **27.3%** | **69.5%** | **4.0%** | **35.0%** | **61.3%** | **3.2%** | **51.8%** | **45.2%** | **3.5%** | **46.2%** | **50.7%** |
| | 3rd Floor | April | 01-Apr | 0% | 21% | 79% | 0% | 24% | 75% | 4% | 42% | 54% | 5% | 47% | 48% |
| | | | 15-Apr | 5% | 13% | 81% | 5% | 14% | 80% | 5% | 42% | 53% | 5% | 45% | 50% |
| | | | Average | 2.5% | 17.0% | 80.0% | 2.5% | 19.0% | 77.5% | 4.5% | 42.0% | 53.5% | 5.0% | 46.0% | 49.0% |
| | 4th Floor | April | 01-Apr | 6% | 14% | 81% | 6% | 17% | 78% | 0% | 32% | 68% | 1% | 38% | 61% |
| | | | 15-Apr | 0% | 20% | 80% | 0% | 21% | 78% | 0% | 31% | 69% | 1% | 36% | 64% |
| | | | Average | 3.0% | 17.0% | 80.5% | 3.0% | 19.0% | 78.0% | 0.0% | 31.5% | 68.5% | 1.0% | 37.0% | 62.5% |
| | April Total Average | | | **2.8%** | **17.0%** | **80.3%** | **2.8%** | **19.0%** | **77.8%** | **2.3%** | **36.8%** | **61.0%** | **3.0%** | **41.5%** | **55.8%** |
| | 3rd Floor | May | 01-May | 6% | 14% | 81% | 5% | 17% | 78% | 5% | 44% | 51% | 5% | 49% | 46% |
| | | | 15-May | 5% | 13% | 81% | 5% | 21% | 80% | 5% | 42% | 54% | 5% | 44% | 51% |
| | | | Average | 5.5% | 13.5% | 81.0% | 5.0% | 19.0% | 79.0% | 5.0% | 43.0% | 52.5% | 5.0% | 46.5% | 48.5% |
| | 4th Floor | May | 01-May | 0% | 20% | 80% | 0% | 23% | 77% | 0% | 30% | 70% | 1% | 40% | 59% |
| | | | 15-May | 0% | 20% | 80% | 0% | 21% | 79% | 0% | 28% | 71% | 1% | 34% | 66% |
| | | | Average | 0.0% | 20.0% | 80.0% | 0.0% | 22.0% | 78.0% | 0.0% | 29.0% | 70.5% | 1.0% | 37.0% | 62.5% |
| | May Total Average | | | **2.8%** | **16.8%** | **80.5%** | **2.5%** | **20.5%** | **78.5%** | **2.5%** | **36.0%** | **61.5%** | **3.0%** | **41.8%** | **55.5%** |
| | Spring Average | | | **2.9%** | **20.4%** | **76.8%** | **3.1%** | **24.8%** | **72.5%** | **2.6%** | **41.5%** | **55.9%** | **3.2%** | **43.1%** | **54.0%** |

**Summer season** analysis is involving June, July and August in the same manner and testing conditions (table 16). The sun altitude is in the highest position in the sky. That might seem like low quantities of sunlight will penetrate into the spaces but in these months, there are the highest solar irradiation with the maximum illuminance for the sun and sky components. Thus, the records are presented as follow:

Through June measures, the optimisation is providing on average 100% coverage more than the existing covered areas within the required illuminance. Mainly, these enhancements are accounted on above threshold reduction. On average, coverage within the limits raised from 16%-16.8% in existing building to achieve 33.5%-37.8% under optimised conditions. Significantly, the main improvements are essentially measured in 3$^{rd}$ floor but these are **lowest monthly performance** for the strategy along the year.

Apparently, July and August are presenting very similar measures as June's. Very slight enhancements in overall both month are found without any significant changes more than the previous month.

Overall the summer season, all the three months are recording the lowest average coverage within the threshold (300-750 lux) among the year. The 4$^{th}$ floor is maintaining 0% areas below the 300 lux along the season. Whilst, the 80.7%-80.1% that recorded for above the limits (>750 lux) are optimised to achieve 62.8%-59.2%. Yet, the indoor spaces are facing excessive illuminance during this season.

Table 16: Average Daylight Coverage During Summer (by Author)

| | | | | EXITING | | | | | | OPTIMISED | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 9am | | | 3pm | | | 9am | | | 3pm | | |
| Season | Floor | Month | Day | <300lx | 300~750 | >750lx | <300lx | 300~750 | >750lx | <300lx | 300~750 | >750lx | <300lx | 300~750 | >750lx |
| SUMMER | 3rd Floor | June | 01-Jun | 6% | 13% | 81% | 5% | 14% | 81% | 5% | 41% | 54% | 5% | 43% | 52% |
| | | | 15-Jun | 6% | 13% | 81% | 5% | 14% | 81% | 5% | 40% | 55% | 5% | 44% | 52% |
| | | | Average | 6.0% | 13.0% | 81.0% | 5.0% | 14.0% | 81.0% | 5.0% | 40.5% | 54.5% | 5.0% | 43.5% | 52.0% |
| | 4th Floor | June | 01-Jun | 0% | 19% | 81% | 0% | 20% | 80% | 0% | 26% | 73% | 1% | 31% | 68% |
| | | | 15-Jun | 0% | 19% | 81% | 1% | 19% | 80% | 0% | 27% | 73% | 1% | 33% | 67% |
| | | | Average | 0.0% | 19.0% | 81.0% | 0.5% | 19.5% | 80.0% | 0.0% | 26.5% | 73.0% | 1.0% | 32.0% | 67.5% |
| | June Total Average | | | **3.0%** | **16.0%** | **81.0%** | **2.8%** | **16.8%** | **80.5%** | **2.5%** | **33.5%** | **63.8%** | **3.0%** | **37.8%** | **59.8%** |
| | 3rd Floor | July | 01-Jul | 6% | 13% | 81% | 5% | 14% | 80% | 5% | 41% | 55% | 5% | 45% | 50% |
| | | | 15-Jul | 6% | 14% | 81% | 5% | 15% | 80% | 5% | 43% | 52% | 5% | 44% | 51% |
| | | | Average | 6.0% | 13.5% | 81.0% | 5.0% | 14.5% | 80.0% | 5.0% | 42.0% | 53.5% | 5.0% | 44.5% | 50.5% |
| | 4th Floor | July | 01-Jul | 0% | 20% | 80% | 0% | 19% | 80% | 0% | 26% | 74% | 1% | 33% | 67% |
| | | | 15-Jul | 0% | 19% | 80% | 0% | 20% | 80% | 0% | 28% | 72% | 1% | 32% | 67% |
| | | | Average | 0.0% | 19.5% | 80.0% | 0.0% | 19.5% | 80.0% | 0.0% | 27.0% | 73.0% | 1.0% | 32.5% | 67.0% |
| | July Total Average | | | **3.0%** | **16.5%** | **80.5%** | **2.5%** | **17.0%** | **80.0%** | **2.5%** | **34.5%** | **63.3%** | **3.0%** | **38.5%** | **58.8%** |
| | 3rd Floor | August | 01-Aug | 6% | 13% | 82% | 5% | 14% | 80% | 5% | 42% | 53% | 5% | 44% | 52% |
| | | | 15-Aug | 5% | 13% | 81% | 5% | 15% | 80% | 5% | 42% | 53% | 5% | 45% | 51% |
| | | | Average | 5.5% | 13.0% | 81.5% | 5.0% | 14.5% | 80.0% | 5.0% | 42.0% | 53.0% | 5.0% | 44.5% | 51.5% |
| | 4th Floor | August | 01-Aug | 0% | 20% | 80% | 0% | 20% | 80% | 0% | 29% | 70% | 1% | 32% | 67% |
| | | | 15-Aug | 0% | 21% | 79% | 0% | 20% | 79% | 0% | 31% | 69% | 1% | 34% | 66% |
| | | | Average | 0.0% | 20.5% | 79.5% | 0.0% | 20.0% | 79.5% | 0.0% | 30.0% | 69.5% | 1.0% | 33.0% | 66.5% |
| | August Total Average | | | **2.8%** | **16.8%** | **80.5%** | **2.5%** | **17.3%** | **79.8%** | **2.5%** | **36.0%** | **61.3%** | **3.0%** | **38.8%** | **59.0%** |
| | Summer Average | | | **2.9%** | **16.4%** | **80.7%** | **2.6%** | **17.0%** | **80.1%** | **2.5%** | **34.7%** | **62.8%** | **3.0%** | **38.3%** | **59.2%** |

**Autumn (Fall) season** calculations are based on the simulations in September (fall equinox included), October and November. The sun altitude is dropping down in the horizon which increases the possibility of having adequate illuminance levels (table 17).

