THE INFLUENCE OF A NEW LAYOUT ARRANGEMENT AND A LIGHT SHELF-REFLECTIVE LOUVER SYSTEM ON SATISFYING VISUAL CONDITIONS IN ACADEMIC LIBRARY READING ROOMS

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ABSTRACT

THE INFLUENCE OF A NEW LAYOUT ARRANGEMENT AND A LIGHT SHELF-REFLECTIVE LOUVER SYSTEM ON SATISFYING VISUAL CONDITIONS IN ACADEMIC LIBRARY READING ROOMS

Higly glazed facades has been increasing with the intention of more daylight gain in buildings. However, more daylight may not always bring more satisfaction considering many factors that influence daylighting quality. Uncontrolled daylight brings visual and thermal problems which end up with negative interactions with user comfort. Library spaces in which different task activities are performed simultaneously need to be well designed in terms of daylight performance, thus the user satisfaction could enhance.

This thesis particularly focuses on the optimization of visual performance in an academic library with a new layout arrangement and a light shelf-reflective louver system. One of the reading rooms of Izmir Institute of Technology Library was chosen as a reference case, where the instrumental monitoring of existing daylighting conditions was performed. The reference case was then analyzed with daylight simulation tool, so that the outcomes would later be used for the performance testing of the new proposals. Luminance patterns and illuminance distribution of different points were evaluated in terms of visual performance recommendations. A new layout arrangement and light shelf-reflective louver system were proposed respectively in accordance with the deficiencies of simulation results. Ultimately, daylight performance of the library was significantly improved regarding illuminance and luminance based distribution.

Despite a diminution in average illuminance due to the dramatic decrease of excessive amount of daylight near the window, the big picture gives the clues on how a simple layout change and a daylighting system can make enhancement on the visual performance of a library reading room.

ÖZET

AKADEMİK KÜTÜPHANE OKUMA SALONLARINDA YENİ YERLEŞİM DÜZENİ VE IŞIK RAFI-AYNALI JALUZİ SİSTEMİNİN GÖRSEL KOŞULLARIN SAĞLANMASINA OLAN ETKİSİ

Bina iç mekanlarına daha fazla miktarda günışığı kazanımı amacıyla, geniş cam yüzeylere sahip binaların sayısı artış göstermektedir. Bununla birlikte; artan günışığı miktarının daha fazla memnuniyet getirdiği yönünde bir ifade tam anlamıyla doğru olmamaktadır. Kontrolsüz günışığı, görsel ve termal problemlere yol açarak kullanıcı konforu ile arasında olumsuz etkileşimler göstererek sonuçlanmaktadır. Çeşitli faaliyetlerin aynı anda icra edildiği kütüphane binaları, günışığı performansı yönünden uygun tasarlanmalıdır ki bu sayede kullanıcı memnuniyeti yükseltilebilir.

Bu çalışma, yeni yerleşim düzeni ve ışık rafı-aynalı jaluzi sistemi yardımıyla bir akademik kütüphanenin görsel performans koşullarının iyileştirilmesine odaklanmaktadır. Örnek mekan olarak İzmir Yüksek Teknoloji Enstitüsü Kütüphanesi'nin okuma salonlarından biri seçilip mevcut doğal aydınlatma koşulları aydınlık ve parıltı ölçer cihazlar yardımıyla ölçülmüştür. Yeni getirilecek önerilerin performans testinde kullanılmak üzere, söz konusu mekan daha sonra günışığı simülasyon aracı kullanılarak analiz edilmiştir. Oturma planındaki farklı noktaların parıltı ve aydınlık değeri dağılımı, görsel performans bazlı öneriler dikkate alınarak değerlendirilmiştir. Mevcut modeldeki günışığı performans değerlendirmesi sonuçlarındaki eksiklikler göz önünde bulundurularak, sırasıyla yeni bir oturma düzeni ve ışık rafı-aynalı jaluzi sistemi önerileri getirilerek iyileştirme amaçlanmıştır. Sonuç olarak; aydınlık değeri, parıltı dağılımı ve üniformite yönünden kütüphane günışığı performansı önemli oranda iyileştirilmiştir.

Pencereye yakın bölümlerdeki aşırı miktardaki günışığının belirgin düşüşü sebebiyle mekandaki ortalama aydınlık seviyesinde bir azalış gözlenmesine rağmen, resmin tamamına bakıldığında, basit bir yerleşim düzeni değişimi ve doğal aydınlatma sistemi tasarımı ile bir kütüphane okuma salonunun görsel performans koşullarında nasıl iyileştirme yapılabileceğine dair ipuçları elde edilmektedir.

To My Grandmother

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CHAPTER 1

INTRODUCTION

1.1. Problem Definition

The use of daylight is mostly linked related with energy-efficient design, as it is the strongest way of decreasing electricity consumption for lighting (Boyce, Hunter and Howlett, 2003). Yet, it is significant to understand that daylighting is a pack of strategies which also has interactions with user comfort, work productivity, well-being and human health (Reinhart and Selkowitz, 2006; Konis, 2013). Previous studies have shown that sufficiency of daylight is a necessity for indoor spaces as it has positive effects on physiological and psychological functioning and to approve the strong relationship between daylight and human circadian rhythms is unevitable (Duffy, 2009; Smolders, 2013). So, the number of highly glazed facades has been increased in the last decades with the intention of more daylight gain.

However, it is not completely proper to claim that more daylight brings more satisfaction as there are many factors such as illuminance uniformity, luminance distribution, glare and color characteristics influencing daylighting quality (Veitch and Newsham, 1998; IEA, 2010). A good daylighting design needs to be a composition of both penetrated diffuse skylight and blocked direct sunlight in order to prevent problems such as visual discomfort and increased solar gains (Keskin, Chen and Fotios, 2015). Consequently, to find the balance between illuminance and luminance based ratios makes daylight design process challenging when the human comfort matters.

Daylighting systems are known as one of the solutions to block the excessive illuminance that causes visual and thermal problems and also supply daylight to deep spaces. Based upon the history of ancient times, these systems have been developed and applied excessively particularly in recent years by means of their capability of energy saving, thermal balance, and visual performance utilities. These systems vary from internal to external, horizontal to vertical, fixed to moveable, manual to automatic, tinted or coated (Osterhaus, 2009). It is highly possible that as technology becomes more advanced, more capabilities are going to be derived.

Along with the increased number of highly glazed facades, the application of daylighting systems has been correspondingly increased. The majority of case studies have been conducted by various researchers to underline the significance of these systems in buildings, in particular in office spaces regarding visual assessment criterias and lighting energy savings. For instance, Kontadakis et al. (2017) used moveable mirrors fixed on a lightshelf that are able to track the sun. A deep office room with a south orientation was chosen as a reference case and the amount of obtained illuminance value increased during both 152% summer and 12.5% winter solstices comparing to the base case. Dogan and Stec (2016) developed a 1:1 mock-up for a south facing office space based on a horizontal light shelf with a row of mirror tiles that can be tilted in two-axis according to sun movement. Following the simulation analyses of different facade setups, climates and orientations, up to 20% of Continuous Daylight Autonomy was observed. Further study taking place in an office was conducted by Hoffmann et al. (2015). Five different complex fenestration systems were compared with the reference case and the results showed that one suggestion might show no glare at all, while the other one causes 74% glare problem. Meresi (2016) carried out a study in a typical Greek classroom in Athens. Different angle and reflectance approaches of light shelves and semi-transparent exterior blinds were applied to a south oriented classroom model which was generated in Radiance. According to the evaluation of scenario results, the most efficient approach both improved daylight distribution and decreased glare. Kazanasmaz et al. (2016) compared three different approaches in order to obtain optimum sDA results in a south-facing classroom in Switzerland. In accordance with the combinations of different WWF and FWR ratios, it was concluded that it was possible with the micro-prism films to reflect daylight even three times far than the height of the case window in the best approach.

Concerning the above studies, hardly any studies were carried out in library spaces in terms of improving visual conditions. As a matter of fact, present-day libraries in which all reading, writing, and computer task activities are performed at the same time, need to be paid much more attention for the assessment of visual conditions. Libraries are the spaces where people fulfill both their learning and working activities; therefore, visual performance ought to be considered initially. These kinds of spaces have to be responsible for occupants to execute their work efficiently with no deficiency in visual acuity or comfort considering the whole aspects of performance issues associated with lighting (Pniewska and Brotas, 2013). Required illuminance values are needed to be satisfied; brightness/contrast relationship is to be well controlled with luminance ratios which are determined by illuminance and reflectance of surroundings in the visual field. Eyes can adapt to varying luminances rapidly in a properly designed visual environment; their tiredness can decrease as well. Particularly academic libraries, where students intensely visit and spend their time, need to be paid much more attention than ordinary libraries regarding user comfort conditions.

In this study, therefore, a two-step method including a new layout arrangement and an application of a daylighting system is proposed to improve the visual conditions of an academic library reading room based on the field and simulation measurements. The first step of the improvement is to consider whether layout change can make an improvement on the visual performance assessment of occupants. There is a lack of knowledge and thus, a little doubt that it can. Following this, the second step is to develop and examine the effectiveness of a light shelf-reflective louver system upon the new layout arrangement. Despite the performance testing of daylighting systems in mostly office and school buildings, there has not been a real evidence in reviewed and analyzed literature for the performance testing of these systems in libraries. Hence, this study offers two new guidelines for enhancing the visual conditions of academic libraries as a first attempt, and then may generate a framework to be followed for academic library reading rooms to convert the spaces into a comfortable studying environment, minimizing the undesirable effects of natural light filtered through windows and maximizing the quality of daylight within the view of field of occupants.

1.2. Objective of the Study

This study focuses on the evaluation of the visual performance conditions in terms of illuminance and luminance distributions in an academic library. It is hoped that the outcomes will be useful in further layout-based studies and daylighting strategy of library spaces so that this study can make contribution to development of faster approaches for applying the accurate layout arrangement and daylighting system. The objectives of this study are as follows:

(i) To assess visual conditions in an academic library in terms of illuminance distribution and luminance-based ratios in the occupational visual field.

(ii) From the findings of the computer analysis, which are primarily validated with the on-site measurements, to identify the most problematic seatings with respect to visual performance assessment.

(iii) To propose a new layout arrangement regarding the recommendations in literature.

(iv) To optimize the daylight distribution by a combination of light shelf-reflective louver system since a glazing alone can not distribute daylight efficiently.

1.3. General Method and Outline

This section identifies briefly the overall outline and method of the thesis. This thesis is comprised of five chapters, of which the first one is ‘Introduction’. In this chapter, importance of daylight quality in educational buildings in terms of visual performance is reviewed and the necessity of proposing a daylighting system for the utilization of daylight distribution is mentioned.

In the second chapter, related literature about the general aspects of daylighting, parameters influencing daylighting performance in buildings, improving daylighting quality in buildings, and daylighting in libraries are investigated, respectively. The literature review seeks to identify the determinants influencing visual conditions in libraries.

In the third chapter, firstly, the case room is introduced and the existing layout arrangement and material attributes of surfaces are clarified. Then, the field experiments are defined to validate the simulation results conducted in Relux. Following the validation of simulation results, the same model is run on equinox and solstice days to determine the visual performance conditions of the library. According to the results, a new layout arrangement and a daylighting strategy are proposed to the existing model in order to utilize the performance of library users.

In the fourth chapter, the results and discussions of the study are explained. Visual performance conditions of the base case and the proposed case are evaluated and compared in terms of illuminance and luminance distribution and uniformity ratios.

In the last chapter, the conclusions are derived from the analysis results, the thesis is summarized briefly, and the future research directions are suggested.

CHAPTER 2

REVIEW OF THE RELATED LITERATURE

The first part of the literature review presents a number of relevant studies that document the influences of daylighting on human being under four major subsections; visual, psychological, environmental, and economical perspectives, respectively. Part 2.2 provides the parameters influencing daylighting performance in buildings e.g. climate, geographical location, orientation and form of the building, outer obstructions, and windows. Part 2.3 discusses a number of methods to improve daylighting quality in buildings with a particular emphasis on daylighting systems. Finally, Part 2.4 documents the literature review regarding daylighting in libraries. The intention with this chapter is to find an answer to the research question based upon the knowledge in earlier studies regarding daylight metrics and occupant preferences in libraries.

2.1. Why Daylighting Matters?

The significance of daylight in the character of a building and in the lives of the people who use it is difficult to ignore. Daylight has always contributed to architecture for both defining the architectural space of a building and creating a spatial atmosphere, as well as providing the needs of occupants with its role in visual comfort and internal climate and its positive contribution on human psychology and physiology. It is important to bear in mind that integrating daylight into the buildings includes energy and money saving resulting from minimizing the energy from lighting and heating. On the other hand, disadvantages of daylight generally occur as a result of the direct sun penetrating into interior spaces as it can cause discomfort, increase interior heat gain, and hence causes excessive energy demands (Laura, 2015). However, it is important for architects to understand that flaws in daylighting strategies could lead to disadvantages as they could hinder vision, cause discomfort, increase interior heat gain, and result in excessive energy demands (Dahlan et al., 2009). Therefore, in Sections 2.2, 2.3, 2.4, 2.5 below, aspects of daylight will be reviewed in the context of four different main parts: visual, psychological, environmental, and economical.

2.1.1. Visual Aspects

2.1.1.1. Visual Comfort

Visual comfort is a term represented by the scale of glare dependent on occupant perception in an indoor environment (Velds, 2000). Therefore, it includes various visual and environmental factors such as colour, brightness, contrast, view size, view quality, direction of light source, light uniformity, as well as thermal visual comfort conditions (Vicent, 2012). Glare is caused by excessive luminance differences or high luminances within the field of view (IESNA, 1993). In general, glare caused by daylight is categorized into three groups: disability glare, discomfort glare, glare reflections (Wienold, 2010).

Disability Glare

Disability glare is defined by the CIE (2002) as glare which reduces visibility. It produces a scattering of light within the human eye and reduces visual contrast in such a way that seeing is impaired (Moore, 1991). Disability glare occurs when a very bright light source is seen in the visual field, e.g. by the sun or specular reflections of the sun in office spaces (Wienold, 2010).

Discomfort Glare

Discomfort glare is a type of visual discomfort caused by the presence of bright light sources, luminaries, windows or other bright surfaces (CIE, 1987; Boyce, 2003; IEA, 2010). It is not determined as necessarily an impairing effect as disability glare, but defined as an irritating or distracting effect (CIE, 2002; Wienold, 2010). Discomfort glare is considered as the main concern in indoor lighting since it is perceived under less bright conditions than disability glare. Therefore, providing a discomfort glare-free indoor environment naturally indicates a disability glare-free indoor environment. There are various established systems for the determination of the magnitude of discomfort glare, e.g. Unified Glare Rating (UGR), British Glare Index (BGI), CIE Glare Index (CGI), Daylight Glare Probability (DGP), Visual Comfort Probability (VCP). However, the physiological or perceptual mechanism for discomfort glare has not been established yet (Boyce, 2003). Thus, the most appropriate way to evaluate is subjective measures such as questionnaires.

Glare Reflections

Glare (veiling) reflections are described as the specular reflections which appear on the object viewed and reduce the contrast on the visual task (CIE, 1987). The determinants that cause glare reflections may be the specularity of the surface and the geometry between the surface, observer and sources of high luminance, such as bright walls, windows, luminaires. Particularly, office spaces are subject to veiling reflections due to having higher amount of glass surfaces, computer screens, glossy papers (IEA, 2010). In order to avoid significant contrast reductions by daylight, the position of the visual display units (VDU) and luminaires should be paid special attention (Wienold, 2010).

2.1.1.2. Visual Performance

Visual performance is defined as the (quantitative) evaluation of performing a visual task in consideration of speed and accuracy (CIE, 1987). The evaluation criteria for visual performance is the task performance of the user which is mainly based on the actual horizontal illuminance of the task. Light level distribution within the observer’s field of view plays an important role as well. Velds (2000) groups the determinants of visual performance under three heading which are (i) task illuminance, (ii) luminance ratios within the observer’s field of view, and (iii) uniformity at a workplane.

Task illuminance

A minimum illuminance level for specific tasks should be assigned to provide lighting conditions for those tasks to perform with normal speed and accuracy. Therefore, recommended illuminance on a task plane is determined by different standards and codes such as The Illuminance Selection Procedure (IESNA, 1987; IESNA 1983), the Lighting Schedule (CIBSE, 1994), and the Illuminance Selection Procedure of the European Committee for Standardisation (CEN, 1998). These standards generally recommend a minimum horizontal work surface illuminance of approximately 500 lux for reading and writing tasks, 300 lux for computer and VDU tasks (Velds, 2000). However, the literature does not unanimously subscribe to these standards.

Begemann et al. conducted two studies related to occupants' preferred illuminance values. (1994, 1995). They have found that the recommended illuminance might not be preferred by the users of the room. The findings of the research displayed high preferred illuminance values with an average of 1900 lux for both horizontal tasks and VDU tasks. Similarly, another work of Begemann et al. (1997) showed that subjects preferred minimum acceptable illuminance levels with an average of 900 lux under daylighting conditions. In a study carried out by Roche (2002) in UK, it was found that the daylight illuminance in the range 700-1800 lux was acceptable for both paper and computer tasks. These findings were confirmed by a extensive study of Veitch and Newsham (1996), which included a literature survey on determinants of lighting quality. The results indicated that illuminance is considered important for visual performance only when the levels are extremely low; and it does not considerably affect the task performance over a wide range of illuminance and types of task.

Conversely, some researchers argue that the general tendency of increased satisfaction with higher illuminance is not entirely true. For instance, a field study conducted by the Institute for Research Construction (Canada) indicated that illuminances more than, or equal to, 150 lux were categorized as 'appreciable daylight' (Reinhart, 2002).

A parallel study was conducted by Schuler in the workspaces of a company that were equipped with computers. In contrast to the standard recommended light levels (300-500 lux), the employees stated that they felt comfortable with a light level of around 100 lux (Schuler, 1995). Moreover, it has been noted that occupants tend to tolerate much lower illuminance than artificial light, especially decreasing daylight conditions at the end of the day, such as reading at illuminance values as low as 50 lux (Baker, 2000).

Based on the above and other sources, it should be noted that there is still noticeable uncertainty in terms of preferred or tolerated limits. Besides the quantitative ways for measuring visual performance, the fact that the perceptual aspect of light brings plenty of controversial arguments in literature about how visual performance can be evaluated ideally. General views rely on the idea that increasing illuminance improves visual performance, on the contrary, there are also various studies that providing abundant daylight into a building is not a solid answer. Confirming this argument, Osterhaus (1993) speculates that high illuminance values can not be considered as a solution for lighting design problems and the fact that the focal point on measuring visual performance has been shifted from illuminance to luminance and qualitative aspects. Rea and Ouellette (1991) also confirms this idea by stating that due to the qualitative aspects of the evaluation, it remains quite difficult to maintain a solid quantitative evaluation of rational targets in the sense of visual performance. Therefore, standards and codes still play a significant role for the determination of visual performance, to be used as a basis for lighting design applications.

Luminance Ratios within the Observer's Field of View

As mentioned above, task illuminance is not the only determinant of the evaluation of visual performance. Luminance is defined as the amount of light reflected from a surface in candela/m^2 and according to a study conducted by Luckiesh (1944), luminance ratios within the center of the visual field might play a significant role as well. General arguments rely on the assumption that visual performance is improved with increasing contrast, which is the difference in luminance between the object being looked and its immediate surroundings. On the other hand, the luminance ratio between the visual field and the remainder of the field should not be too high to prevent discomfort of large changes in eye adaptation levels. Contrast is preferred in the object of view but it is unpreferable in the wider surrounding field of view (Stein, Reynolds, and McGuinness, 1992; Alrubaih et al., 2013). Large luminance contrasts also diminish the contrast of the image and thus reduce visibility and performance (Hannaford, 2002). As the eyes move from one grade of luminance to another grade, the adaptation is required. Hence, people feel uncomfortable when significant differences in luminance occur.

In general, to prevent the influences of temporal adaptation and disability glare, the luminance ratios between specific areas should not exceed the following (IESNA Lighting Handbook, 2000):

• between paper task and adjacent VDT (Video Display Terminal)	3:1 or 1:3
• between task and adjacent surroundings	3:1 or 1:3
• between task and remote surroundings	10:1 or 1:10
• between luminaires, windows or skylights and adjacent surfaces	40:1

Uniformity at a workplane

Uniformity is accepted as a quality measure for illuminance ratios on the horizontal plane. It refers to the amount of illuminance on the task and its immediate surroundings. Generally a certain number of task areas on the working plane are defined for determining this feature instead of the whole working space. The illuminance uniformity is described as the ratio of the minimum illuminance to the average illuminance of a certain surface, and can be acceptable or less acceptable subject to the type of the space and the activity. An entirely uniform space is mostly not preferred while too non-uniform space may result in discomfort and distraction (IEA, 2010). Various standards and codes (EN12464-1, 2002; CIBSE, 1997, IESNA, 2000) give recommended uniformity ratios between the task area and its immediate surroundings. In general, it is recommended that the illuminance uniformity ratio on the working plane should be around 0.8. However, there are no certain guidelines in the determination of uniformity ratio for different type of spaces and activities, which is supported by various studies in literature. For instance, in a research of Boyce and Cuttle (1994), focused on the uniformity of desk, a minimum to maximum illuminance ratio of 0.7 or 0.5 was desirable if the task was performed at the central area of the desk (Boyce and Cuttle, 1994; Velds, 2000). Other related research includes a study by Chou et al. (2004), who analyzed a single-sided, daylight-illuminated classroom and the recommended uniformity illuminance conditions were found in the range 0.30-0.37.

2.1.2. Biological, Psychological, Productivity Aspects

During the last few centuries, specifically in most western countries, spending time in indoor spaces because of social, economic and cultural reasons has caused a radical change in human activities; in a sense, resulted as a labored time dictated by i.e. timetable, clock, and compulsorily disclaimed the paces of our body’s impulses and demands which are basically related with the non-visual effects of daylight (Van den Beld, 2001; Altomonte, 2008). The fact that an average adult spends only 2,4-2,6 h outdoor per day in northern latitudes has led to pay more attention on the use of daylight in enclosed spaces (Cole et al., 1995; Hebert et al., 1998; Crowley et al., 2015). As a result of this, a number of research has been conducted in the field of the effects of daylight on human activity exclusively after the late 1990s, when it was understood that lighting recommendations were not only for visibility, but also for a wider description of lighting quality including human needs (Veitch, 1998).

The lighting of a space does not only have influences on visual functions, but also on biological and perceptual systems (Christoffersen, 2015). Therefore, in this review, impacts of light on human being will be considered in the context of *biological*, *psychological* and also *productivity* aspects, one of the most influential variables of which is lighting.

2.1.2.1. Biological Effects of Light

A number of scientific research has proven the health-related biological outcomes of daytime light specifically when the existence of a novel photoreceptor was discovered by Berson et al. in 2002 (Berson et al., 2002). This recently-detected photoreceptor, which is called intrinsically photosensitive retinal ganglion cells (ipRGCs), distinctly supports circadian rhythms compared with two other existing photoreceptors which are directly contributing to visual system (Khademagha et al., 2015). According to this approach, light falling on retina is sent to hypothalamus via the novel photoreceptor cells and an independent nerve system. Herein, biological clock receives the light and regulates the circadian (daily) and circannual (seasonal) rhythms of a wide range of bodily functions (van Bommel, 2006). The impacts of light on circadian rhythms in human being are analyzed based on physiological variables, e.g. core body temperature, sleep/wake rhythm, hormone secretions, heart rate, alertness and so on (Light, Sight, and Photobiology, 1998; Edwards and Torcellini, 2002). A few variables of typical circadian rhythms (i.e. cortisol, melatonin, body temperature and alertness) that are regulated by light/dark cycle are shown in Figure 2.1. With a regular 24h light/dark cycle, the process of these daily rhythms runs well, however, in a circumstance in which desynchronisation occurs in regulating the secretion of hormones, i.e. cortisol and melatonin, it results with disorders in the rhythm of alertness and sleepiness. For instance, the same indications, because of the same reasons, are also relevant for people who experience jet lag or shift-work (Boulos et al., 1995; van Bommel, 2006).

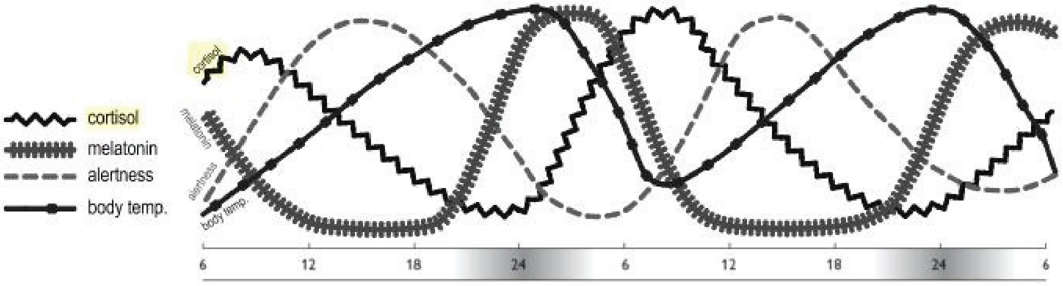


Figure 2.1. A few variables of circadian rhythms.
(Source: van Bommel, 2006)

The biological outcomes of light are a quite new field of research due to the recent discovery of the third novel photoreceptor. In such a manner that a regular human spends only ~2h outdoor per day, biological effects of daylight remain highly vital as daylight is the best source of light with its unique color rendering (Li, 2010). A wealth of research is still needed to contribute to a more coherent and clearer definition of how non-visual effects of light can be used in lighting practice (IEA, 2010). When this happens, research will ease to develop a better understanding of the effects of daylighting on visual performance and to explore more human-centric approaches in daylight design.

2.1.2.2. Psychological Effects of Light

Psychological effects of light on human behaviour have not been the main concern in lighting applications in buildings so far (Webb, 2006). However, the newly emerging fact that people spend between 80% and 90% of their time indoors has led to new studies on the psychological aspects of light and in which ways and how they affect human behavior (Klepeis et al., 2001; Schweizer et al., 2007). For now, it appears safe to say that changing light conditions affect overall feeling of well-being, which is also called as perceptual system in some sources.

In respect of the assessment of light conditions, there is no doubt that artificial light could be as beneficial as natural light in determining visual performance. However, unique features such as excellent luminous and color variations give daylight a higher chance than most types of artificial lighting to perform an effective stimulation for the human perceptual system. These variations make several impacts on human perception; for example, manipulating the senses of happiness, attractiveness, concentration, motivation and so on (Altomonte, 2008). Along with the benefits in well-being, an efficient daylighting has also verified advantages on lower error, absenteeism and accident rates, higher speed, better safety etc. during performing a task, which in turn are expected to result with enhanced productivity (van Bommel, 2006). In literature, several references to the correlation between lighting and productivity are found. However, the fact that lighting is not the only variable that affects human performance makes the evaluation of productivity a more complex process (Juslén, 2007). Therefore, only the effects of lighting factor on productivity change are going to be demonstrated in the following subsection.

2.1.2.3. Lighting and Productivity

The definition of productivity is explained as the ratio of output to input, which can be measured in various ways depending on the context and content of the input and output (Oseland & Bartlett, 1999; Al Horr et al., 2016). Little is known about the exact measurement method to describe productivity; in some cases it can be subjectively evaluated by asking about the influences of work environment (Vischer, 1996), and sometimes measured in a more objective way by asking about the lost percentage of time (Raw, 1990; Learnan, 1994; Bergs, 2002). Besides, a wide range of influential factors such as thermal comfort, lighting, air quality, ventilation, noise, acoustics, view and layout make this process more difficult to evaluate and still there is a lack of knowledge about the level of impact and the interconnection of these individual factors (Clements-Croome, 2006).

In a broad sense, the reasons behind the productivity change have not been clearly established yet; could be visual, biological, psychological reasons, or syntheses of different reasons. It should come as no surprise that the potential productivity increase may emerge through something else than the lighting change since it seems quite difficult to control all changing factors (Juslén, 2007). Nonetheless, the importance of lighting change on the productivity of an individual or an organization has been addressed in various studies. The main idea in case of a healthy luminous environment is that lighting should be designed to meet visual, biological and psychological needs so that human performance and productivity may be enhanced through better physiological and psychological conditions (Gligor, 2004; IEA, 2010). Therefore, this section highlights the significance of the impacts of the lighting-related variables on a higher productivity rate.

Based on the conclusions drawn from the literature, initially, the understanding of which type of lighting positively influences productivity is strong. Different studies have stressed the importance of having preferable type of light source, window, and view as predictor variables of productivity in mostly office and educational buildings. A study by Cuttle (1983) investigated the preferences of office workers in terms of importance of windows and lighting sources. The results indicate that 86% preferred natural light than artificial lighting and almost 99% felt satisfied in offices with windows. Pniewska and Brotas (2013) examined the lighting design of a school library and its influence on occupants' productivity. Lighting was considered 'the most important' by 42% and 'important' by 22% of the voters, which was also found to have the greatest impact on perceived productivity. In case of work performance, daylighting (35%) was preferred than artificial lighting (33%) with a slight distinction. Another interesting research regarding the influence of having window in an office environment was performed by Figueiro et al. (2002), who examined all the workers under the condition of identical work functions, but in different types of office, as 'windowed' and 'windowless'. It was observed that employees in the windowless offices spent more time talking to others and less time working on their computer in comparison to the employees in the windowed offices. A more detailed study in organization scale was conducted by Pape (1998) in terms of productivity change of a company called VeriFone. After the company moved to a new well-daylit building, productivity at Verifone boosted more than 5% and amount of total product increased between 25% and 28%. Similarly, employees of West Bend Mutual Insurance constructed a new building which was designed in order that workers would be close to window perimeter, and also enabled them to have personal task lighting and temperature control over their workstations. Comparing before and after the change, the number of workers having a workstation with a window increased from 30% to %96 (Heerwagen et al., 1998) and this resulted with a 16% enhancement in productivity (Romm & Browning, 1994; Edwards & Torcellini, 2002).

The assumption for the correlation between daylight and productivity is based on a idea that a well-daylit space is an essential contributor to human being with its positive impacts on senses and concentration, and consequently improves learning and productivity rates by providing a less stressful, more comfortable zone (CIBSE Lighting Guide 5, 2011). However, according to some sources, the assertion that more illumination brings more productivity is not entirely accurate. The main contradiction in the assessment of correlation between productivity and daylighting is that the overall performance of persons depend on so many variables as long as the lighting conditions are not completely uncomfortable (Boyce, Hunter and Howlett, 2003). Furthermore, one might reason in this contradiction is the statement on beliefs and preferences of individuals (Veitch et al., 1993) which is explained in a way that who believe bright light is better for productivity will go for bright light, and who consider there is no association between bright light and productivity will not be influenced by different types of lighting exposure. An example supporting this theory is that a study conducted in an office environment observed 9% increase in the performance of office workers after an increase in illuminance from 500 lux to 1500 lux (Hughes and Mc Nelis, 1978), whereas another study by Baron et al. (1992) indicated that lower illuminance levels (500 lux) were likely to provide a boost to performance of complex word order task in comparison to higher illuminance levels (1500 lux). Also Gifford et al. (1993) performed a meta-analysis of the literature findings on the impacts of illuminance on intellectual task performance and they did not find a significant effect on the performance improvement by means of illuminance increase.

As can be seen above, defining the impact of lighting on productivity is still ambiguous. Based on the lack of knowledge on which kind of variables influence productivity more and which aspect of light (e.g. illuminance, veiling reflections, direction, spectral qualities, or luminance distribution) is identified as the most important that people would like to control (Veitch et al., 1993), previous research are found to be relatively conflicting to each other. The problem in finding the accurate estimation to address the impact of lighting on productivity is that the each occupant has different types of beliefs and habits, which in turn results with unclear assessment of lighting and productivity correlation.

However, in the long run, it is certain that previous findings in literature will provide insight for more and better specified future research which may close the gap between lighting and productivity and also be used as a daylight design guidance for future works.

2.1.3. Energy and Economy Related Aspects

What is undoubtful about economical benefits of an efficient daylighting is that it stands far beyond the reduced electricity cost from artificial lighting, while taking into account the immense impact of natural daylight on overall energy use of buildings (Bernardi and Bauer, 2013). To choose the incorrect amount of daylight intakes (e.g. extensive or restricted) in the early stages of design may cause extra financial cost since it has consequences on not only electrical energy load, but also on heating and cooling loads (Boyce, Hunter, and Howlett, 2003). Early studies and reports unanimously agree on this statement. According to Swiss Federal Office of Energy (2009), building sector corresponds to over 50% of total energy consumption in industrialized countries whereas lighting accounts for almost 22% alone. This rate rises for a typical US commercial building, which approximately stands for a percentage of around 25-40% of the overall electrical energy use (Krarti, 2000); moreover, extends over half of a building's energy use with the impact on heating and cooling loads (Ihm et al., 2009). A scientific report, published by International Energy Agency (IEA), announced that electricity energy consumption has excessively risen with a ratio of 161,8% between 1973 and 2004 (IEA, 2006), and is predicted to rise by 53% until 2030 (IEA, 2007; Shaikh et al., 2016). With this in mind, it is worth noting that daylighting alone is able to reduce 25-30% of total energy consumption (Köster, 2013; Gago et al., 2015), which should be accepted as one of the cost and energy efficient solutions if properly designed. However, the relationship between daylighting and the total building energy use is hardly paid attention, which is very likely because of avoiding expenses at the early stages of design, and also not straightforwardly considering the potential benefits of an efficient daylighting design over the life of a building (Guglielmetti et al., 2010).