Apparently in September, the fall equinox date is offering stunning coverage within the required illuminance limits. The values with optimisation are increasing in September 21st to achieve the highest levels in the month as 70% recorded at 9am of the day. On the other hand, September averages are continuing to proof the efficiency of the proposed strategy rather than the total percentages are yet below the standards (as expected).

Subsequently, the values offered by the proposal in October and November are following the same uptrend improvement to achieve the fall peak-performance in November (particularly on November 15th). On average, around 66.5%-69% (at 9am and 3pm respectively) of both floors are having sufficient daylighting in November convoyed by the lowest measures of over-limit (>750 lux) illuminances achieving (averagely) 28.8% at 9am and 26.3% at 3pm.

Rather than the appearance of minor spaces with gloomy light levels in the 3rd floor, the performance of the proposed strategy in autumn is sharing with winter performance the highest capacity to control the daylighting, providing the adequate illuminance for visual tasks.

Table 17: Average Daylight Coverage During Autumn (by Author)

| Season | Floor | Month | Day | EXITING | | | | | | OPTIMISED | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 9am | | | 3pm | | | 9am | | | 3pm | | |
| | | | | <300lx | 300~750 | >750lx | <300lx | 300~750 | >750lx | <300lx | 300~750 | >750lx | <300lx | 300~750 | >750lx |
| AUTUMN | 3rd Floor | September | 01-Sep | 6% | 13% | 81% | 5% | 15% | 80% | 4% | 42% | 54% | 5% | 47% | 48% |
| | | | 15-Sep | 6% | 14% | 80% | 5% | 17% | 77% | 4% | 42% | 53% | 5% | 48% | 47% |
| | | | 21-Sep | 6% | 25% | 69% | 7% | 23% | 70% | 6% | 66% | 27% | 7% | 23% | 70% |
| | | | Average | 6.0% | 17.3% | 76.7% | 5.7% | 18.3% | 75.7% | 4.7% | 50.0% | 44.7% | 5.7% | 39.3% | 55.0% |
| | 4th Floor | September | 01-Sep | 0% | 20% | 79% | 0% | 23% | 77% | 0% | 29% | 70% | 1% | 37% | 62% |
| | | | 15-Sep | 0% | 21% | 78% | 1% | 25% | 74% | 0% | 31% | 69% | 1% | 39% | 61% |
| | | | 21-Sep | 1% | 47% | 53% | 1% | 44% | 55% | 1% | 70% | 29% | 2% | 68% | 31% |
| | | | Average | 0.3% | 29.3% | 70.0% | 0.7% | 30.7% | 68.7% | 0.3% | 43.3% | 56.0% | 13.0% | 48.0% | 51.3% |
| | September Total Average | | | **3.2%** | **23.3%** | **73.4%** | **3.2%** | **24.5%** | **72.2%** | **2.5%** | **46.7%** | **50.3%** | **3.5%** | **43.7%** | **53.1%** |
| | 3rd Floor | October | 01-Oct | 6% | 16% | 79% | 6% | 21% | 73% | 5% | 44% | 51% | 5% | 52% | 42% |
| | | | 15-Oct | 6% | 19% | 76% | 6% | 25% | 69% | 5% | 46% | 49% | 6% | 55% | 38% |
| | | | Average | 6.0% | 17.5% | 77.5% | 6.0% | 23.0% | 71.0% | 5.0% | 45.0% | 50.0% | 5.5% | 53.5% | 40.0% |
| | 4th Floor | October | 01-Oct | 0% | 24% | 75% | 1% | 33% | 66% | 1% | 34% | 66% | 1% | 47% | 52% |
| | | | 15-Oct | 0% | 27% | 72% | 1% | 45% | 55% | 1% | 37% | 63% | 1% | 61% | 38% |
| | | | Average | 0.0% | 25.5% | 73.5% | 1.0% | 39.0% | 60.5% | 1.0% | 35.5% | 64.5% | 1.0% | 54.0% | 45.0% |
| | October Total Average | | | **3.0%** | **21.5%** | **75.5%** | **3.5%** | **31.0%** | **65.8%** | **3.0%** | **40.3%** | **57.3%** | **3.3%** | **53.8%** | **42.5%** |
| | 3rd Floor | November | 01-Nov | 7% | 46% | 47% | 6% | 30% | 64% | 9% | 72% | 19% | 7% | 62% | 31% |
| | | | 15-Nov | 6% | 24% | 70% | 7% | 34% | 59% | 6% | 55% | 39% | 8% | 67% | 25% |
| | | | Average | 6.5% | 35.0% | 58.5% | 6.5% | 32.0% | 61.5% | 7.5% | 63.5% | 29.0% | 7.5% | 64.5% | 28.0% |
| | 4th Floor | November | 01-Nov | 2% | 76% | 22% | 1% | 61% | 38% | 3% | 85% | 12% | 2% | 70% | 28% |
| | | | 15-Nov | 1% | 39% | 60% | 2% | 71% | 27% | 1% | 54% | 45% | 3% | 77% | 21% |
| | | | Average | 1.5% | 57.5% | 41.0% | 1.5% | 66.0% | 32.5% | 2.0% | 69.5% | 28.5% | 2.5% | 73.5% | 24.5% |
| | November Total Average | | | **4.0%** | **46.3%** | **49.8%** | **4.0%** | **49.0%** | **47.0%** | **4.8%** | **66.5%** | **28.8%** | **5.0%** | **69.0%** | **26.3%** |
| | Autumn Average | | | **3.4%** | **30.4%** | **66.2%** | **3.6%** | **34.8%** | **61.6%** | **3.4%** | **51.1%** | **45.4%** | **3.9%** | **55.5%** | **40.6%** |