2.2. Parameters Influencing Daylighting Performance in Buildings

The performance of daylighting strategies is based on the availability of luminance distribution from sun, sky, and buildings. These strategies mostly depend on the presence of natural daylight, which is regulated by latitude of the building and the external conditions enclosing the building, such as the obstructions or reflections in the building's immediate surrounding. In addition, they are also affected by climatic conditions, which are key elements together with daylight availability in determining the operating conditions of a building's facade at a construction site. IEA (2000) classifies the performance of daylighting strategies under three main categories: daylight availability on the building envelope, physical and geometrical attributes of window(s), physical and geometrical characteristics of the space (Binol, 2008). In this section, the variables influencing daylight design will be analyzed under five subsections which are;

- Climatic conditions,
- Building area and orientation,
- External obstructions,
- Glass types,
- Windows

2.2.1. Climatic Conditions

Daylight in an interior space particularly depends on the availability of natural light which is affected by two key variables: prevailing climate and latitude-related variations (Mardaljevic and Christoffersen, 2016).

Latitude-related variations are considered as the first variables that occur due to the changes in the solar position in the sky. The attributes of the sun position for a certain geographic location provide information and give clues to designers at the very early stages of the building design process for a better daylight condition (Li and Lam, 2001). For example, the fact that high latitudes have distinct summer and winter conditions makes the seasonal variation of daylight levels less visible in comparison to lower latitudes. The main purpose of a daylight design in high latitudes should be to maximize the daylit area, for instance, redirecting daylight to areas away from the openings from the brightest zones of the sky by using daylight redirecting components is regarded as a suitable strategy for these latitudes. On the contrary, avoiding overheating by reducing the amount of natural light inside the building should be emphasized in low latitudes, where daylight levels are too high over the whole year (IEA, 2000). Otherwise, any failure to achieve the daylight level balance may lead to significant problems like increased energy use for lighting, cooling, heating and also an unhealthy, displeasant environment for the occupants (Mardaljevic et al., 2009).

Second variable is the sky conditions which is based on the climate-related variations. Sky conditions are difficult to estimate in a broad sense. According to Brown and De Kay (2001), they may be predicted by plotting the average number of sunny, cloudy and partly cloudy days as a percentage of the total days in a month, and categorized into clear, partly cloudy and overcast sky types by the prevailing climatic parameters. Egan (1983) describes the overcast sky as completely cloudy sky (100% covered). This sky type is mostly used to determine daylighting performance analysis as to calculate the worst case scenario with the prediction that for other sky types, daylighting performance would be better (Longmore, 1975). The other sky types are clear sky with 30% cloud cover and partly cloudy sky which has a constantly changing cloud cover between 30% and 70%. For the estimation of peak design loads and applicable air-conditioning device capacity, the assumption that the building is under clear sky conditions is generally accepted for the calculations (Li and Lam, 2001).

Accordingly, latitude-related variations and prevailing sky conditions are considered as non-negligible factors that form a building at early stages of the design process and affect a building’s performance over its lifetime, therefore, a strong understanding of these factors is required for a better performance of a building.

2.2.2. Building Area and Orientation

Other than climatic conditions, daylight availability also depends on the orientation and design of a building. According to IEA (2000), each orientation needs different requirements for daylight design strategies and the optimum daylighting solution is determined by setting the building on its site and its relationship with the sun. Sun path diagram is considered helpful as serving information about the effect of sun on the building all year round. Taking a residential building in the northern hemisphere as an example and using the fact that sun rises in the east and sets in the west, the best solution would be to place the rooms that might benefit most from early morning light on the east side while those that are more likely to be used in the afternoon or evening should be placed on the west or south side. In a larger scale, this approach is directly linked to the statement which claims that the function of buildings determines the orientation requirements, e.g. a school and an office have diverse needs of orientation (Phillips, 2004). Along with this, analysis of previous successful daylighting designs and local architecture is a useful way to find out the relationship between building orientation and daylighting performance (Papathanasiou, 2016). Building design is also one of the most influential determinants of daylight availability which should be considered during the initial design phase due to the reason that it influences the building's capability to distribute adequate daylight inside the space. To avoid failures by making incorrect assumptions about the daylight distribution within the space, performance parameters should be analyzed carefully at initial steps, otherwise it may result in poor daylighting performance. For example, in a deep building interior it is only possible to achieve a sufficient daylight distribution a few meters from the facade regardless of the glass area covering the facade (Andersen, 2013).

2.2.3. External Obstructions

A building's immediate surrounding, the presence or absence of external obstructions and reflections are considered as the further factors influencing the amount of daylight that a building receives. Mostly nearby buildings block the daylighting performance in interiors by reducing the daylight penetration and reflecting sunlight which causes visual discomfort (See Figure 2.2), (Binol, 2008). An office building in a northern European industrial city, located in a narrow street surrounded by tall buildings which are covered in dark stone receives far less daylight than a building on the Mediterranean coast, located on a detached, open, light-coloured sandy site (THERMIE, 1994). For that reason, IEA (2000) strongly recommends that new buildings' obstruction of daylight for existing buildings should be taken into account for a healthier daylighting performance.

Figure 2.2. Components of view-roof window and view-facade window situation. (Source: Ruck et al., 2000)

2.2.4. Glazing Types

Choosing the right window glazing is a major issue in daylighting design since the functions of windows are not only view to the outside, but also to meet the solar, thermal and acoustic needs of a building. A wide range of glazing types for windows are presently available to be selected concerning orientation of the window, its thermal and acoustic characteristics along with its capacity for solar shading for a better performance of the building (Phillips, 2004). These glazings are grouped into three main categories as explained below.

2.2.4.1. Clear Glazing

Clear glazings can be single sheet, double or triple glazed or preferably a thick glass. The thickness of the glazing and the number of sheets directly affects the daylight penetration; greater thickness or more sheets may cause diminished daylight level however the perception of the colour of the exterior still remains natural (Phillips, 2004). For example, a typical single-glazed window with clear float glass transmits approximately 85% of the light while double or triple glazing lets in 70% and 60% of the light respectively (THERMIE, 1994).

2.2.4.2. Tinted Glazing

Tinted glass is divided into two types according to their production. First type is a modified clear glass which is able to produce diverse radiant heat transmission characteristics. The second type is a coated glass with microscopically thin layers of metallic oxides so as to reflect the heat away. Having a very thin layer of reflective material, both types of tinted glasses can be produced to have high daylight transmission while giving an appearance of almost clear glass and therefore do not restrict the view, however, due to the fact that their cost of application is higher than conventional clear glazing, they should only be preferred when it is required (Phillips, 2004).

2.2.4.3. Miscellaneous Glazing

This category consists of different types of glazing which are patterned glass, wired glass, laminated glass, glass blocks and high-tech glazings. Patterned glass is a semi-molten glass which is used to provide decorative or diffusing sheets for diverse purposes. However it is seldom used for windows because their capability for light transmission will be modified (Phillips, 2004). Wired glass is produced similarly to patterned glass by sandwiching a wire mesh within the sheet of glass. It is generally used for security purposes such as fire protection, burglar protection etc. (Bülow-Hübe, 2001). Laminated glass is also manufactured with similar methods for laminating sheets of plastic between sheets of glass together with a plastic or resin. It is again mostly used for security purposes as resistant to impact, and also to prevent UV lights, reduce noise and provide thermal insulation (Aguilar, 2005). They are in particular preferred for glass roofs to avoid the glass from falling down with a potential impact, also for spaces where the control of ultraviolet (UV) lights is necessary, e.g. museums, shop windows (Bülow-Hübe, 2001). Glass blocks are a form of glass wall that was so popular in the 1930s. These glass walls have thermal characteristics by reason of the hollow nature of the blocks. Today they are still in use to introduce daylight into the building, but special openings are required for view to the outside (Phillips, 2004). Nowadays high-tech glazings involve a wide range of glazing types owing to the new emerging technologies. Most common and advanced ones are considered as photovoltaics and electrochromic glasses. Photovoltaic glass is a highly innovative type of glazing which generates electricity itself from solar radiation and also can be used to reduce energy consumption due to artificial lighting. This type of glass responds straight-forwardly to an environmental impulse such as temperature or light (Phillips, 2004). However, it has some limitations, for example, when it reacts to light and not heat, a serious amount of heat through solar gain, would already be inside before it blocks out (Ogwezi et al., 2011). The other type of glazing, electrochromic glass, is produced to respond indirectly by the implementation of an electrical current that changes their visual and thermal characteristics (Phillips, 2004). This type of glass is possible to be controlled by users to regulate the amount of heat or temperature. However, there are also questions related the to durability of materials on how their performance will be after some years and also their time to change from, for example, from clear to opaque and back again, that takes minutes, not seconds as expected. Nevertheless, electrochromic glasses are still under development and with the advent of technology it is highly possible that they become viable.

2.2.5. Windows

Windows are defined as the openings in a wall or side of a building which have several functions directly influencing indoor environmental quality and energy demand of buildings. One of the primary functions is considered as view to the outside. View plays a significant role in occupants' appraisal of the indoor environment even if the exterior scene is not notably inviting. Therefore, size and position of the windows, which also influences the brightness of a space, need to be considered carefully as they affect the mood and well-being of occupants (Ruck et al., 2000). Previous studies predominantly agreed on that workspaces with larger windows have positive influences on occupant satisfaction through the widened view and increased penetration of daylight (Keighley, 1973; Boubekri et al., 1991; Leather et al., 1998; Özdemir, 2010). However, there is no straighthead statement that more daylight always brings more satisfaction since it can be associated with visual discomfort or over-heating, and it can therefore reduce visual performance and give inability to see objects (Boyce, Hunter, and Howlett, 2003). To minimize undesirable effects of excessive daylight, it is recommended to limit the room depth to around 2.5 times the height of a window (Osterhaus, 2005).

A proper design of a window not only provides sufficient indoor daylight distribution, but also improves thermal comfort and reduces energy demand for electric lighting. The balance between glazing and opaque areas has influences on various aspects of the daylight availability, energy balance, and heat loss. The window-to-wall ratio (WWR), which means the ratio between the glazing to opaque area, thus has a deep impact on both the energy balance and the appearance of the building (Lee et al., 2013; Shen and Tzempelikos, 2013; Goia, 2016). An optimal facade configuration needs to be carefully considered in the very first stage of the design process considering that any change can not be applied at a later stage. For this reason, optimal WWR should be determined at the very beginning in consideration of building parameters such as climate, orientation, size etc., which later will be directly associated with energy, daylighting and thermal comfort in indoor building environment, and therefore the overall satisfaction of occupants.

2.3. Improving Daylight Quality in Buildings

To utilize daylight more efficiently and effectively in buildings not only reduces energy consumption, but also fulfills the psychological and physiological needs of occupants; therefore, a clear understanding of enhancing indoor daylight conditions is of great interest to building designers (Wai, 2010). However, traditional window designs have a common problem concerning uniform daylight distribution since they alone do not have the capability of directing the light (Bubekri, 2008). For instance, under clear sky conditions transmitting adequate amount of daylight to the far end of a deep plan building is highly impossible whereas the excessive brightness near the window may cause discomfort and glare for occupants (Smith, 2001; Al-Jubiuri, 2012). In order to cope with this kind of situations, daylighting systems need to be used for the purpose of improving natural light distribution, glare control and shading. A wide range of daylighting systems such as light shelves, static and dynamic reflective louvers, blind systems, prismatic panels, laser-cut panels, light pipes, anidolic ceilings and many more have been developed to address daylight distribution problems. Each of these systems has their own performance and characteristics. There are several discussions on choosing the appropriate system to improve the daylighting design. For instance, Littlefair (1990) suggested eight guidelines for designing and choosing the right daylighting system. These guidelines involve climate, diffuse skylight availability, direct sunlight utilisation and shading, occupant behaviour, internal layout considerations, lighting control system and energy saving, initial cost control and maintenance issues. Later, Ruck et al. (2000) underlined some factors at critical level of design which cover the following elements:

i. Site daylighting conditions - latitude, cloudiness, obstructions
ii. Daylighting objectives
iii. Daylighting strategies implied in the architectural design
iv. Window scheme and function
v. Energy and peak power reduction objectives
vi. Operational constraints - fixed/operable, maintenance considerations
vii. Integration constraints - architectural/construction integration
viii. Economic constraints

Regardless of which technique is applied, these systems should improve the indoor lighting conditions under a proper design (Wai, 2010). According to Littlefair (1996), a daylighting system should fulfill the following key aspects:

- Increase daylight levels at the far end of deep rooms
- Improve daylight uniformity inside a space and therefore its appearance
- Control direct sunlight and enhance daylighting effectiveness
- Avoid glare and discomfort for occupants

Next, Ruck et al. (2000) suggested the following aspects under the report of the International Energy Agency (IEA) – Solar Heating and Cooling Programme.

- Redirect daylight to non-daylit zones
- Enhance daylighting for task illumination
- Increase visual comfort and glare control
- Obtain shading thermal control

As mentioned earlier, daylighting systems assign numerous techniques to supply an adequate distribution pattern of light for different intentions. Several categorisation methods have been developed to ease the understanding of the proper application of each system. According to Poyan (2012), there are four main groups of daylighting system which are tubular daylight devices (TDDs), vertical systems, horizontal systems and fibre optical devices.

Baker and Steemers (2012) use the type of redirecting technique applied by the system. Daylighting systems are divided into three groups in this approach. ‘Reflectors and light shelves’ is the first group which reflects the daylight through a reflector or a polished surface towards the ceiling, e.g. light shelf. The second group is ‘integrated windows elements’ in which the aperture combines an array of optical devices to distribute daylight more uniformly. Prismatic films and laser cut panel are involved in this group. ‘Light guides’ is the last group which transfers daylight from one location to another and generally focuses on the use of direct sunlight. Light pipes and optical fibres are members of this group. This categorization method is comparatively simple and easy to understand, but there are some weaknesses in terms of informing users about the usage of these devices.

More complex but at the same time more effective in providing designers their functional requirements is another classification system which was introduced and embraced by IEA (Ruck et al., 2000). In this method, daylighting systems are categorized according to their applications; which means under this framework one daylighting device may be under more than one category. A brief overview of daylighting system categorization is presented in Table 2.1 (Ruck et al., 2000; Kischkoweit-Lopin, 2002).

As illustrated below, there are many different daylighting system options for serving numerous purposes in terms of improving indoor environmental quality. However, analysis of most of them remains out of scope of this thesis. The main characteristics of daylighting systems used in this study, light shelves and louvers, are explained below in Section 2.3.1.1 and Section 2.3.1.2.

Table 2.1. Categorization, description and examples of daylighting systems. (Source: Ruck et al., 2000, Kischkoweit-Lopin, 2002)

	Category	Description	Examples
Shading System	Primary using diffuse skylight	•Redirection of diffuse light •Protection from glare •Blocking direct sunlight •Transparent for diffuse skylight	•Prismatic panel •Sun protecting mirror element •Anidolic zenithal opening •Prism and venetian blind •Directional selective shading system with Holographic optical elements (HOE)
	Primary using diffuse skylight	Diffuse sunlight or redirect sunlight onto the ceiling or above eye level	•Light guide shade •Louvers and blinds •Light shelf for redirection of sunlight •Glazing with reflecting profiles •Skylight with laser cut panels •Turnable lamellas
Daylighting System without Shading Included	Diffuse light guide system	•Used in locations with heavy obstructions •Redirection of light from zenith region to deeper part of the room •Mainly used under overcast skies	•Light shelf •Anidolic integrated system •Anidolic ceiling •Fish system •Zenith light guiding elements with HOE
	Direct light guide system	•Highly efficient redirection and distribution of sunlight •Room illuminated by direct sunlight •Glare and overheating need to be avoided	•Laser cut panel •Prismatic panels •HOE in the skylight •Light guiding glass
	Scattering system	•Used for skylight or toplit aperture •Provides uniform daylight distribution •Avoid use in vertical windows to prevent glare problem	•Light diffusing glass •Capillary glass •Frosted glass
	Light transport	Transport light over a long distance into floor areas or rooms with no window opening	•Heliostad •Light pipe •Solar tube •Fibres •Light guiding ceiling

2.3.1. Overview of Light Shelf System

A light shelf is a horizontal or a nearly horizontal plane designed to reduce the sunlight near a window as a shading device and also increase the daylight penetration to the rear of the room by redirecting the light. It may be external, internal, or both external and internal and generally positioned above eye level. It divides the window into two; a view zone below and a clerestory zone above (Ruck et al., 2000). As serving two purposes, it blocks the direct sunlight from entering the room, thus controls glare and heat gain, and also improves uniformity and reflects sunlight off the ceiling to the back of the room as illustrated in Figure 2.3 (Raphael, 2011).

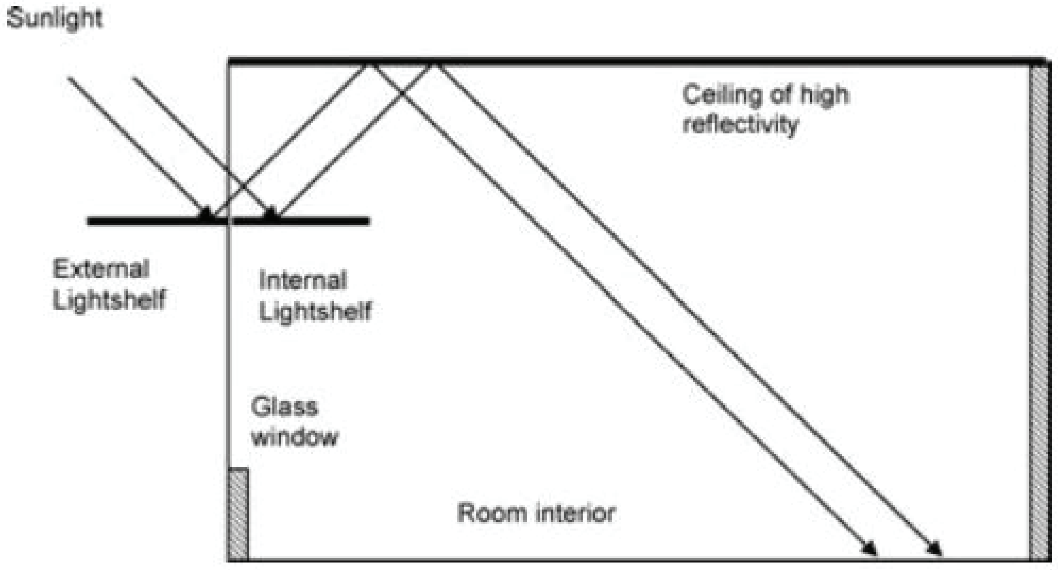


Figure 2.3. Cross-section of a room and the working principle of the light shelf.
(Source: Raphael, 2011)

Performance of a light shelf depends on some significant factors such as the light shelf's dimensions, reflectance attributes, location, reflectance of inner surfaces, and ceiling geometry and reflectance. The physical characteristics of the structural design should be analyzed initially before a light shelf is applied. Window orientation, room arrangement, and latitude should be considered particularly for each light shelf design. Climates with excessive direct sunlight and south faced deep spaces in the northern hemisphere or north faced deep spaces in the southern hemisphere are preferable for a high performance.

Several studies have investigated the effect of light shelf application on different solar geometry and climate types. Soler and Oteiza (1997) tested performance of a light shelf with scale models. The results showed that a light shelf could improve daylight uniformity, reflects sunlight to the back of a room and achieve a higher efficacy of illuminance at a specific angle of solar altitudes and specific days of the year. Ochoa and Capeluto (2006) investigated a number of daylighting systems in terms of their shading and daylighting potential under highly luminous climate conditions of the tropics. The study revealed that the light shelf provided reduced contrast between levels at the window and those at the rear of the room; however decreased the illuminance levels. In addition, various studies concentrated on light shelf characteristics and configurations, such as the shape of the light shelf and its material reflectance. Beltran et al. (1997) focused on the structure of a light shelf with different layers and material attributes and tested the performance of four light shelves which are horizontal base case, single level light shelf, bi-level light shelf and multi-level light shelf. The results showed that sunlight was successfully redirected deeper into the room not only when the sun is in front of the window, but also when it is inclined at different angles. In a very recent study of Ganga and Raphael (2017), various light shelf configurations were evaluated on a scaled prototype with by using illuminance sensors. Following the analysis of more than one million data points, the results indicated that an average illuminance improvement of 21% could be possible with a horizontal light shelf. Moreover, up to 300% improvement would be achievable by rotating the external light shelf to an optimal angle. Influence of room geometry and inner surfaces characteristics on performance of light shelves were also investigated by many researchers. Studies mostly emphasized the ceiling geometry, window opening ratio, and reflectance characteristics of surfaces. Freewan et al. (2008) tested ceiling geometries through physical model experiments and simulations in order to optimize the performance of a light shelf. The results revealed that the ceiling shape which is curved at the front and rear of the window is the best option for subtropical climate regions. In a study of Al-Sallal (2007) which was conducted in hot region, it was suggested that tilting the ceiling by 5^0 could improve the illuminance uniformity between the ceiling and the back and side walls in a tested space. Berardi and Anaraki (2015) evaluated the influence of light shelves over The Useful Daylight Illuminance (UDI) in a south facing office building in Toronto. In this study in which four different window-to-wall ratios (WWR) were compared with and without light shelves, it was found that light shelves improved the

UDI levels especially six meters in distance from the windows and provided a more uniform daylight distribution for any WWR scenarios. Claros and Soler (2002) studied the light shelf performance on different solar geometry and surface reflectance configurations and the obtained results remarked the importance of model reflectance as well as solar angle and time of year and day.

2.3.2. Overview of Louver System

Louvers are another type of daylighting systems to provide solar shading, glare control, and penetration of daylight. Louvers may be composed of multiple horizontal, vertical, or sloping slats and positioned on the exterior or interior of a window or a skylight, or between glazing. They partly or fully obstruct the view to the outside depending on slat angle, therefore many of them are aimed to be fully or partially retracted. All orientations and latitudes are suitable for the application of louver systems whenever required. Generally, horizontal louvers are used on all building orientations, whereas vertical louvers mainly give better performance on east and west facing windows. The effectiveness of louvers depends on the sun position, their location (exterior or interior), slat angle, and slat surface characteristics. These systems are able to increase penetration of daylight, most particularly when skies are overcast. When the slats of fixed systems are tilted downwards under sunny sky conditions, they produce efficient shading, but, on cloudy days, they may considerably reduce indoor daylight with an unfavourable shading. When movable systems are taken into account, slat angle, slat surface attributes and the spacing between slats should be considered carefully so that both sunlight and skylight may be reflected to the interior. Light-directing louvers are also highly effective daylighting systems which consist of an upper surface of very specular material that has perforations and concave curvature. They are mostly placed between glazing and typically have 10-12 mm width. These louvers are aimed at reflecting the maximum possible amount of daylight to the ceiling while lowering brightness at angles below the horizontal (Ruck et al., 2000). Various studies on the effectiveness of louver systems have been performed by researchers. These studies are mostly about the comparison of louver systems with other type of daylighting systems in terms of daylight distribution, energy consumption and visual comfort assessments, louver systems with different shape and characteristics, and the impact of room geometry and surface characteristics on the performance of louver systems. Chiang et al. (2015) investigated various louver shapes in a classroom in Taipei in order to achieve maximum daylighting and ventilation. It was found that louvers of curved shapes were the most successful in maximizing the diffuse daylight and enhancing ventilation. A recent Chilean study by Vera et al. (2016) aimed to optimize a fixed exterior complex fenestration system (CFS) component of four different offices which were located in Montreal (Canada), Boulder (USA), Miami (USA) and Santiago (Chile). The analyzed CFS was composed of a set of opaque, curved, and perforated horizontal louvers and the main optimization concern was to minimize total energy consumption and meet the visual comfort metrics, which are spatial daylight autonomy (SDA) and annual sunlight exposure (ASE). The findings pointed out that a CFS optimized merely as regards total energy consumption did not entirely fulfill the visual comfort metrics. Another louver system was developed to improve daylighting performance in buildings through a reflective ceiling, transmitting daylight to deeper spaces. Both computer simulation and physical measurement were carried out in a south faced deep plan office. Results indicated that the system performance was effective in providing adequate daylight and controlling glare (Thuot and Andersen, 2011). Freewan, Shao and Riffat (2008) studied the impact of ceiling geometry and louver parameters on the performance of daylighting by using Radiance simulation program and physical model experiments. In this study conducted in a subtropical climate region, iluminance level and distribution uniformity have been considered as performance indicators. As a result, it was seen that the performance of the louvers could be improved by modifying the ceiling geometry in such a way that it was curved at the front and rear of the room. One study from Konis and Lee (2015) focused on the comparison of a louver system with another daylighting system. They made parallel comparisons over solstice-to-solstice variances in sun and sky conditions between an optical louver system (OLS) and a conventional Venetian blind positioned at a horizontal slat angle and located in a south facing full-scale office testbed. The main indicators were daylight autonomy (DA), window luminance, and ceiling luminance uniformity for the performance assessment. Under clear sky conditions, the OLS was found to enhance the ceiling luminance, likewise provide a more uniform luminance distribution over the ceiling surface. Similarly, in a recent study of Borisuit et al. (2016), a novel Camera-Like Light Sensor (CLLS) was used to monitor luminance and circadian weighted radiance (Lec) in two test rooms equipped with different daylight redirecting systems, which are venetian blinds (VB) and optical louver systems (OLS). In addition, a computer simulation was carried out for the two test rooms. From the results, the VB obtained overall higher illuminance compared to the OLS, however when a virtually seated observer was in front of the desk, larger circadian weighted irradiance was provided by the OLS. Differently, Hashemi (2014) developed a novel automated reflective louver system to perform as a daylighting system while yielding shading for deep plan office buildings. The system was produced in such a way that each louver slat could be controlled separately. The findings of the study demonstrated that the system could considerably improve daylighting and reduce electricity consumption for lighting up to 60%.

2.3.3. Determination of Photometrical Properties of Surfaces

Characteristics of surfaces also affect occupants' well-being and performance through their influences on users' visual perceptions. Current recommendations for reading and computer tasks suggest that the luminance of surfaces within the field of view carries greater importance than desktop illuminance (IESNA, 2000). However, there is an understandable shortcoming in the experimental designs of physical luminance separation of different surfaces due to the fact that for a long time horizontal desktop illuminance was the main concern for the aim of providing sufficient visual conditions (Newsham et al., 2002). This results with uncertainties on the determination of surface characteristics which satisfy occupants' needs. Finnish architect and philosopher Juhani Pallasmaa describes: "The design of a building and its interior space influences its atmosphere and lends a specific character. Together with the features of the room itself the lighting, the materials used, their surfaces, textures and colourings help creating the effect of space" (Sørensen, 2014). Therefore, interior finishing -i.e. characteristics of surfaces- should be part of the daylighting strategy since the appearance and atmosphere of an environment have influences on occupants' well-being, performance and also for contributing to better daylighting conditions. Thus, the following subsections will address some basic concepts of surface attributes and daylighting for a good visual environment in indoor spaces.

2.3.3.1. Surface Colour

Before all else, light and colour can not be considered individually. Previous studies on light and colour are mostly related to colour characteristics of artificial light sources and occupants’ preferences for various conditions, however, light can also be reflected from one surface onto another surfaces by their reflectance abilities with different irradiances, and thus influence visual perception (Liljefors, 2006; Kronqvist, 2012). Surfaces with different colours and hence various reflectance properties have diverse impacts on the reflectance of light; for instance, the reflectance of white is considered to be 82% and a dark gray is 14% (Laura, 2015). Therefore, in such built environments receiving insufficient natural light, it is strongly advised to prefer light coloured surfaces for maximizing daylight and reducing artificial lighting. Additionally, it was discovered that colour is needed to distinguish surrounding objects (Cold et al., 1998), and that it contributes to positive moods (Küller et al., 2006; Paredes, 2016), and also that human psychological responses differ due to various colours (Mahnke, 1996); such as the case that green colour gives calm and harmonious feelings (Ou et al., 2004).

A long history of speculation is found in literature regarding influences of light and colour on task performance, comfort and well-being by creating different colour distributions within the field of view, but the question is, since the liking and acceptance of a colour palette is a subjective assessment which depends on both social norms and personal preferences, how high or how low should be the colour, thus luminance differences? For answering this, a design pattern for different types of indoor environments (e.g. office, school, library etc.) could be helpful to understand the occupant preferences for each case.

2.3.3.2. Surface Reflectance

Contrary to what is believed, light colours might have low reflectance values whereas dark colours might adequately reflect the light falling upon its surface. Here, the characteristics of surfaces, chosen material attributes, their texture etc. carry an important role for the assessment of daylighting performance. The reflectance of walls, floor, ceiling, and also furniture have a significant influence in indoor environments. For instance, the floor reflectance should not be below 0.3. To illustrate the concept how surface reflectance influences the amount and distribution of daylight, Hagenlocher (2012) conducted a simple experimental analysis in a room with a single window. As the reflectivity of all room surface went from 90% to 10%, the daylight factor at the back of the room dropped by 13-1.75%. In addition, in the case of daylight redirecting applications, reflectance attributes of the ceiling play a key role in the way of daylight distribution; specular surfaces redirect light to the back of a room but also might be a source of glare; and a diffuse surface of high reflectance can also distribute light from daylight redirecting systems, which could be more satisfying for occupants than an excessively reflecting environment (Aschehoug et al., 2000).

2.4. Daylighting in Libraries

2.4.1. Academic Library in General

A library is defined as a place in which reading materials such as books, newspapers, periodicals, and also CDs, DVDs and other digital sources are provided for use or lending. There are different types of libraries categorized according to their sizes and roles, such as academic libraries, public libraries, school libraries, special libraries etc. Academic libraries are vital parts of university education as being a core of learning and research. They symbolically and physically contribute to the education of students as holding a unique position on campus (Freeman, 2005). Therefore, some key factors such as efficiency, function and usability should be considered as a priority in planning academic library as a place since the design of libraries may increase or decrease students' performance and motivation (Bundy, 2004). It is indispensable to understand how humans feel about space and how they act within it hence space is a very crucial concept in designing and planning academic libraries. With that behavioral information, a space can be designed or reorganized in order that it works better for occupants and occupants work better within it (Cohen and Cohen, 1979; Ugwuanyi, Okwor, and Ezeji, 2011). Accordingly, regardless of the type of a library, a number of standards and guidelines are recommended in order to provide for the needs of users and therefore increase the length and quality of stay. These standards and guidelines involve various design principles such as distances between tables, book stack spacings, furniture dimensions, as well as variety of collections, infrastructure system criteria etc.

Presenting all the principles goes beyond the scope of this thesis. Therefore, recommended minimum distances between units in library planning are briefly introduced in Figure 2.4 (Neufert and Neufert, 2002), which afterwards, in Chapter 3, will be used as reference knowledge for the new layout proposal on the case study.