Table 18: Annual Threshold Measures and Averages (by Author)

| | | | | EXITING | | | | | | OPTIMISED | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 9am | | | 3pm | | | 9am | | | 3pm | | |
| Season | Floor | Month | Day | <300lx | 300~750 | >750lx | <300lx | 300~750 | >750lx | <300lx | 300~750 | >750lx | <300lx | 300~750 | >750lx |
| WINTER | 3rd Floor | December | 01-Dec | 6% | 26% | 68% | 7% | 36% | 57% | 6% | 59% | 35% | 9% | 67% | 24% |
| | | | 15-Dec | 6% | 28% | 66% | 7% | 36% | 57% | 4% | 38% | 58% | 5% | 47% | 48% |
| | | | Average | 6.0% | 27.0% | 67.0% | 7.0% | 36.0% | 57.0% | 5.0% | 48.5% | 46.5% | 7.0% | 57.0% | 36.0% |
| | 4th Floor | December | 01-Dec | 1% | 47% | 52% | 3% | 74% | 23% | 2% | 62% | 37% | 3% | 79% | 18% |
| | | | 15-Dec | 1% | 54% | 46% | 3% | 74% | 23% | 0% | 13% | 87% | 0% | 15% | 85% |
| | | | Average | 1.0% | 50.5% | 49.0% | 3.0% | 74.0% | 23.0% | 1.0% | 37.5% | 62.0% | 1.5% | 47.0% | 51.5% |
| | December Total Average | | | 3.5% | 38.8% | 58.0% | 5.0% | 55.0% | 40.0% | 3.0% | 43.0% | 54.3% | 4.3% | 52.0% | 43.8% |
| | 3rd Floor | January | 01-Jan | 7% | 35% | 58% | 8% | 45% | 48% | 8% | 67% | 25% | 12% | 70% | 18% |
| | | | 15-Jan | 6% | 29% | 65% | 7% | 33% | 61% | 7% | 63% | 30% | 8% | 65% | 27% |
| | | | Average | 6.5% | 32.0% | 61.5% | 7.5% | 39.0% | 54.5% | 7.5% | 65.0% | 27.5% | 10.0% | 67.5% | 22.5% |
| | 4th Floor | January | 01-Jan | 2% | 68% | 31% | 4% | 80% | 17% | 3% | 76% | 22% | 4% | 82% | 13% |
| | | | 15-Jan | 1% | 59% | 40% | 2% | 69% | 29% | 2% | 68% | 30% | 2% | 75% | 22% |
| | | | Average | 1.5% | 63.5% | 35.5% | 3.0% | 74.5% | 23.0% | 2.5% | 72.0% | 26.0% | 3.0% | 78.5% | 17.5% |
| | January Total Average | | | 4.0% | 47.8% | 48.5% | 5.3% | 56.8% | 38.8% | 5.0% | 68.5% | 26.8% | 6.5% | 73.0% | 20.0% |
| | 3rd Floor | February | 01-Feb | 6% | 27% | 67% | 7% | 33% | 61% | 6% | 59% | 35% | 7% | 64% | 29% |
| | | | 15-Feb | 6% | 23% | 71% | 6% | 24% | 70% | 6% | 55% | 39% | 6% | 54% | 40% |
| | | | Average | 6.0% | 25.0% | 69.0% | 6.5% | 28.5% | 65.5% | 6.0% | 57.0% | 37.0% | 6.5% | 59.0% | 34.5% |
| | 4th Floor | February | 01-Feb | 1% | 48% | 51% | 1% | 65% | 34% | 1% | 62% | 37% | 2% | 73% | 25% |
| | | | 15-Feb | 1% | 38% | 62% | 1% | 42% | 58% | 1% | 53% | 47% | 1% | 54% | 45% |
| | | | Average | 1.0% | 43.0% | 56.5% | 1.0% | 53.5% | 46.0% | 1.0% | 57.5% | 42.0% | 1.5% | 63.5% | 35.0% |
| | February Total Average | | | 3.5% | 34.0% | 62.8% | 3.8% | 41.0% | 55.8% | 3.5% | 57.3% | 39.5% | 4.0% | 61.3% | 34.8% |
| | Winter Average | | | 3.7% | 40.2% | 56.4% | 4.7% | 50.9% | 44.8% | 3.8% | 56.3% | 40.2% | 4.9% | 62.1% | 32.8% |
| SPRING | 3rd Floor | March | 01-Mar | 6% | 20% | 75% | 7% | 33% | 61% | 5% | 50% | 45% | 5% | 51% | 44% |
| | | | 15-Mar | 6% | 17% | 77% | 6% | 18% | 77% | 5% | 46% | 50% | 5% | 47% | 48% |
| | | | 21-Mar | 6% | 25% | 69% | 7% | 23% | 70% | 6% | 66% | 27% | 7% | 23% | 70% |
| | | | Average | 6.0% | 20.7% | 73.7% | 6.7% | 24.7% | 69.3% | 5.3% | 54.0% | 40.7% | 5.7% | 40.3% | 54.0% |
| | 4th Floor | March | 01-Mar | 1% | 30% | 69% | 2% | 64% | 34% | 1% | 43% | 57% | 1% | 46% | 53% |
| | | | 15-Mar | 0% | 25% | 74% | 1% | 28% | 71% | 1% | 36% | 63% | 1% | 42% | 58% |
| | | | 21-Mar | 1% | 47% | 53% | 1% | 44% | 55% | 1% | 70% | 29% | 2% | 68% | 31% |
| | | | Average | 0.7% | 34.0% | 65.3% | 1.3% | 45.3% | 53.3% | 1.0% | 49.7% | 49.7% | 1.3% | 52.0% | 47.3% |
| | March Total Average | | | 3.3% | 27.3% | 69.5% | 4.0% | 35.0% | 61.3% | 3.2% | 51.8% | 45.2% | 3.5% | 46.2% | 50.7% |
| | 3rd Floor | April | 01-Apr | 0% | 21% | 79% | 0% | 24% | 75% | 4% | 42% | 54% | 5% | 47% | 48% |
| | | | 15-Apr | 5% | 13% | 81% | 5% | 14% | 80% | 5% | 42% | 53% | 5% | 45% | 50% |
| | | | Average | 2.5% | 17.0% | 80.0% | 2.5% | 19.0% | 77.5% | 4.5% | 42.0% | 53.5% | 5.0% | 46.0% | 49.0% |
| | 4th Floor | April | 01-Apr | 6% | 14% | 81% | 6% | 17% | 78% | 0% | 32% | 68% | 1% | 38% | 61% |
| | | | 15-Apr | 0% | 20% | 80% | 0% | 21% | 78% | 0% | 31% | 69% | 1% | 36% | 64% |
| | | | Average | 3.0% | 17.0% | 80.5% | 3.0% | 19.0% | 78.0% | 0.0% | 31.5% | 68.5% | 1.0% | 37.0% | 62.5% |
| | April Total Average | | | 2.8% | 17.0% | 80.3% | 2.8% | 19.0% | 77.8% | 2.3% | 36.8% | 61.0% | 3.0% | 41.5% | 55.8% |
| | 3rd Floor | May | 01-May | 6% | 14% | 81% | 5% | 17% | 78% | 5% | 44% | 51% | 5% | 49% | 46% |
| | | | 15-May | 5% | 13% | 81% | 5% | 21% | 80% | 5% | 42% | 54% | 5% | 44% | 51% |
| | | | Average | 5.5% | 13.5% | 81.0% | 5.0% | 19.0% | 79.0% | 5.0% | 43.0% | 52.5% | 5.0% | 46.5% | 48.5% |
| | 4th Floor | May | 01-May | 0% | 20% | 80% | 0% | 23% | 77% | 0% | 30% | 70% | 1% | 40% | 59% |
| | | | 15-May | 0% | 20% | 80% | 0% | 21% | 79% | 0% | 28% | 71% | 1% | 34% | 66% |
| | | | Average | 0.0% | 20.0% | 80.0% | 0.0% | 22.0% | 78.0% | 0.0% | 29.0% | 70.5% | 1.0% | 37.0% | 62.5% |
| | May Total Average | | | 2.8% | 16.8% | 80.5% | 2.5% | 20.5% | 78.5% | 2.5% | 36.0% | 61.5% | 3.0% | 41.8% | 55.5% |
| | Spring Average | | | 2.9% | 20.4% | 76.8% | 3.1% | 24.8% | 72.5% | 2.6% | 41.5% | 55.9% | 3.2% | 43.1% | 54.0% |
| SUMMER | 3rd Floor | June | 01-Jun | 6% | 13% | 81% | 5% | 14% | 81% | 5% | 41% | 54% | 5% | 43% | 52% |
| | | | 15-Jun | 6% | 13% | 81% | 5% | 14% | 81% | 5% | 40% | 55% | 5% | 44% | 52% |
| | | | Average | 6.0% | 13.0% | 81.0% | 5.0% | 14.0% | 81.0% | 5.0% | 40.5% | 54.5% | 5.0% | 43.5% | 52.0% |
| | 4th Floor | June | 01-Jun | 0% | 19% | 81% | 0% | 20% | 80% | 0% | 26% | 73% | 1% | 31% | 68% |
| | | | 15-Jun | 0% | 19% | 81% | 1% | 19% | 80% | 0% | 27% | 73% | 1% | 33% | 67% |
| | | | Average | 0.0% | 19.0% | 81.0% | 0.5% | 19.5% | 80.0% | 0.0% | 26.5% | 73.0% | 1.0% | 32.0% | 67.5% |
| | June Total Average | | | 3.0% | 16.0% | 81.0% | 2.8% | 16.8% | 80.5% | 2.5% | 33.5% | 63.8% | 3.0% | 37.8% | 59.8% |
| | 3rd Floor | July | 01-Jul | 6% | 13% | 81% | 5% | 14% | 80% | 5% | 41% | 55% | 5% | 45% | 50% |
| | | | 15-Jul | 6% | 14% | 81% | 5% | 15% | 80% | 5% | 43% | 52% | 5% | 44% | 51% |
| | | | Average | 6.0% | 13.5% | 81.0% | 5.0% | 14.5% | 80.0% | 5.0% | 42.0% | 53.5% | 5.0% | 44.5% | 50.5% |
| | 4th Floor | July | 01-Jul | 0% | 20% | 80% | 0% | 19% | 80% | 0% | 26% | 74% | 1% | 33% | 67% |
| | | | 15-Jul | 0% | 19% | 80% | 0% | 20% | 80% | 0% | 28% | 72% | 1% | 32% | 67% |
| | | | Average | 0.0% | 19.5% | 80.0% | 0.0% | 19.5% | 80.0% | 0.0% | 27.0% | 73.0% | 1.0% | 32.5% | 67.0% |
| | July Total Average | | | 3.0% | 16.5% | 80.5% | 2.5% | 17.0% | 80.0% | 2.5% | 34.5% | 63.3% | 3.0% | 38.5% | 58.8% |
| | 3rd Floor | August | 01-Aug | 6% | 13% | 82% | 5% | 14% | 80% | 5% | 42% | 53% | 5% | 44% | 52% |
| | | | 15-Aug | 5% | 13% | 81% | 5% | 15% | 80% | 5% | 42% | 53% | 5% | 45% | 51% |
| | | | Average | 5.5% | 13.0% | 81.5% | 5.0% | 14.5% | 80.0% | 5.0% | 42.0% | 53.0% | 5.0% | 44.5% | 51.5% |
| | 4th Floor | August | 01-Aug | 0% | 20% | 80% | 0% | 20% | 80% | 0% | 29% | 70% | 1% | 32% | 67% |
| | | | 15-Aug | 0% | 21% | 79% | 0% | 20% | 79% | 0% | 31% | 69% | 1% | 34% | 66% |
| | | | Average | 0.0% | 20.5% | 79.5% | 0.0% | 20.0% | 79.5% | 0.0% | 30.0% | 69.5% | 1.0% | 33.0% | 66.5% |
| | August Total Average | | | 2.8% | 16.8% | 80.5% | 2.5% | 17.3% | 79.8% | 2.5% | 36.0% | 61.3% | 3.0% | 38.8% | 59.0% |
| | Summer Average | | | 2.9% | 16.4% | 80.7% | 2.6% | 17.0% | 80.1% | 2.5% | 34.7% | 62.8% | 3.0% | 38.3% | 59.2% |
| AUTUMN | 3rd Floor | September | 01-Sep | 6% | 13% | 81% | 5% | 15% | 80% | 4% | 42% | 54% | 5% | 47% | 48% |
| | | | 15-Sep | 6% | 14% | 80% | 5% | 17% | 77% | 4% | 42% | 53% | 5% | 48% | 47% |
| | | | 21-Sep | 6% | 25% | 69% | 7% | 23% | 70% | 6% | 66% | 27% | 7% | 23% | 70% |
| | | | Average | 6.0% | 17.3% | 76.7% | 5.7% | 18.3% | 75.7% | 4.7% | 50.0% | 44.7% | 5.7% | 39.3% | 55.0% |
| | 4th Floor | September | 01-Sep | 0% | 20% | 79% | 0% | 23% | 77% | 0% | 29% | 70% | 1% | 37% | 62% |
| | | | 15-Sep | 0% | 21% | 78% | 1% | 25% | 74% | 0% | 31% | 69% | 1% | 39% | 61% |
| | | | 21-Sep | 1% | 47% | 53% | 1% | 44% | 55% | 1% | 70% | 29% | 2% | 68% | 31% |
| | | | Average | 0.3% | 29.3% | 70.0% | 0.7% | 30.7% | 68.7% | 0.3% | 43.3% | 56.0% | 1.3% | 48.0% | 51.3% |
| | September Total Average | | | 3.2% | 23.3% | 73.4% | 3.2% | 24.5% | 72.2% | 2.5% | 46.7% | 50.3% | 3.5% | 43.7% | 53.1% |
| | 3rd Floor | October | 01-Oct | 6% | 16% | 79% | 6% | 21% | 73% | 5% | 44% | 51% | 5% | 52% | 42% |
| | | | 15-Oct | 6% | 19% | 76% | 6% | 25% | 69% | 5% | 46% | 49% | 6% | 55% | 38% |
| | | | Average | 6.0% | 17.5% | 77.5% | 6.0% | 23.0% | 71.0% | 5.0% | 45.0% | 50.0% | 5.5% | 53.5% | 40.0% |
| | 4th Floor | October | 01-Oct | 0% | 24% | 75% | 1% | 33% | 66% | 1% | 34% | 66% | 1% | 47% | 52% |
| | | | 15-Oct | 0% | 27% | 72% | 1% | 45% | 55% | 1% | 37% | 63% | 1% | 61% | 38% |
| | | | Average | 0.0% | 25.5% | 73.5% | 1.0% | 39.0% | 60.5% | 1.0% | 35.5% | 64.5% | 1.0% | 54.0% | 45.0% |
| | October Total Average | | | 3.0% | 21.5% | 75.5% | 3.5% | 31.0% | 65.8% | 3.0% | 40.3% | 57.3% | 3.3% | 53.8% | 42.5% |
| | 3rd Floor | November | 01-Nov | 7% | 46% | 47% | 6% | 30% | 64% | 9% | 72% | 19% | 7% | 62% | 31% |
| | | | 15-Nov | 6% | 24% | 70% | 7% | 34% | 59% | 6% | 55% | 39% | 8% | 67% | 25% |
| | | | Average | 6.5% | 35.0% | 58.5% | 6.5% | 32.0% | 61.5% | 7.5% | 63.5% | 29.0% | 7.5% | 64.5% | 28.0% |
| | 4th Floor | November | 01-Nov | 2% | 76% | 22% | 1% | 61% | 38% | 3% | 85% | 12% | 2% | 70% | 28% |
| | | | 15-Nov | 1% | 39% | 60% | 2% | 71% | 27% | 1% | 54% | 45% | 3% | 77% | 21% |
| | | | Average | 1.5% | 57.5% | 41.0% | 1.5% | 66.0% | 32.5% | 2.0% | 69.5% | 28.5% | 2.5% | 73.5% | 24.5% |
| | November Total Average | | | 4.0% | 46.3% | 49.8% | 4.0% | 49.0% | 47.0% | 4.8% | 66.5% | 28.8% | 5.0% | 69.0% | 26.3% |
| | Autumn Average | | | 3.3% | 28.9% | 67.6% | 3.5% | 33.7% | 62.8% | 3.4% | 48.9% | 47.7% | 3.9% | 53.8% | 42.3% |
| Annual Average | | | | 3.2% | 26.8% | 70.0% | 3.5% | 31.9% | 64.8% | 3.1% | 45.9% | 51.1% | 3.8% | 49.8% | 46.7% |