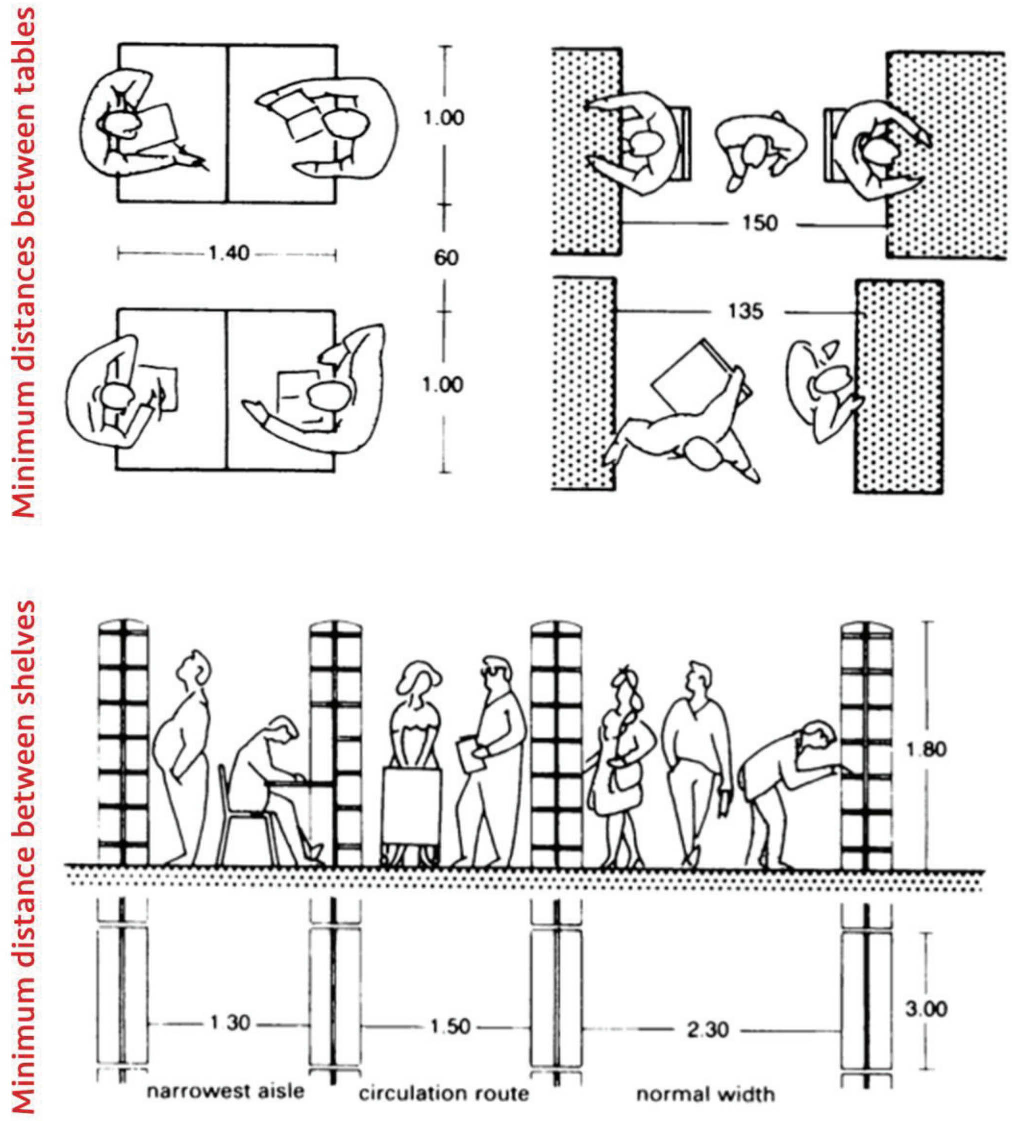


Figure 2.4. Recommended minimum distances between units in libraries.
(Source: Neufert and Neufert, 2002)

2.4.2. Selected Examples of Academic Libraries

This section focuses on the selected 21th century libraries, namely Rolex Learning Center (2010), Oxford Brookes University Headington Library (2007) University of Aberdeen New Library (2005) and University of Birmingham's Library (2016) according to their daylight use.

2.4.2.1. Rolex Learning Center (2010)

Rolex Learning Center in École Polytechnique Féderále de Lausanne (EPFL) is the heart of the university campus which is designed by the holders of 2010 Pritzker Prize and 2014 VELUX Daylight Award, Japanese-duo SANAA. This learning center is more than what is expected of a library building with student work places, offices for researchers, cafes, a top restaurant, a bookshop, a multifunctional auditorium and a bank branch as well as a large library. Being far more than the provision of functional space, the design of the building is highly fascinating which is combined by an undulating floor and ceiling topography with the dimensions of 166 x 121 m. The structure has also 14 round patios with diameters ranging from 7 m to 50 m, which look as if they have been extracted from the building (See Figure 2.5).

Figure 2.5. External view of the Rolex Learning Center.
(Source: Zumtobel, 2011)

Considering the requirements on the supporting structure, the loads are distributed on only a few delicate cylindrical columns, which provides very particular specifications in regard to a uniform and modest appearance.

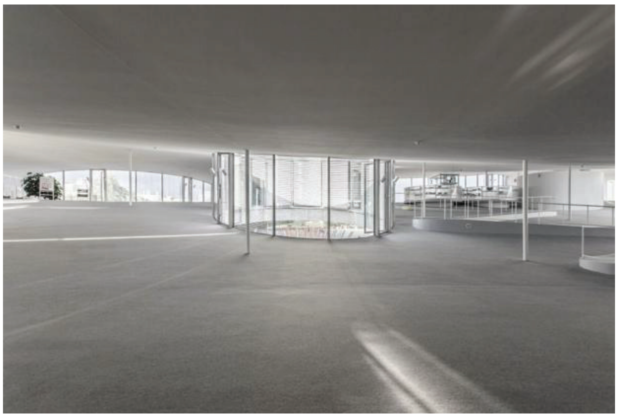


Figure 2.6. Interior overview of the Rolex Learning Center.
(Source: Zumtobel, 2011)

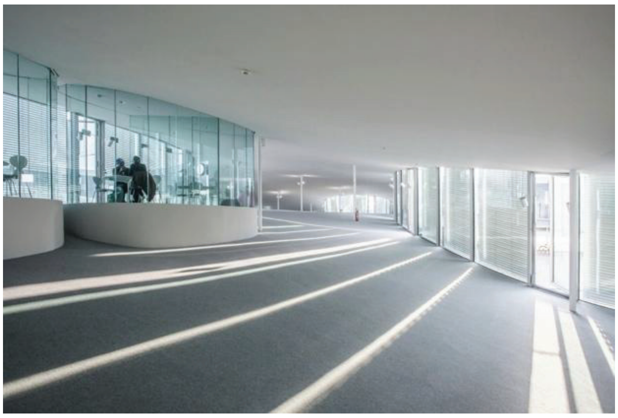


Figure 2.7. Effects of daylight created inside.
(Source: Zumtobel, 2011)

There is no doubt that the role that daylight played in this building is a radical attempt to create an innovative educational setting by modulating the landscape and providing it the necessary form to transform the building into a walk-in sculpture. Various possible views and perspectives are presented into, out of, and also through the structure, and a variety of effects of the light are created with no virtually no partitions on the inside, and glass completely around the outside (See Figure 2.6, Figure 2.7). Moreover, the impression of spaciousness comes from the light not only inside the building, but also underneath it. Accordingly, the light reflected beneath the delicate concrete arches makes the Learning Center appear like floating in mid-air (Zumtobel, 2011).

Figure 2.8 also illustrates the plan of the learning center in which library and workspaces are located at the northern part and gives clues about the organizational-orientational planning of learning spaces.

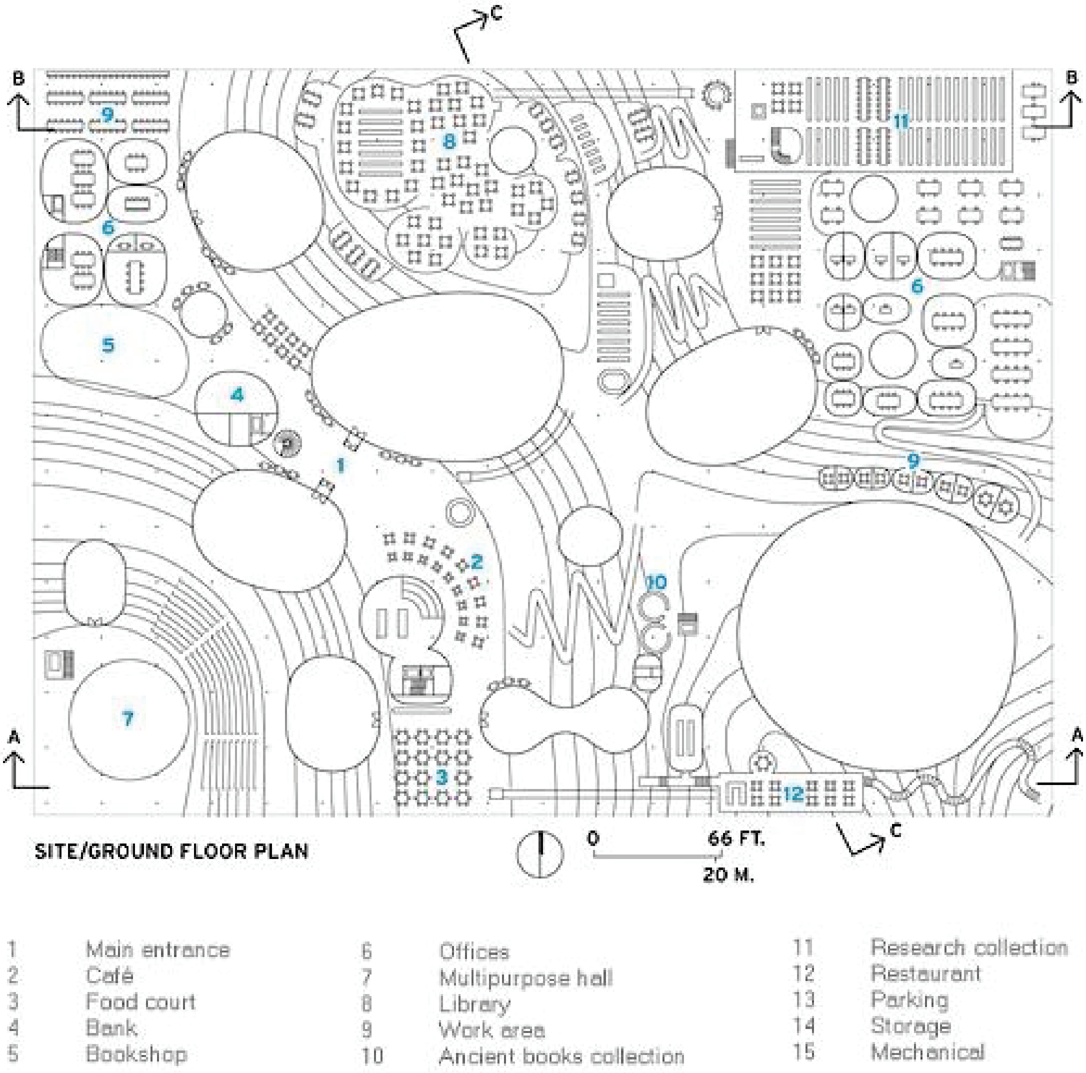


Figure 2.8. Ground floor of the Rolex Learning Center.
(Source: http://leejungha.blogspot.com.tr/2013/04/rolex-learning-center-plans.html)

2.4.2.2. University of Aberdeen New Library (2005)

Won in an architectural competition in 2005 by Danish Schmidt Hammer Lassen Architects, the construction of the building was finished in 2007. This 21st century learning and research environment simply proves how architecture can make a difference with its significant increase in visitors according to the statistics. The founding partner of Schmidt Hammer Lassen Architects, Morten Schmidt states on this non-negligible change in the use of library: “The increase in visitors shows that the new library has affected the students' everyday behaviour. The students come to study in the new library and to be a part of the social community of the University." (Archdaily, 2012).

The high performance facade composed of irregular pattern of insulated panels and advanced glazing which allows plenty of daylight to penetrate into the building and also provides a view over the city of Aberdeen (See Figure 2.19). The library with its facade shimmering during the day and glowing softly at night creates a landmark for the city of Aberdeen. Structurally, the focus of the library is a spiralling atrium all along eight storeys, which is in contrast with the clean-cut exterior profile (See Figure 2.10 and Figure 2.11).

Figure 2.9. Exterior view of the University of Aberdeen New Library.
(Source: http://www.archdaily.com/276161/university-of-aberdeen-new-library-schmidt-hammer-lassen-architects)

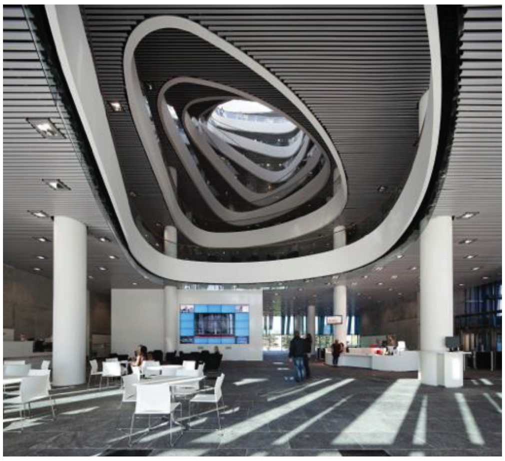


Figure 2.10. Spiralling atrium inside of the University of Aberdeen New Library.
(Source: http://www.archdaily.com/276161/university-of-aberdeen-new-library-schmidt-hammer-lassen-architects)

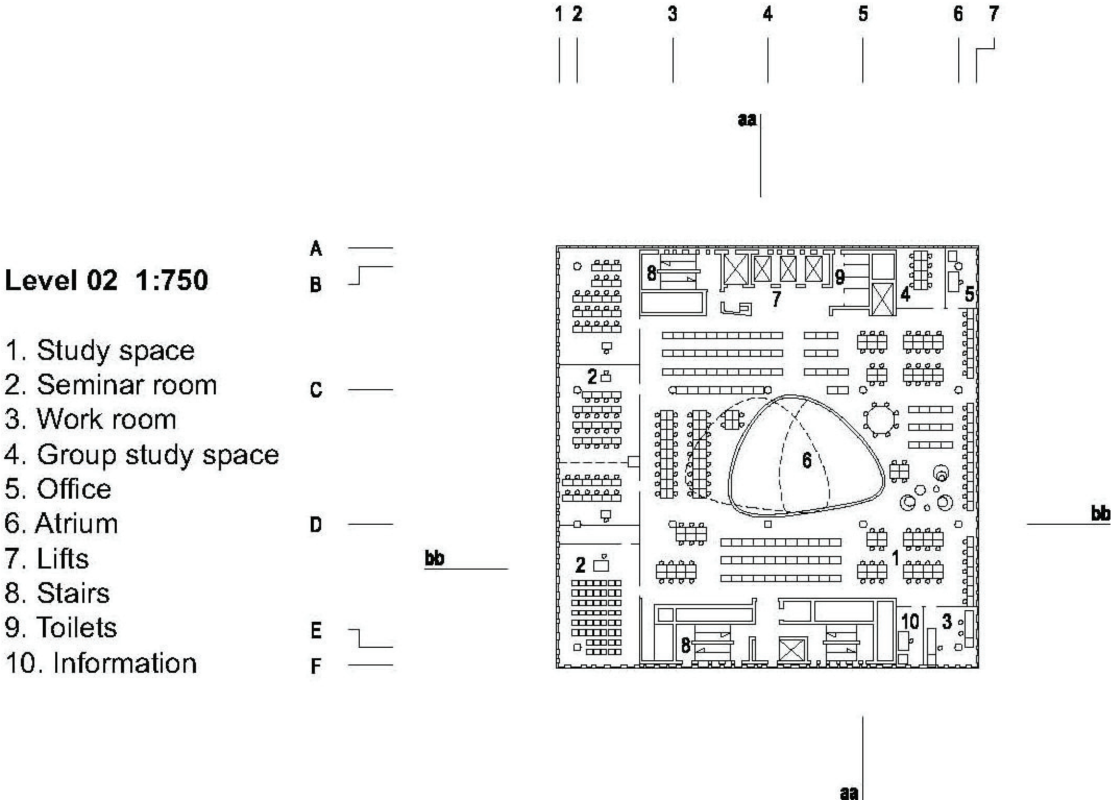


Figure 2.11. Upper level plan of the University of Aberdeen New Library. (Source: http://www.archdaily.com/276161/university-of-aberdeen-new-library-schmidt-hammer-lassen-architects)

2.4.2.3. Free University's Faculty of Philology Library (2004)

The campus library of Free University in Berlin was designed by Foster and Partners in 2004. The building is also known as “Berlin Brain”. The structure is formed on a radical geometry and the white translucent panels around the dome that diffuse daylight all through the space (See Figure 2.12 and Figure 2.13). Daylight is filtered through an inner fabric membrane of glass fibre, and this provides an atmosphere of concentration inside the space whereas the transparent openings allow instant views of sky. The building is basically a combination of a concrete structural mass with a curved translucent shell that distributes daylight and necessarily ventilates the space. Foster and Partners also confirms the characteristics of the building by stating the main idea behind the design of this library was to enable generations of students to study in an building that is filled with daylight and air (Foster and Partners, 2005).