**Annual threshold averages** demonstrate the overall impacts of the suggested strategy on the lighting quantities in the library's active spaces. By scanning through the year, there is a smooth rhythm of performances either in the existing building or optimized conditions (table 18).

The general performances in morning hours are averagely maintaining the same coverage percentages around 3.1%-3.2% with or without integration of new strategy. Significant raises on the areas within the 300-750 lux are found with the shading strategy integration. In the existing building, 26.8% of both floors are experiencing optimal illuminance throughout the year. This value is increased to achieve 45.9% on average for the optimized conditions. Accordingly, noteworthy reduction measured in areas with illuminance above the limit of 750 lux.

In parallel, the strategy kept its upward performance in afternoon hours, exactly at 3pm. Similar percentages for the dark areas (<300 lux) are recorded (as the morning averages) with 3.5%-3.8% on average during the year. Additionally, the optimum coverage within the required light quantities is achieving 49.8% on yearly average.

### 4.1.6 Impacts of Automation in Equinoxes and Solstice Thresholds

Without denying the option of automated systems as a solution for the building challenges, it has been studied as a promising alternative which could enhance the building performance in different aspects. These systems are dynamic and responsive to conditions in the space by sensors and monitoring methods.

It has been shifted to second alternative related to the correlated complications such as energy consumption, initial and maintenance costs. It provides the best choices, if the mentioned complications are ignored or adjusted in sustainable and energy efficient ways.

In tables 19 and 20, the shading strategy automation is tested with the existing condition of the building and with the proposed strategy. Extensive improvements in the lighting qualities in both levels can be achieved. Averagely in 21 March, 21 June and 21 September at morning hours, the existing conditions are offering 18~25% of adequate daylight levels within (300~750 lux) threshold in level 3. Meanwhile, about 57% ~66% of level 3's area is predicted to be within the adequate levels of light (300-750 lux) with the fixed shading strategy at 9am in same days, (see table 19). Although, this expands to 74~94% if automation is adopted to the system. Yet, there are noticeable improvements from 16~23% in existing conditions to 57~64% in case of implementing fixed shadings and 93~94% for the integration of the automated system a 3pm on other measured dates (21 March, 21 June and 21 September).

Otherwise, during winter season (exactly on 21 December), fixed strategy is reducing the optimum lighting coverage from 82% to 53% of the floor area at 9am (300-750 lux) but without causing discomfort glare probabilities. Simultaneously in afternoon period at 3pm, the area coverage with adequate lighting is decreased from 83% to 51% on 21 December within the threshold (300~750 lux).

Table 19: Threshold Analysis Table for the Effect of Automated and Fixed Strategies on Level 3 (by Author)

| | | | | Level 3 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Area | | | | 1555 m² | | | | | | | | |
| | | | | 21 June | | | 21 March/September | | | 21 December | | |
| | | | | Current | Optimised | | Current | Optimised | | Current | Optimised | |
| Within Threshold range 300-750 lux | | | | 9am: 18% | 9am: 59%* 3pm: 57%* | | 9am: 25% | 9am: 66%* 3pm: 64%* | | 9am: 82% | 9am: 53%* 3pm: 51%* | |
| | | | | Existing | Fixed Shading | Automated Shading | Existing | Fixed Shading | Automated Shading | Existing | Fixed Shading | Automated Shading |
| 9am Threshold Results | Within threshold | 300~750 lux | % | **18** | **59** | **94** | **25** | **66** | **74** | **82** | **53** | **86** |
| | | | Area ($m^2$) | 280 | 890 | 1468 | 390 | 999 | 1458 | 1275 | 799 | 1335 |
| | Above threshold | >750 lux | % | 76 | 36 | 0 | 69 | 27 | 0 | **4** | **2** | 0 |
| | | | Area ($m^2$) | 1188 | 546 | 0 | 1068 | 416 | 0 | 60 | 31 | 0 |
| | Below threshold | <300 lux | % | 6 | 6 | 6 | 6 | 7 | 6 | **14** | **45** | **14** |
| | | | Area ($m^2$) | 88 | 85 | 88 | 98 | 106 | 98 | 220 | 691 | 220 |
| 3pm Threshold Results | Within threshold | 300~750 lux | % | **16** | **57** | **94** | **23** | **64** | **93** | **83** | **51** | **86** |
| | | | Area ($m^2$) | 243 | 865 | 1448 | 359 | 979 | 1452 | 1298 | 772 | 1338 |
| | Above threshold | >750 lux | % | **78** | **37** | 0 | 70 | 28 | 0 | **3** | **2** | 0 |
| | | | Area ($m^2$) | 1218 | 563 | 0 | 1093 | 425 | 0 | 40 | 26 | 0 |
| | Below threshold | <300 lux | % | 6 | 6 | 6 | 7 | 8 | 7 | 14 | 48 | 14 |
| | | | Area ($m^2$) | 94 | 93 | 94 | 103 | 117 | 103 | 218 | 723 | 218 |

*Optimised by fixed strategies.

Table 20: Threshold Analysis Table for the Effect of Automated and Fixed Strategies on Level 4 (by Author)

| | | | | Level 4 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Area | | | | 904 m² | | | | | | | | |
| | | | | 21 June | | | 21 March/September | | | 21 December | | |
| | | | | Current | Optimised | | Current | Optimised | | Current | Optimised | |
| Within Threshold range 300-750 lux * | | | | 9am: 27% 3pm: 28% | 9am: 54%* 3pm: 52%* | | 9am: 47% 3pm: 44% | 9am: 70%* 3pm: 68%* | | 9am: 92% 3pm: 93% | 9am: 91%* 3pm: 92%* | |
| | | | | Existing | Fixed Shading | Automated Shading | Existing | Fixed Shading | Automated Shading | Existing | Fixed Shading | Automated Shading |
| 9am Threshold Results | Within threshold | 300~750 lux | % | **27** | **54** | **99** | **47** | **70** | **99** | **92** | **91** | **94** |
| | | | Area (m²) | 234 | 471 | 866 | 406 | 606 | 864 | 797 | 794 | 814 |
| | Above threshold | >750 lux | % | **73** | **45** | 0 | **53** | **29** | 0 | 2 | 1 | 0 |
| | | | Area (m²) | 632 | 391 | 0 | 458 | 252 | 0 | 17 | 10 | 0 |
| | Below threshold | <300 lux | % | 1 | 1 | 1 | 1 | 1 | 1 | 6 | 8 | 6 |
| | | | Area (m²) | 4 | 7 | 4 | 6 | 13 | 6 | 56 | 67 | 56 |
| 3pm Threshold Results | Within threshold | 300~750 lux | % | **28** | **52** | **100** | **44** | **68** | **99** | **93** | **92** | **94** |
| | | | Area (m²) | 240 | 452 | 867 | 381 | 588 | 862 | 807 | 799 | 812 |
| | Above threshold | >750 lux | % | **72** | **47** | 0 | **55** | **31** | 0 | 1 | 0 | 0 |
| | | | Area (m²) | 627 | 411 | 0 | 481 | 267 | 0 | 5 | 3 | 0 |
| | Below threshold | <300 lux | % | 0 | 1 | 0 | 1 | 2 | 1 | 7 | 8 | 7 |
| | | | Area (m²) | 3 | 7 | 3 | 8 | 15 | 8 | 58 | 68 | 58 |

*Optimised by fixed strategies.

Contrasting with that, lighting qualities in level 4 are not negatively affected by additions. Some improvements are recorded with extra 23% (70-47%)~27% (54-27%) coverage with optimum luminance among the upper floor with fixed strategy, for example on 21 June at 9am, areas within threshold (300-750 lux) increased from 27% to 54%, see table 20.

The considerable changes with fixed strategy are shown throughout the year except in winter season (21 December). In morning hours at 9am, values within the threshold (300-750 lux) are dramatically increasing from the range of 27~47% to the double and reach 54~70% on (21 March, 21 June and 21 September). Parallelly, values are doubled to achieve 52~68% in late afternoon time at 3pm of the same days. Impressively, the automated system has kept the same optimum performance within 99% coverage on these days as well. During 21 December, daylight coverage within the threshold of 300~750 lux is maintaining the high values within the limits of 91~94% coverage either with or without integrating the shading strategies.

Additionally, there are distinguishable reduction in the areas that covered with illuminance above the threshold (>750 lux). For instance, on 21 March and 21 September, proposed fixed strategies are succeeding to optimise additional 24% of level 4's study areas (from 53% to 29% at 9am and from 55% to 31% at 3pm). Furthermore, on 21 June, the reduction of areas with excessive light is achieving 45% improvement from 73% at 9am, and 47% enhancement from 72% at 3pm with the implementation of fixed shading strategies.

Automated systems highly enhance these records to reach the limits of 94~100% along the selected days of the year. This massive efficiency in automated system is relayed on the absence of areas with above-threshold lighting levels. Realising its purpose, the automated strategy is totally preventing any excessive light above the pre-set threshold (300~750 lux). These values are indicating the efficiency of the lightshelf strategy in providing diffused daylight in the upper floor (level 4).

Table 21: General Coverage Within the Threshold Of 300~750 Lux in Both Floors (Retrieved from the Software Results by Author)

| | Time | 21 June | 21 March<br>21 September | 21 December |
|---|---|---|---|---|
| Existing | 9am | 21% | 33% | 85% |
| | 3pm | 20% | 31% | 87% |
| Optimised* | 9am | 57% | 67% | 67% |
| | 3pm | 55% | 66% | 66% |

*Optimised by fixed strategies.

Generally, as daylighting manner, optimisation showed significant improvements in light qualities and dispersal when fixed strategy is implemented, especially in level 3 of the library where wide areas were suffering from above threshold light amounts. The presented values for both floors, as retrieved from Revit®, in table 21 is showing noticeable average increases with more than 34~36% in areas covered within proper threshold at 9am and 3pm on 21 June, 21 March and 21 September. Even areas in high section within threshold are optimised to be in adequate levels for visual tasks in the library buildings as illustrated in table 11.

On 21 December, the adequate coverage is decreasing from 85~87% to 66~67% of both floors in this day of the year. Thus, there might be a necessity for electrical support by artificial lights at certain points of that day during winter season. Yet as seen in table 20, level 4 has kept the adequate levels of light in the same day without any need for supportive lighting system as providing the satisfying coverage required. Remarkably, the lower floor (level 3) is suffering from decreases amounts of daylight in 21 December with 29% (82-53=29%) at 9am and 31% of the floor area (83-51=32%) at 3pm, see table 19.

Meanwhile, by looking in detail to table 19,20 and 21, the changes between the original condition and the three plans for integration; fixed strategy and automated strategy could be analysed and summarised according to threshold scale as follow:

- ***Within threshold (300-750 lux):*** areas are increased to double percentage achieving around (66~67%) in both levels during spring and fall seasons, particularly on 21 March and 21 September. Although, it is upsurge more improvements in summer period (21 June) by maintaining the same increasing behaviour to (55~57%) when it was much lesser in existing circumstances (20~21%), see table 21.

- ***Above threshold (>750 lux):*** generally, all the increases that obtained by fixed shading strategy within thresholds were disparage from areas above limits of lighting illuminance. For instance, as shown in table 19 (level 3) by the fixed strategy on 21 June at 3pm, the reduction from 78% to 37% (78-37= 41%) in above threshold areas that obtained are totally added to the values of the areas within the threshold (300-750 lux) to achieve 57% with 41% improvement (16+41= 57%). This attitude can be followed in all the measurements of (21

March, 21 June and 21 September) dates in all times with ±1% as correcting value. As previously mentioned in both floors, the integration of automation to the system is totally eliminating the category of above threshold and adjust it within the illuminance limits without affecting the existing below threshold areas. Yet, this appreciated advantage is compromising the visual contact with outdoor space in order to accomplish the optimum exclusion of any excessive daylight.

- ***Below threshold (<300 lux):*** in all the conditions with or without integrations the areas where positioned below the edge lighting required for performing visual tasks in library building. As previously mentioned, the fixed additions are reducing the areas within thresholds on 21 December in level 3. Approximately 18~21% in both levels (85-67= 18% and 87-66= 21%) as seen in table 21 during this day. Mainly, the negative effect is occurred in level 3, while level 4 did not show similar affect by the proposed strategies. Rather than the slight reductions on areas with above threshold (>750 lux) in level 3 by 2% at 9am (4-2= 2%) and 1% at 3pm (3-2=2%) (table 19), the proposed strategies are dimming the spaces in level 3 which is causing losses in areas within the threshold (300-750 lux). The lighting levels in areas within the threshold (300-750 lux) are dropped from 82% to 53% at 9am which is turned to be below the required threshold (<300 lux) with 31% escalation from 14% to 45%. This 31% in addition to 2% obtained from above threshold are added to percentage below threshold (14+31+2= 47% in total), see table 19. This is indicating the need for additional supportive system like automated system or artificial lighting system as mentioned above.

Overall, the automation suggestion is providing results that highly meet the standard illuminance required by LEED, CEN and ASHRAE. The only concern is the visual contact with outdoors which presenting a big challenge facing its performance.

### 4.1.7 Critical View on Visual Comfort Standards in Libraries

Recommendations proceeded by the Passive House Institution has generality scheme where it is applied to modifications according to the building location on Earth. On the other hand, BRE and BREEAM are relying on the classical method of Daylight Factor which is totally reliant on environment conditions and it is not specifying neither light quality nor quantity for specific visual task. Thus, proposed methods by European Standards and LEED are presenting the most suitable assessment criteria.

Under the regular simulation conditions required by LEED the building is passing the evaluations related to daylight quantities in indoor spaces according to its code, see table 22. The existing building is achieving (87.5% - 88.25%) in the tested days and times which qualifying the building to get (1 point) in LEED Rating System. Meanwhile, the optimization is increasing the average coverage to 94% to get (2 points) on the scale.

Table 22: Average Coverage in March and September Related to LEED Rating System (by Author).

| Month | Day | 300-3000 Lux | | Required average by LEED |
|---|---|---|---|---|
| | | Existing Average | Optimised Average | |
| March | 15 Mar<br>21 Mar | 87.5% | 94% | 75%-90% |
| September | 15 Sep<br>21 Sep | 88.25% | 94% | |
| LEED Rating System result | | Satisfying (1 point) | Satisfying (2 point) | |

Nevertheless, by revising the light qualities required by the European Standard, there are high potentials of facing glare discomfort in the spaces as mentioned in glare metric analysis. The selected sample in glare analysis (*see section 4.1.4, fig.60*) is showing that even if the illuminance levels are falling within LEED standards (300-3000 lux), the users can face visual difficulties as glare problems. This explains the shorter-range illuminance average recommended by the European Standards (CEN) of (300-750 lux) which seems it considers the qualities in its metrics.