Figure 2.12. The inside view of Free University’s Faculty of Philology Library. (Source:http://images.adsttc.com/media/images/525d/59c2/e8e4/4e67/bf00/09b3/slideshow/0980_FP102963.jpg?1381849499)

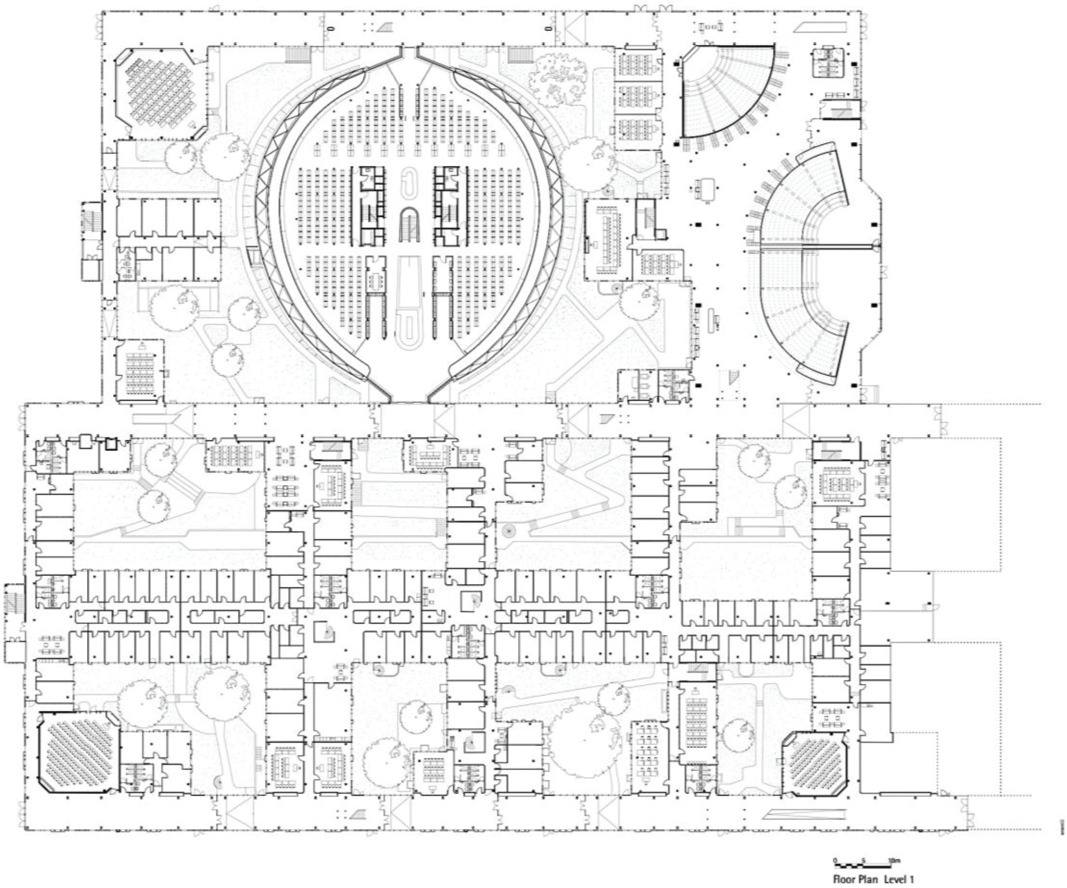


Figure 2.13. 1st floor plan of the Free University’s Faculty of Philology Library. (Source:http://images.adsttc.com/media/images/525d/59c2/e8e4/4e67/bf00/09b3/slideshow/0980_FP102963.jpg?1381849499)

2.4.2.4. University of Birmingham's Library (2016)

The new library building of University of Birmingham is planned by Associated Architects with a design goal of creating a 'green heart' to the campus, enhancing both site circulation and the setting of the historic buildings. Here, the focus point is user, rather than the collection, with its intuitive, natural circulation. The plan is divided by a central street along the north-south axis which makes the internal planning, providing quiet study zones around the building's perimeter (See Figure 2.14 and Figure 2.15).

Figure 2.14. Upper floor plan of the University of Birmingham's Library. (Source: http://www.archdaily.com/869126/university-of-birminghams-library-associated-architects)

Figure 2.15. Interior of the University of Birmingham's Library.
(Source: http://www.archdaily.com/869126/university-of-birminghams-library-associated-architects)

With a high level of glazing, views in and out to are maximized and optimum daylighting to quiet perimeter study zones is achieved. Also solar shading is provided by anodised aluminium fins and automatic blinds (See Figure 2.16). So, the facade of the building meets various criterias such as balancing between maximum natural light gain and overheating from solar gain. Here, active solar shading plays a significant role to control internal temperature, which creates an active appearance to the building that changes at different times of day (Archdaily, 2017).

Figure 2.16. Facade of the University of Birmingham's Library.
(Source http://www.archdaily.com/869126/university-of-birminghams-library-associated-architects)

2.4.3. Visual Performance Assessment in Libraries

Lighting is an indispensable application for libraries influencing many factors such as user comfort, perception, work productivity, motivation and so on (Both, Heitor, and Medeiros, 2013). A well daylit library stimulates success, increases the duration of stay, enhances well-being and regulates the seating distributions. Recently, daylight has become more significant in library planning within the context of visual comfort for different intended purposes such as desk work, computer based work, bookshelf browsing and reading books, journals, digital sources (Osterhaus, 2009; Hoffmann et al., 2015). The amount of daylight for different purposes is associated with the brightness of surfaces within the field of view (Baker et al., 2002). To obtain a good visibility, sufficient amount of light for the task and the glare control are ought to be precisely existing (SHCP, 1999).

Available standards give recommendations depending on the effects of light. Visual performance is evaluated by using recommended horizontal illuminance values on a task and its surrounding, and the recommended luminance values on surfaces within the field of view; whereas visual comfort deals with the luminance distribution in the occupants' field of view (Khademagha et al., 2015).

Different sources in the lighting field gives recommendations regarding the minimum lighting levels for different purposes of use. IESNA (1984) recommends illuminance levels at or below 500 lux on the horizontal work plane whereas CIBSE (1994) recommends maintaining horizontal illuminance within the range of 300-500 lux. In this thesis, CIBSE recommendations were taken into consideration since defining a range would give a better understanding of analyzing visual conditions.

Table 2.2 presents instructions about the recommended illuminance depending on different tasks, activities and specific zones. Recommended horizontal illuminance for computer desks and desks for handwriting are going to be taken as a basis since this study deals with the visual performance of seating zones.

Table 2.2. Related recommended illuminance according to CIBSE (1994).

Function	Recommended illuminance
General offices	500 lux
Drawing offices	500 lux
CAD design areas	300-500 lux
Computer workstations	300-500 lux
Libraries	300-500 lux
Classrooms	300 lux
Workplaces for writing, typing, reading etc.	500 lux

Illuminance uniformity, also, is considered as one of the factors influencing visual performance. Including minimum/average and minimum/maximum illuminance ratios on the workplane, two types of uniformity ratio criterias are found based on the research results. In an early study of Saunders, it was found that the minimum:maximum ratio lower than 0.7 caused valuable dissatisfaction while the drop from 1.0 to 0.7 made almost no effect (Saunders, 1969). Based on the experiment results of tasks on desk, Slater and Boyce (1990) stated that the minimum:maximum ratio could vary between 0.2 and 0.8 across the desk with no distinction among a variety of paper-based tasks. Also, in the same study, they found that the minimum:maximum ratios as fallen as 0.5 in the center of the desk would be acceptable for most of the occupants. Besides of earlier studies, CIBSE (1987) explains the recommended illuminance uniformity as the following standards given below:

1. minimum/average: 0.8
2. minimum/maximum: 0.2

Luminance values on surfaces within the field of view influence the visual performance of occupants. Exceeded luminance ratios between different surrounding surfaces may cause dissatisfaction or distraction during the task performance. Especially at computer workstations, luminance balance is one of the main factors in lighting design influencing visual performance (Osterhaus, Hemphälä, and Nylén, 2015). Visual complaints of Visual Display Unit (VDU) operators are found to be increasing over the years and along with the growing use of VDU in workplaces, decrease in performance resulting from high luminance or irregular luminance ratios in the occupant's field of view has been recently standing as a significant problem that needs to be paid attention (Piccoli et al., 2015). Considering the fact that modern-day libraries are mostly occupied for both paper and VDU tasks, luminance of surrounding surfaces carries a great role for the library occupants' satisfaction. Table 2.3 summarizes the recommended luminance ratios for the user's field of view including task, surroundings, remote surfaces and light source in general spaces (IES, 1993).

Table 2.3. Recommended luminance ratios in workplaces.

Area	Ratio
Task to immediate surrounding (e.g., book to desk, paper to screen)	2.5:1 to 3:1
Task to general surrounding (e.g., book to partition)	5:1
Task to remote surfaces (e.g., walls, ceiling, floor)	10:1
Light source to adjacent surface (e.g., window to adjacent window)	20:1 to 40:1

2.4.4. Occupants' Preferences in Libraries Based on Previous Studies

Daylight directly affects human emotions and behaviours in an architectural space by bringing significant improvements in occupants' health, well-being, productivity and stimulation. Thus, success in design is highly related to how well the architectural space answers the occupant needs in the form of physical, technical, social, and functional limitations (Bell et al., 2005). Daylight should form the architectural space by provoking a visual environment which is healthy, inspiring and stimulating for the occupants, specifically in educational environments, since visual tasks are regularly performed. As a matter of fact, present-day libraries in which all reading, writing, and computer task activities are performed at the same time, need to be paid special attention for providing satisfactory visual conditions. Libraries are the spaces where people fulfill both their learning and working activities; therefore, visual aspects ought to be considered initially. These kinds of spaces have to be responsible for users to execute their work efficiently with no deficiency in visual acuity or comfort considering the whole aspects of performance issues associated with lighting (Pniewska and Brotas, 2013). By embracing various features with an efficient daylighting, libraries can enhance learning outcomes as standing vital spaces for improving the quality and performance of higher education, lifelong learning and well-being (Both, Heitor, and Medeiros, 2013). In libraries, required illuminance values are needed to be satisfied;

brightness/contrast relationship is to be well controlled with luminance ratios which are determined by illuminance and reflectance of surroundings in the visual field. Eyes can adapt to varying luminances rapidly in a properly designed visual environment; their tiredness can decrease as well. Particularly academic libraries, where students intensely visit and spend their time, need to be paid much more attention than ordinary libraries regarding user comfort conditions.

There has been a considerable amount of study that focuses on daylight in libraries. Most of them were based on the interaction of post-occupant surveys and measurements to analyze the influences on seating preferences. Fishman and Walitt (1972) explored the seating choices of college reserve room users. Users were willing to prefer seats to avoid others and the first person's seating choice affected the choice of others entered later. In a study of Parpairi et al. (2002), a new index called "Luminance Differences" was introduced with the intention of making a connection between users' subjective assessments of daylight quality and the new index. In this way, it could be used for prediction of users' seating preferences in libraries. Keskin et al. (2015) investigated the association between occupancy behaviour and quantitative measurements in two different library spaces. They found that daylight and seating choice may not have a strong relationship, and daylight factor shows better correlance with seating choice in comparison to other daylight performance metrics; useful daylight illuminance and daylight autonomy. Kilic and Hasirci (2011) analyzed the effects of daylight within the frame of visual comfort on university library users in relation to privacy, personal space, crowding and territoriality. The results of the study in which questionnaire, observation, heliodon and artificial light were used as instruments showed that there was a relationship between daylight and four different environmental processes. One such study by Othman et al. (2012) investigated the impact of daylight on users' perception and visual comfort in a public library and they found that users chose daylit area more but yet daylighting could not only criteria to affect visual comfort and users' satisfaction. Unfortunately, almost none of the studies above were related to improving visual performance of users in library spaces. Accordingly, the scope of this thesis is based on a library case due to the lack of number of visual performance studies conducted in this kind of spaces in which diverse visual task types are performed.

CHAPTER 3

THE PROCEDURE

This chapter involves the description of the facility, actual measurements and the simulation process under four sections. Two main objectives of this chapter: first, to determine the physical characteristics of the case room in terms of the current daylight condition and secondly, to develop a virtual model representing the case room by embracing its characteristics. The representation of the existing condition by the simulation model is determined as a previous step to the assessment of the performance of the new layout and daylighting system proposal.

The physical characteristics of the library reading room and the photometrical features of the surfaces obtained are presented in Section 4.1 and Section 4.2. The simulation process, which includes (i) the base model, (ii) the second model with a new layout arrangement and (iii) the final model with both the new layout arrangement and the daylighting system, is introduced in the last section.

According to the Illuminating Engineering Society of North America, light is connected with the human visual perception as being a radiant energy that is able to excite human retina and create a visual sensation (IESNA, 1984). A successful daylighting condition is achieved when various aspects related to human vision are combined together in a way that a satisfactory visual performance is allowed (Boyce, 1995).

In an indoor environment, quantitative and qualitative aspects of daylighting performance are assessed in order to evaluate the daylight condition. The lighting quality of a workplace has been primarily evaluated under artificial lighting conditions; however, a certain number of studies have promoted to distinguish the main factors affecting the impression of the environment together with their interaction that can provoke a robust visual environment (Basurto, 2014). In a study that focused on the lighting quality in workplaces, three main factors were determined: visual capability, visual comfort and visual perception (Boyce, 2006). With the constant interplay of these factors, task performance, mood and motivation to perform a task, accordingly the feeling of well-being and health is influenced. Concerning the improvement of this interplay of three main factors, an advanced distribution of two main photometric variables is recommended, which are workplane illuminance (lx) and luminance (cd/m^2). Therefore, main purpose in this section is to optimize the distribution of these two variables, and hence the illuminance uniformity to meet the demands of a sound visual performance.

3.1. Description of the Existing Library Reading Room

In this study, a library reading room which is in use all day long by students is chosen as a reference room since it requires comfortable daylighting quality to perform well visually. The library of Izmir Institute of Technology was evaluated in terms of visual performance criterias, which are task illuminance, luminance ratios within the observer's field of view, and uniformity at a workplane (Velds, 2000). The first criterion for the selection and evaluation of this library was primarily based on the highly glazed facade of the building without exterior solar protection, which unavoidably cause visual discomfort or distraction and thus result in poor performance of visual tasks. The second criterion was related to the layout organization of the space that could be considered conventional but also insufficient according to the layout-related recommendations; therefore needed to be rearranged with reference to the latter analysis of daylighting performance.

The library of Izmir Institute of Technology is located at latitude 38.19°N, longitude 26.37°E and has an orientation along the 60° east of south axis; hence, direct sunlight is admitted into the room from early in the morning until the late afternoon. One of the reading halls on the upper floor of the building was chosen as the experimental room. Having internal dimensions of L 29.70 m x W 19.00 m x H 4.30 m, the room has north-east, south-west, and north-west oriented facades which are fully glazed and have no daylighting device as stated before. The detailed geometrical description of the room and the windows are given in Table 3.1.

Table 3.1. Geometrical description of the case room.

	Type	Orientation	Length (m)	Depth (m)	Height (m)	Floor Area (m^2)
ROOM	Library Reading Room	south-east	19.00	29.70	4.30	564.30

	No	Orientation	Width (m)	Height (m)	Height from Floor (m)	Total Glazed Area m^2	WWR (%)
WINDOWS	1	north-east	19.00	3.80	0	72.20	57
	2	south-west	19.00	3.80	0	72.20	57
	3	north-west	4.80	3.80	0	18.24	22

Regarding the organization of the layout, the workplane is divided into three zones; two seating zones located perpendicular to the south-west and north-east facing windows, and the center zone with bookshelves positioned along the whole length, parallel to the seating zones' alignment angle (Figure 3.1). Exceptionally, two seating units are placed at the roughly center of the stacks zone. There is another study desk parallel to the north-west window wall, which is kept out of the experiment.

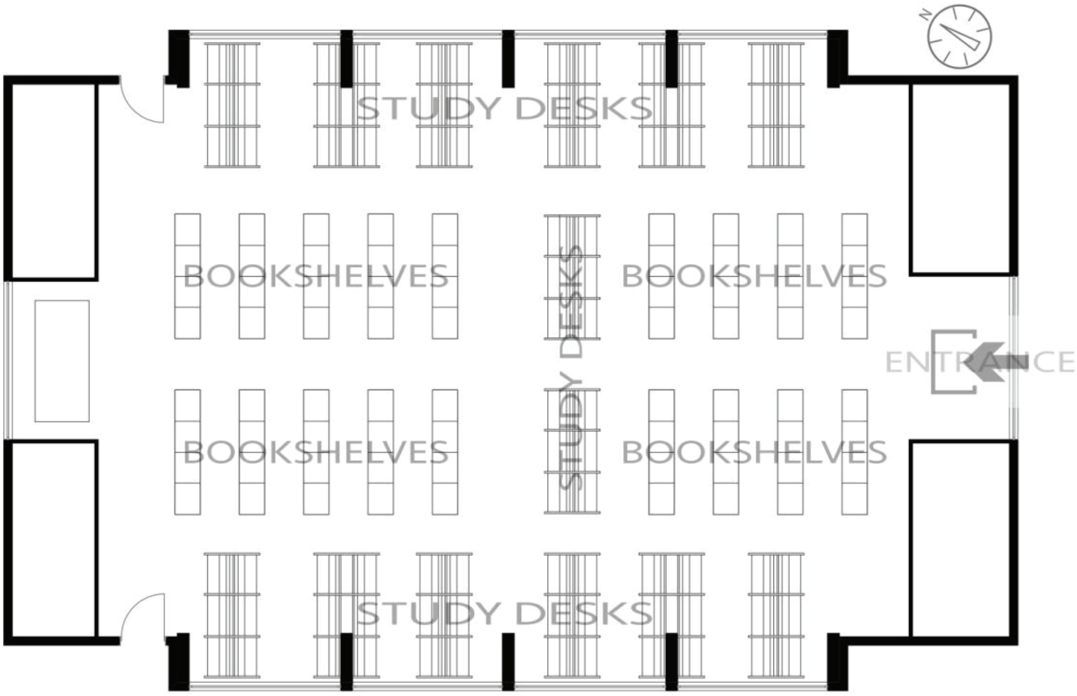


Figure 3.1. The plan layout of the library.

There are 28 study desks consisting of 3 seatings per unit, which correspond to 84 seatings in total. Each unit has dimensions of L 3.60 m x W 0.65 m with a height of 0.75 m from the ground. The units are covered with partitions (1.25 m in height) from three sides in such a way as to block excessive levels of daylight filtering through windows and probably provide privacy. The total number of bookshelves is 18 with the dimensions of L 3.60 m x W 0.70 m x H 2.10 m. They are placed one by one in order at the center zone of the reading room with circulation paths around themselves. Figure 3.2 presents interior photos of the library space from different angles.

Figure 3.2. Interior view of the reading room from north-west direction on 20 June at 10:00 am under intermediate sunny sky conditions (left) and from south-west direction on 20 June at 1:30 pm (right).

3.2. Field Measurements and the Photometrical Features of the Surfaces

According to the CIBSE (Chartered Institution of Building Services Engineers) Code for Interior Lighting, an interior or a representative area, is divided into a number of equal areas which should be as square as possible. The illuminance at the center of each area is measured and the mean calculated. This gives an approximate calculation of the average illuminance (CIBSE Factfile, 1996; Binol, 2008). In this study, it was impossible to divide the room into equal square areas due to the presence of the bookshelves placed inside the space. Besides, here the main purpose at first step was to evaluate visual performance of library users. Hence, one part of the measurement points (indicated with green colour in Figure 3.3) were chosen from the locations of study desks while the remaining part (yellow coloured points in Figure 3.3) represented the center zone. Horizontal illuminance (E_h) was chosen as the indicator where the paper and computer task was performed and the measurements were carried out to validate the simulation model. In total, 131 measurement points were set with a height of 0.76 m above the ground since the height of the study desks was measured 0.75 m. 54 measurement points were located on study desks whereas the rest of them were distributed in the center of room; vertically with equal distances (0.95 m) and horizontally with the distances of 0.90 m and multiples of 0.90 m. Also note that not all the study desks were included in the field measurements due to being in use during the instrumental monitoring; therefore some of them were not involved in the validation of the simulation model. Figure 3.3 presents the description of the on-site measurements layout indicating measurement points marked with yellow and green colors. As previously stated, green points stand for seating zones whereas yellow points represent the center zone measurement points around and between bookshelves.

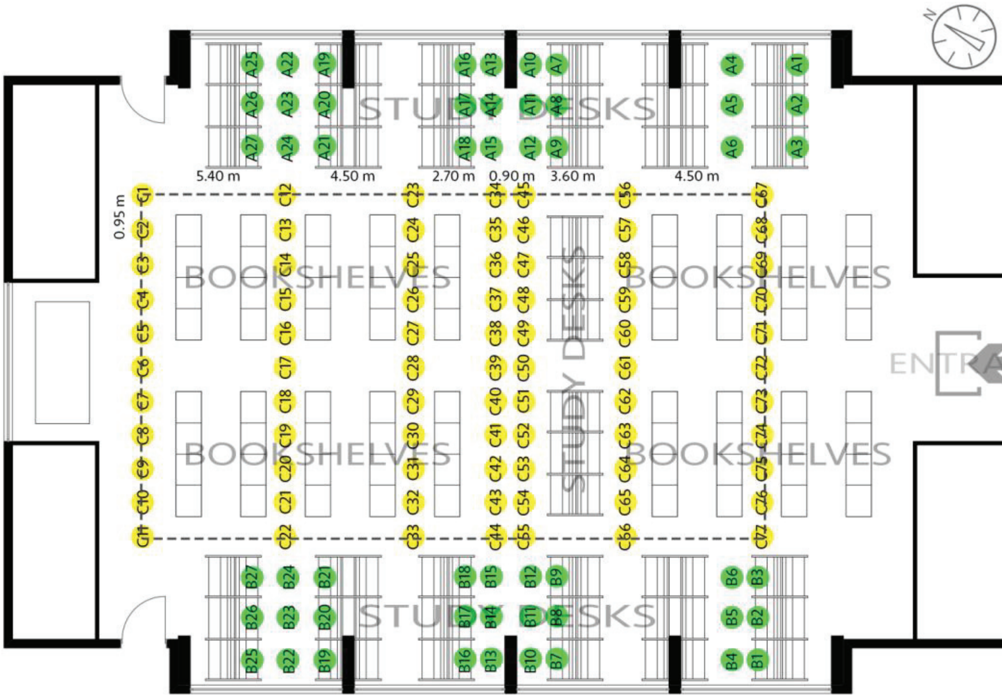


Figure 3.3. The determined on-site monitoring points for the horizontal illuminance measurement.

A digital illuminance meter and a luminance meter were used for the field measurements. Horizontal illuminance (E_h) on study desks were obtained by placing the illuminance meter on desks while the other measurements were carried out by the help of a portable metal stand with a height of 0.7 m from the floor level (Figure 3.4).

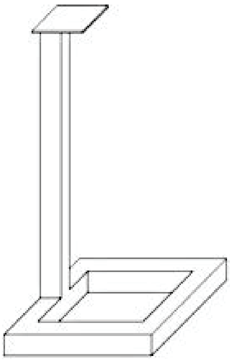


Figure 3.4. The portable stand to fix the measurement height of the illuminance meter. (Source: Binol, 2008)

The on-site test took place on June 20 and July 20. The measurement time was 2:00 pm for June 20, and 11:00 am, 12:30 pm and 3:30 pm for July 20. Sky condition was intermediate sunny for both days. Material characterization was performed on-site due to literature. Although in laboratory conditions, a spectrophotometer can better result in this sense, a total of six measurement techniques (so-called informal ways) can be used in conducting survey in actual spaces. They can provide us rough estimations about materials photometric qualities. These are defined as illumimance/illuminance, luminance/illuminance, Macbethcal, benchmark, CIBSE color chart, RAL color fan. Their accuracy ranges from 10% to 20% (Jakubiec, 2016). To practically and basically get information about materials on-site, luminance/illuminance based technique was used here. The monitored interior material properties for walls, floor, ceiling, and furnitures are found as 0.75, 0.35, 0.75 and 0.50 respectively and specified in Table 3.2. Taken pictures while monitoring photometric features and the identical simulated scenes of those pictures with their luminous variability within the field of view are also available in Appendix A. Although two key features which decrease the accuracy are observed --instability or inconsistency of daylit environment throughout the survey and observing specularity of materials--, such a measurement can provide us rough estimations about material reflections. The equation of Lambertian reflectance was the basis for this calculation (3.2).

$$L = \frac{E \, x \, \rho}{\pi} \tag{3.2}$$

Where L is luminance (cd/m^2), E is illuminance (Lux), ρ is reflectance of the surface.

Table 3.2. Photometrical features of the surfaces.

Surface	Reflectance/Transmittance [%]
Walls	73
Floor	37
Ceiling	78
Furnitures	47
Glazing	80

No daylighting strategies have been associated with the glazings as to guide daylight into the building efficiently. The windows consist of double layer glazing with visible light transmission of 0.75. To get the transmittance of glazing (Foytonont, 1999), similar equipment was used to measure the illuminance and luminance values when the windowpane was either open or closed.

The formulation to calculate the transmittance is given as (3.3).

$$\tau = \frac{\mathrm{E}_{in}}{\mathrm{E}_{out}} \tag{3.3}$$

Where E_{in} is the vertical illuminance of a single point when the windowpane is closed, E_{out} is the vertical illuminance of the same point when the windowpane is open.

3.3. Simulation Models in Relux

The results of the absolute measurements in Section 3.2 were afterwards used for the validation of the simulation model which was generated with identical building characteristics and day/hour configuration (See in Section 4.1). Computer simulations throughout the study were carried out using Relux Pro. Relux Suite is a Switzerland based freeware lighting simulation tool that offers both daylight and artificial light simulations (Relux, 2016). It provides interface to generate a new model of a building including materials, furnishings and color as well as enables to export 3D models from other applications (Yu, Su, and Chen, 2014). Simulations in Relux are generally based on the radiosity method; however, an improved version of Radiance has been applied in Relux Pro that authorises ray-tracing calculations for lighting analysis and renderings.

In this section, three virtual models were created using Relux Pro on solstice and equinox days at 12:30 pm, which are:

(i) the base model with the identical data collected on-site such as the photometrical features of surfaces, building characteristics and the placement of the interior furniture,
(ii) a new model with a rearranged layout with the same surface properties and the building dimensions,
(iii) the final model consisted of the second model with a new light shelf-reflective louver system.

In order to achieve a better agreement of the simulation models with the actual conditions, CIE intermediate sky with sun was chosen as the sky model since Izmir receives sunlight 68,6% of daylight hours yearly with a remaining 31,4% of daylight hours like cloudy or with shade (Izmir Climate and Temperature, 2017).

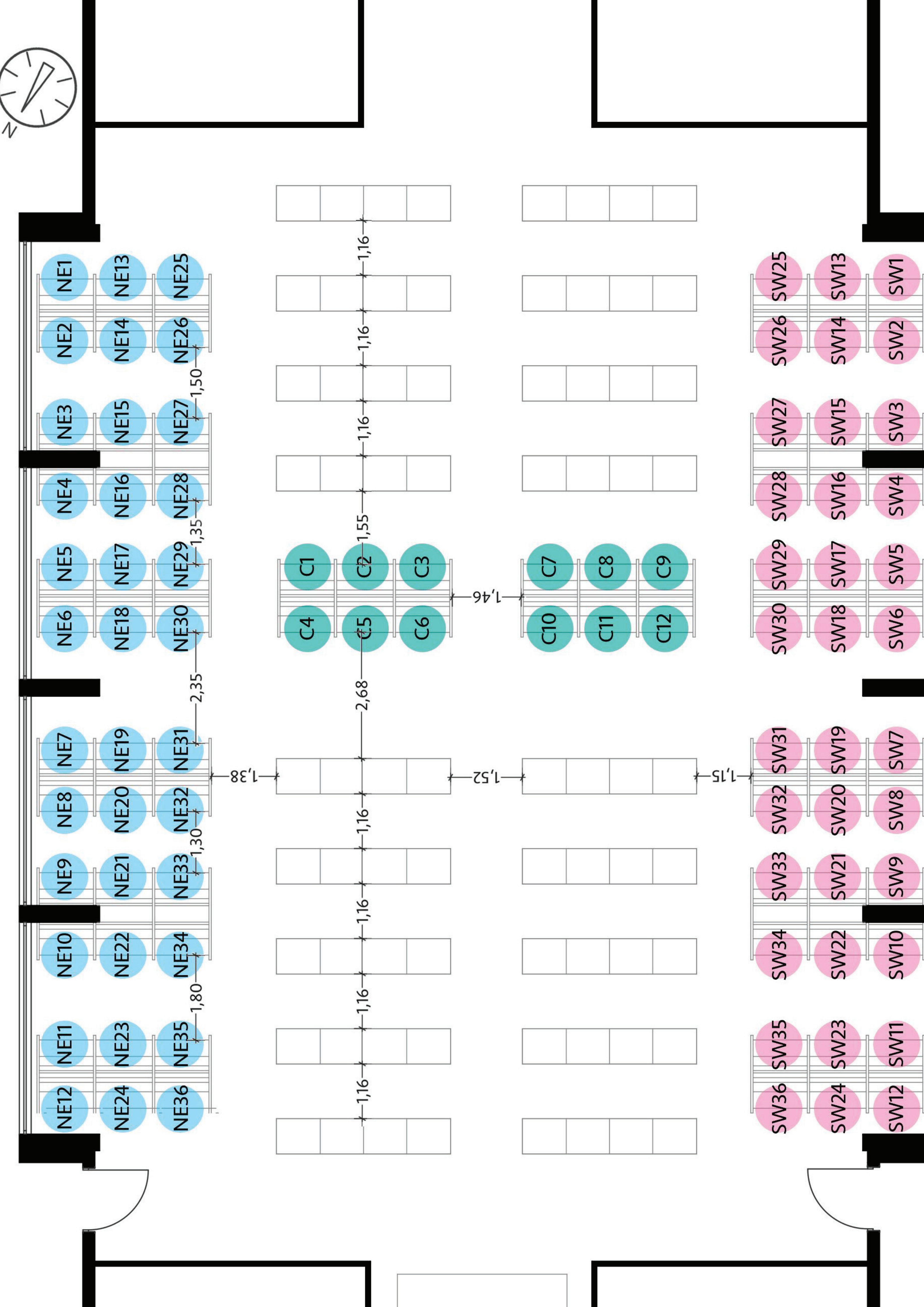
The final values of the interior material properties used in the virtual models are given in Table 3.3, which are almost identical with the on-site monitored values. Once the features of the monitored room were fixed identically in the base model, illuminance and luminance based analysis were performed so as to evaluate the visual performance of the existing case situation. Then the second model was created to find out how a simple change in the layout arrangement could make a difference on the assessment of visual conditions. Andersen et al. (2013) states that “It is impossible to ‘optimise’ buildings for good daylighting performance with static glazing alone, since daylight intensity varies dramatically.” The final model was developed based upon the expression of Andersen et al. since a further improvement is possible with a reasonable daylighting strategy. Therefore, Subsection 3.3.1, Subsection 3.3.2, and Subsection 3.3.3 will briefly explain the improvement phases and the underlying factors for each implementation phase. As a following step, in Chapter 4, the results of each phase in terms of illuminance, luminance, and uniformity will be compared within the scope of the standards and recommendations.

Table 3.3. The measured interior material properties of the case room and those employed to the virtual models.

Case Room			
Interior Room Surface	Parameter	Measured Data	Virtual Models
Internal wall	Reflectance (%)	73	75
White ceiling		78	75
Dark grey floor		37	35
Furniture		47	50
Internal glazing	Transmittance (%)	80	75

3.3.1. The Base Case Model

As mentioned before, the simulations for each case were identically run on solstice and equinox days at 12:30 pm under CIE intermediate sky with sun conditions. Initially, the analysis of the base case model was carried out which entails the following steps in Subsection 3.3.2 and Subsection 3.3.3: rearrangement of the layout organization and implementation of a new daylighting strategy. For all cases, the assessment of visual performance was the main criteria, which consists of task illuminance, luminance ratios within the field of view, and the uniformity at a workplane. Therefore, 84 points (indicating the total number of seats in the library reading room) in total were evaluated in terms of visual performance standards and recommendations in libraries (See Table 2.2 and Table 2.3). Note that special attention was paid to the dimensions between furniture in terms of library design recommendations, whose accuracy latter will be checked in Chapter 4.2. A description of the base case measurement points marked with different colours and the distances between furnitures measured at the site are shown in Figure 3.5.


N
NE1
NE2
NE3
NE4
NE5
NE6
NE7
NE8
NE9
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NE11
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NE16
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SW33
SW34
SW35
SW36
1,16
1,16
1,16
1,55
2,68
1,16
1,16
1,16
1,16
1,50
1,35
2,35
1,30
1,80
1,46
1,38
1,52
1,15

3.3.2. The Second Case with the New Layout Arrangement

For this step of improvement, such basic layout-related changes were applied to the base case model that mainly emphasized on the significance of space arrangement that could benefit more from daylight while considering the library space planning requirements. The analysis of virtual base case model has shown that:

(i) the south-west part of the library, especially around the measurement points of SW1-SW12 (See in Figure 3.5), displayed peaks of horizontal illuminance values,

(ii) on the contrary, rapid decreases of illuminance are observed with the distance from the windows in the same zone (SW25-SW36 in Figure 3.5),

(iii) the measurement points adjacent to window in the north-east part (NE1-NE12 in Figure 3.5) performed a better daylight performance; however, dramatic decreases in illuminance were found as the distance from the window increased,

(iv) due to the large and deep floor area, daylight was distributed inside the space in a way that the zones close the windows were excessively illuminated whereas the center zone received poor levels of daylight,

(v) general observation on the illuminance distribution relied on the basic orientational fact that the north-east part of the room had a more satisfactory illuminance and luminance distribution within the context of recommended illuminance values for libraries whereas south-west part had seriously unbalanced distribution due to having no sun protection,

(vi) another significant finding was that such minimum dimensions between furniture were not in accordance with the recommended minimum distances.