On the other hand, the European Standards are setting specific illuminance for each visual task on work-surface which is very applicable with consistent source of light (as artificial light). Unlikely, the daylight behavior is totally based on changeability and varieties. This is what makes a lot of difficulties in daylighting controlling and evaluations for specific visual task. Additionally, EU codes are not giving general coverage scale to measure the space performance with changing lighting conditions as the LEED Rating System offers.

Undoubtedly, these codes are focusing on two different approaches toward visual comfort, either light quantities (LEED standards) or light qualities (EU Standards). In the case of spaces with one particular task as libraries, both light qualities and quantities are matter to perform visual task perfectly in the space. Thus, this study is testing a combination of both performance assessment based on both criteria. Firstly, it assures the light qualities and secondly evaluates the space performance and the daylight (changeable) conditions.

As resulted from glare metric evaluations, the proposed strategy is controlling the glare throughout the year. The proposal has two objectives to achieve visual comfort. When the strategy insured glare-levels within the limits for comfortable visual experience in the most critical views in the case study, it is automatically reduced the excessive light that might cause difficulties. To insure the availability of adequate light, the required illuminance is limited to EU Standard (300-750 lux). To evaluate to total space performance, LEED Rating System is offering an evaluation method to assess the annual visual performance in indoor spaces.

Table 23: Space Visual Performance in March and September under EU Standards Illuminance Range Combined with LEED Rating System (by Author).

| Month | Day | 300-750 Lux | | Required average by LEED |
|---|---|---|---|---|
| | | Existing Average | Optimised Average | |
| March | 15 Mar<br>21 Mar | 28.37% | 49.75% | 75%-90% |
| September | 15 Sep<br>21 Sep | 27.25% | 48.37% | |
| European Standard (CEN) | | Not specified in codes | Not specified in codes | |
| LEED Rating System | | Unsatisfying (0 points) | Unsatisfying (0 points) | |

Regardless the limit of threshold implied in this study (300-750 lux) which equals just 16.66% of the required illuminance limits for LEED Rating System (300-3000 lux), the proposed strategy is offering unexpected positive performance. It is achieving 49.75% out of 75% needed with appropriate glare levels but yet it is unsatisfying according to LEED as seen in the table 23. Unfortunately, EU standards has no specification for these ratios.

The way this study looks to the visual comfort standards and the way to retrieve and adapt these codes to evaluate visual performance in spaces with specific visual tasks is represented in *fig.63*.

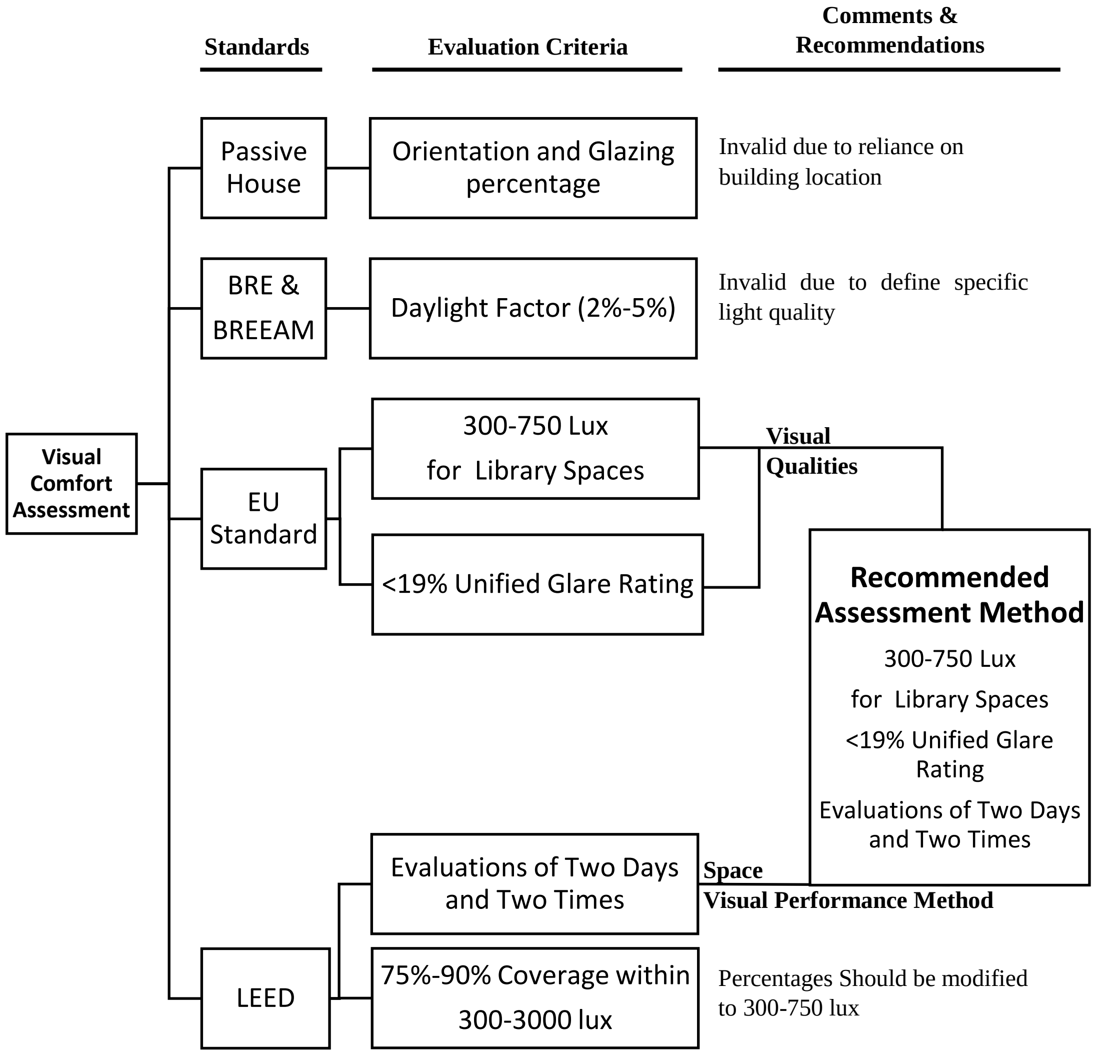



Figure 63: A Critical View to Visual Standards and Study Recommendation (by Author)

# Chapter 5

# CONCLUSION AND RECOMMENDATIONS

Overall, prediction of visual comfort is significantly confounded analogous analysis correlated to other comfort issues. For instance, effective temperature for certain performance can contrived spatially easily by measuring average air temperature and surface's temperature in the space (Webb 2012). Considerable amounts of time and energy can be saved basically by calculating visual metrics and mapping the natural light qualities in the space.

The visual comfort metrics are not incorporated in the design of EMU Main Library, that might be due to design conceptual intentions. All the data collection methods that implemented in this research are evidently clarifying the fact of existence of large areas with insufficient daylighting to perform visual tasks in the library. This fact is creating visual challenges in indoor spaces and increasing the levels of dissatisfaction in user's experiences.

The building is oriented 55$^{o}$ toward the South to give equal levels of daylight to all areas internally, that led to all building elevations be facing either east or west partially. Although, this issue forced to apply same treatments and techniques shown as vertical shading devices and the daylight is not adequately distributed to do visual tasks comfortably. The factors that led the building to be not appropriately passive solar building and not optimizing daylight can be summarised as:

1. The building orientation exposed interiors to excessive daylight. High levels of direct sunlight that enters through building is causing glare effect.
2. Vertical shading devices on vertical windows are not serving appropriate daylight to perform visual tasks properly.
3. Shading devices are not efficient to control glare. Unified size in all direction is highly indicating the ignorance of responses related to sunlight control.
4. Both natural and artificial lighting are used in the library. Although, the areas are located near the openings which are covered in high level of sunlight zones.
5. The dark green carpet flooring is absorbing part of the light. This absorbance role applicable to both sunlight and artificial light too, therefore part of artificial lighting is lost during adaptation of sunlight by interior surfaces. This causes a continuous much higher demand on artificial lighting than needed to cover blind spots of natural light.
6. The seating layout design is unified in everywhere, all directions and all floors. Neither orientation, sunlight luminance nor indirect illumination is considered while furniture setup.
7. The sky light design introduces daylight without controlling system.
8. Glare effect is the main source of visual discomfort especially if users are using electronic devices or they are moving their eyes in a field with high contrast.

By the exemption of thermal effect on users as the indoor space is balanced by mechanical air condition, visual metrics are showing the need for optimisation in a way to provide adequate lighting levels. This optimisation approach dealt with two variables: Fixed shading devices and Automated shading system.

Fixed shading strategy is enhancing the areas within the threshold as it prevents direct solar-irradiation penetration into space, reducing the discomfort glare probability, yet its improvements are not equal to the values occurred by automated system.

Optimally, automated shading devices evaluation showed high improvement in providing balanced light qualities throughout the year and carrying out several concerns. Creating depressive space experiences due to blocked space proportions were taken as an important concern. Since 100% efficiency is requiring the total coverage for the openings, loosing visual contact with outdoor space at certain periods of the day was considered as design limitation. In addition, if other concerns are added into the optimisation equation as initial costs, maintenance and energy consumption, fixed strategy would be more preferred as problem solving method instead of automated systems.

There is a need to improve the daylighting conditions in the library according to evaluations and standard-based assessments. General overview on optimisation results show the building's high potentials to meet some standards recommendations and requirements of certifications related to daylight conditions but conflicted with other standards and codes.

The derived results in chapter 3 and chapter 4 are consisted of methodologies which can be implemented directly into architectural performance analysis as design assessment that helps to evade visual discomfort existence and possibilities.

Additionally, the study showed a way to evaluate visual metrics in academic library spaces based on standard methods combination to meet the levels of satisfaction. The proposed assessment criteria are a combination of the EU Standards which is concerned by the lighting quality and the LEED recommendations that give value to daylight quantities and visual contact to outdoors.

To conclude, insuring long-range visual satisfaction in indoor space can be measured, predicted and mapped spatially as presented in chapter 4. Outcomes of that chapter are mapping the optimised daylight over the studied areas and providing assessment criteria to evaluate the visual performance of library spaces. However, such results can be advantageous for architectural design and re-design cases.

## 5.1 Recommendations

Since many daylight control strategies are examined, it is found that automated shading devices are the best solution to adapt daylight to achieve optimum visual conditions for visual tasks in the library with a limitation of the need to keep visual contact with outdoor environment. This motorized shades could be internal or external devices but the externals are most preferred. This system can be utilised with some compromises in lighting levels as it is designed with a possibility of move and permitting clear vision to outer views. If this design feature is added to sunlight tracker, it will be possible to obtain both benefits of automated system and visual contact with outdoor spaces. Further studies can demonstrate the exact response of the automated strategy with integrated sensors in the spaces. It can be movable to allow partial contact with outdoor spaces. Also, the artificial lighting system can be integrated in this system to provide a holistic system without gaps on efficient coverage.

Likewise, redesigning the skylight system to trail the sun path by considering the library location and the required levels of daylight for optimum visual performance can improve the daylighting quality in the deep spaces.

Additionally, furniture layout can help to reduce the effect of unwanted high reflect screens. It is recommended to place workstations in deep areas far from sources of exposure. While study desks can be rotated parallelly to the sun azimuth. This will allow to prevent the drop shadows on reading surface or facing high illumination sources can be achieved.

Finally, for further studies, it is recommended to extend the research in the way to find the most acceptable coverage percentage with merging both lighting qualities and daylighting quantities that is needed to perform several visual tasks in one space, e.i. academic libraries.

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# APPENDICES

# Appendix A: Questionnaire Survey Sample

**1.Gender:**

a. Male b. Female

**2. Age: (_______)**

## Your use of the Library

Choose your answer by (√)

**3. How often do you come to the Library?**

- o Most days
- o About once or twice a week
- o Several times a month
- o Once a month
- o Several times a year
- o Never

**4. What time you prefer to be at Library?**

- o Morning Hours
- o Noon Hours
- o Afternoon Hours
- o At Night Hours

**6.How's the Natural light in the area that you are in?**

| | Too Dim | Dim | Average | Bright | Too Bright |
|---|---|---|---|---|---|
| 10am-11pm | ○ | ○ | ○ | ○ | ○ |
| 12:30pm-1:30pm | ○ | ○ | ○ | ○ | ○ |
| 3pm-4pm | ○ | ○ | ○ | ○ | ○ |

**7.How strongly do you agree or disagree with the following statements?**

**7.1. Natural Daylight affects your time spent in library.**

| | Strongly Agree | Agree | Neither/Nor | Disagree | Strongly Disagree |
|---|---|---|---|---|---|
| 10am-11pm | ○ | ○ | ○ | ○ | ○ |
| 12:30pm-1:30pm | ○ | ○ | ○ | ○ | ○ |
| 3pm-4pm | ○ | ○ | ○ | ○ | ○ |

**7.2. Design of seating arrangement of the library in relation to Daylight.**

| | Strongly Agree | Agree | Neither/Nor | Disagree | Strongly Disagree |
|---|---|---|---|---|---|
| 10am-11pm | ○ | ○ | ○ | ○ | ○ |
| 12:30pm-1:30pm | ○ | ○ | ○ | ○ | ○ |
| 3pm-4pm | ○ | ○ | ○ | ○ | ○ |

**7.3. Levels of Natural Daylight influence your selection of seating location.**

| | Strongly Agree | Agree | Neither/Nor | Disagree | Strongly Disagree |
|---|---|---|---|---|---|
| 10am-11pm | ○ | ○ | ○ | ○ | ○ |
| 12:30pm-1:30pm | ○ | ○ | ○ | ○ | ○ |
| 3pm-4pm | ○ | ○ | ○ | ○ | ○ |

**8. Is Natural Lighting level available and enough in library?**

- Only Morning time
- Only Noon time
- Only Afternoon time
- All the time

**9. Where do you prefer to sit related to the windows during the day?**

| | Very far | Far | Average | Near | Very Near |
|---|---|---|---|---|---|
| 10am-11pm | ○ | ○ | ○ | ○ | ○ |
| 12:30pm-1:30pm | ○ | ○ | ○ | ○ | ○ |
| 3pm-4pm | ○ | ○ | ○ | ○ | ○ |

**10. Does using internal blinds protect you from over brightness?**

**A. Yes** **B. No**

**11. Do you feel comfort by sitting near the windows?**

**A. Yes** **B. No**

**12. Do you feel visually comfortable with interior finishes (flooring, walls, colours, ceiling,..)?**

**A. Yes** **B. No**

**THANK YOU FOR YOUR TIME**

# Appendix B: Draft Calculations for Finding Fixed Shading Strategy

The appendix contains a series of equations were useful in calculating analysis in this research during finding suitable strategy stages.