Therefore, based on the identified deficiencies of the base case layout, as a first step, a new layout proposal was entailed as shown in Figure 3.6. The number of furniture and their material properties were kept identical for a better understanding of the utilization, but only the partitions between C1-C12, SW1-SW4, SW9-SW16, SW21-SW28 and SW33-36 were removed in an attempt to increase daylight availability on the workplane of those points that were located roughly at the center of the room that received less sunlight compared to the workplaces near windows.

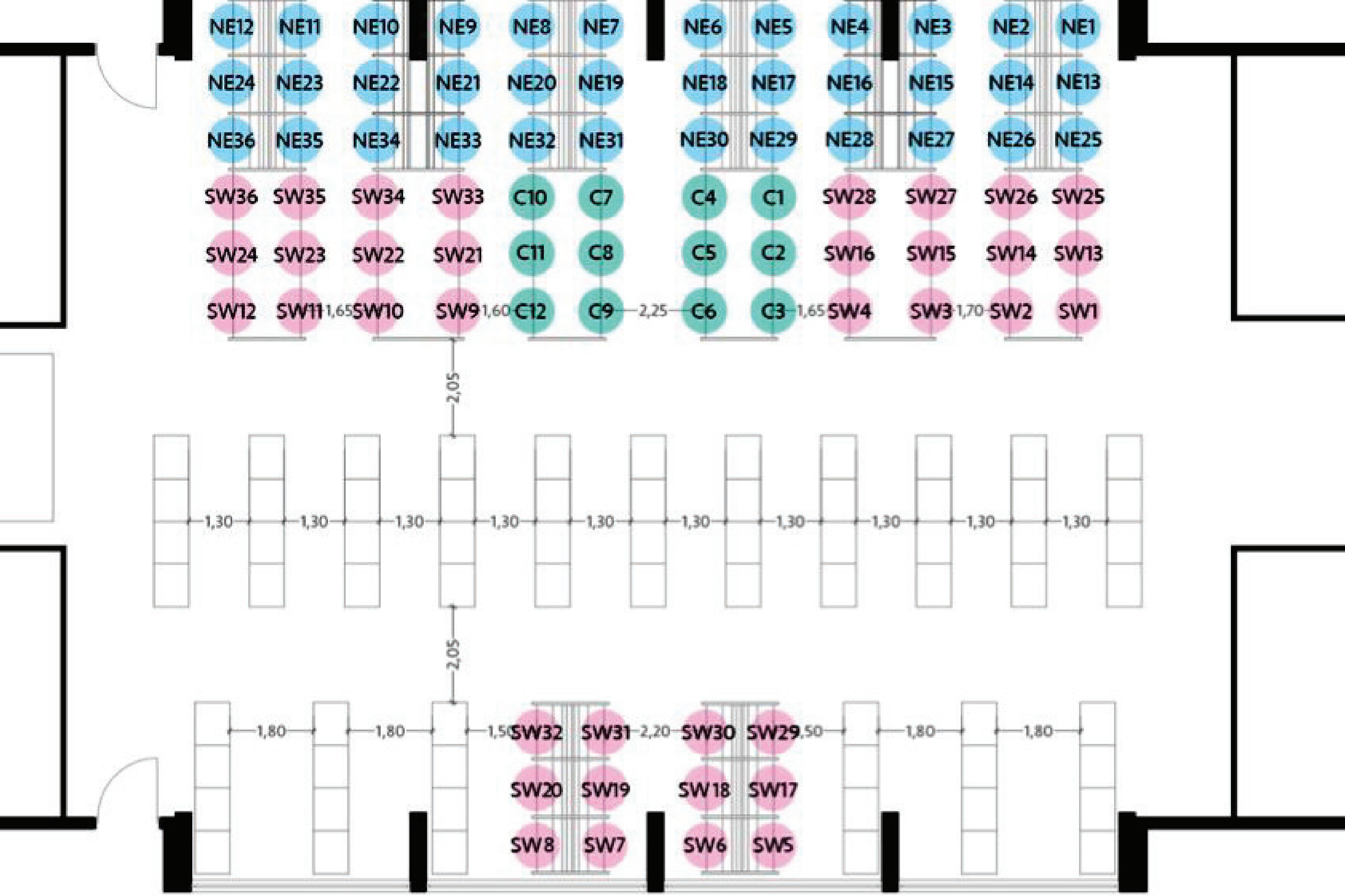

Figure 3.6. The new layout arrangement measurement positions.

3.3.3. The Final Model with the Application of Light Shelf-Reflective Louver System

This is the final step of the improvement which includes a new light shelf-reflective louver system applied on the south-west and north-east facade of the building. The new layout arrangement in Subsection 3.3.2 particularly emphasized on finding the optimal space planning by taking orientational recommendations into consideration. Yet, a better version of improvement was intended due to the fact that static glazing alone in buildings with these kind of geometrical characteristics results in dramatic light level changes among different seatings and thus influences the overall visual performance of occupants in a bad way.

The system was chosen due existing literature and actual products. Moazzeni and Ghiabaklou (2016) tested the performance of light shelves according to the combinations of their dimensions angles and orientations. In the south facing case, a 1.9m-long-light shelf whose half is located inside and other half on outside, performed better with almost 80% daylight availability. Similarly, Freewan (2010), focused on the interactions between the geometry of light shelves and curved ceiling. Daylight performance and redirection were attained best when externally curved light shelf was used at 3 m high from floor and its depth was 1.65 m. Variations of reflective louver systems are produced and available in the market. One of them was chosen from Retrolux Archive (Retrosolar, 2017).

Light shelf was positioned to the south-west facade throughout the glazing at 3.00 m from the floor with a depth of 1.6 m. Modeled as external and internal, the light shelf was defined as specular with a reflectance value of 85%. The internal reflective louver components for the south-west facing window were placed between 1.40 m and 2.85 m above the ground. Each of lamella has 13 mm depth and the spacing between two lamellas is 0.5 cm. Reflectivity of the surface was assigned to the value of 85% in the same way as the light shelf. The identical reflective louver system was applied to the north-east facing window as well between 2.00 and 2.85 m (Figure 3.7).

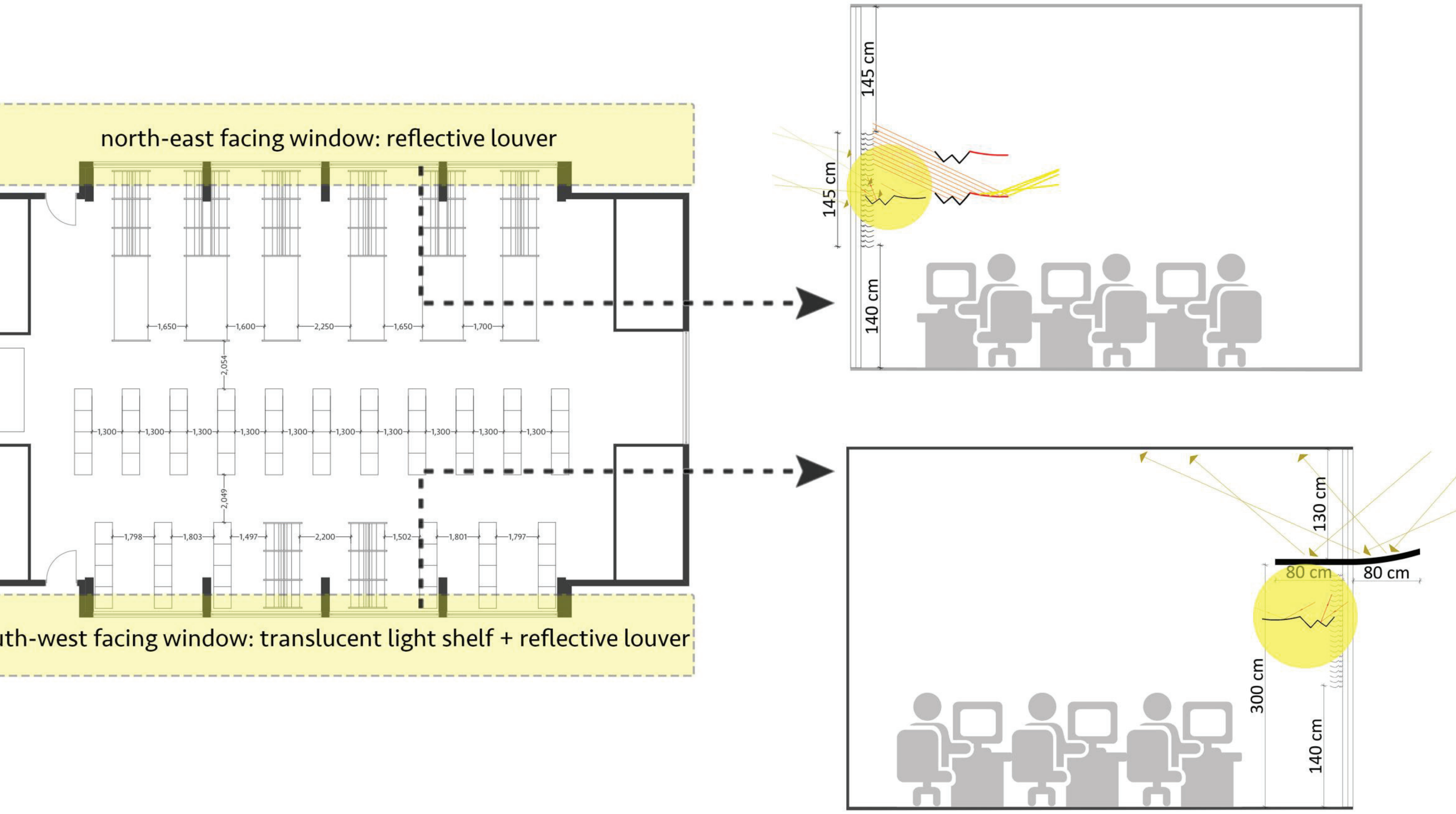

Figure 3.7. Daylighting strategy on the plan layout and the cross sectional views showing its shape and principle.

The properties and the placement details of the two suggested systems are summarized in Table 3.4 and the views from the interior of the simulation model are shown in Figure 3.8.

Table 3.4. Properties of the suggested systems.

System	Orientation	Depth	Height	Reflectivity (%)
Light shelf	South-west	1.60 m	3.00 m (above the ground)	85
Reflective louver	South-west	13 mm	1.40-2.85 m (above the ground)	85
	North-east	13 mm	2.00-2.85 m (above the ground)	85

Figure 3.8. The application of the light shelf-reflective louver system on south-west facing window (above) and the reflective louver system on north-east facing window (below).

CHAPTER 4

RESEARCH FINDINGS

This chapter presents the following sections:

Section 1.01 - field measurement and the validation of the simulation model,

Section 1.02 - visual performance analysis results of the base case with existing layout,

- visual performance analysis results of the base case with a new layout proposal,
- visual performance analysis results of the final model that consists of a new layout and a light shelf-reflective louver system proposal.

4.1. Field Measurement and Validation of the Simulation Model

The same model of the on-site test was run in Relux simulation software and identical days and hours of the absolute measurements were chosen for the simulations. Photometrical features of the surfaces are assigned similarly at the values in Table 3.2. Likewise, illuminance values of the same measurement points are calculated. Figure 4.1 shows the comparison between the measured results and simulated results of illuminance values at 131 measurement points in total.

Yellow points were measured on June 20 at 2:00 pm and July 20 at 11:00 am, and green points were measured on July 20 at 12:30 pm and 3:30 pm. Validation of Relux simulation tool has mostly known with its consistency for daylight calculations. Yet, in this case, the coefficient of determination (R^2) values ranged between 51% and 78% for all simulations on the above dates; showing the acceptable accuracy of the simulation model when Relux outputs and field measurements were compared (Figure 4.1). This means that knowing the illuminance at a point by the simulation gives an almost 51- 78 percent chance of predicting their values on the measurement. Yet, considering the large floor area of the experimental space and furniture, the error margin might be considered acceptable.

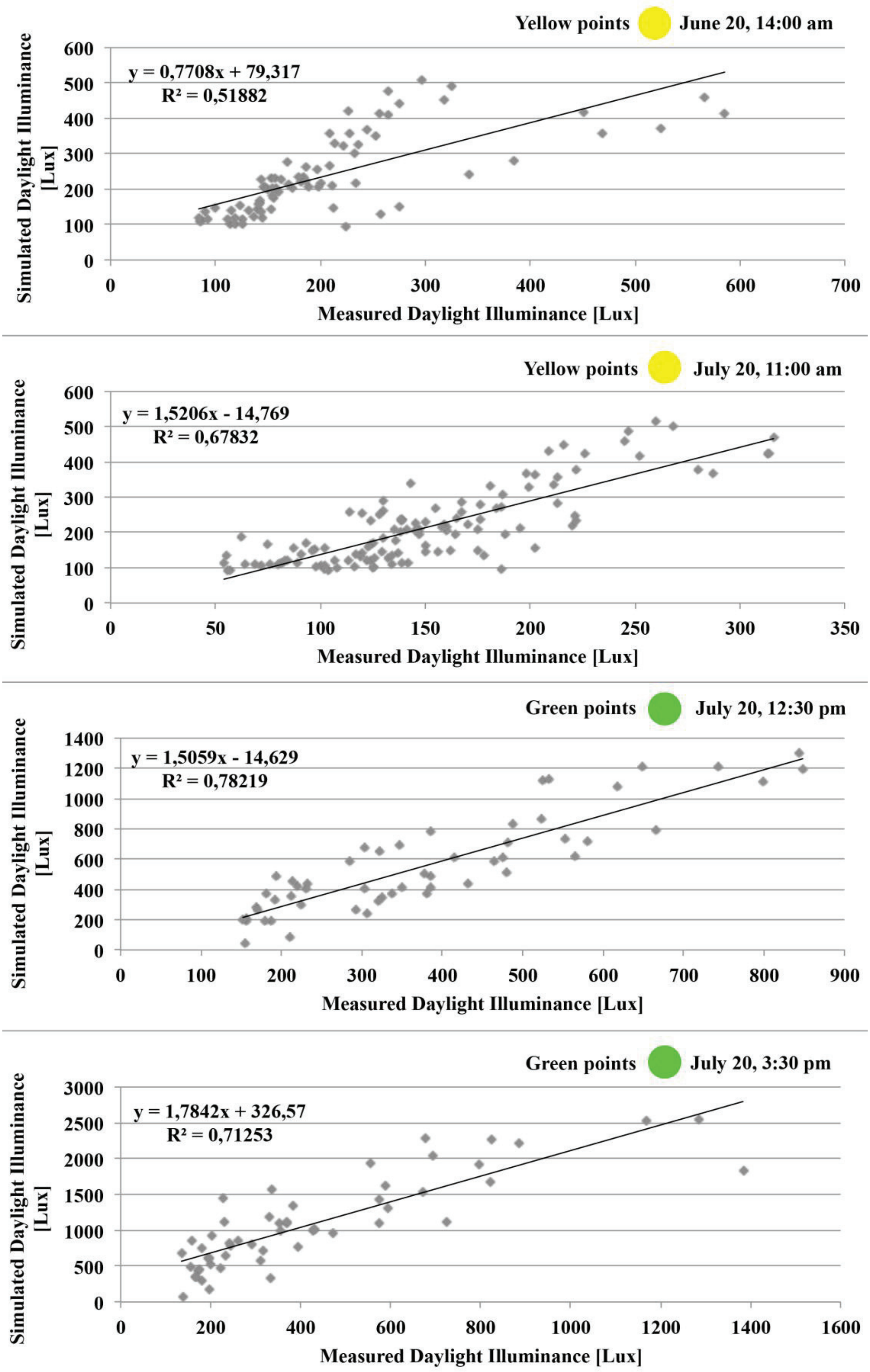

Figure 4.1. Validation of simulation results of the yellow and green measurement points on plan layout.

In detail, MPE values and CV(RMSD) are calculated to indicate the averaged error and deviation of measured to simulated illuminance values (Table 4.1).

Table 4.1. The averaged error and deviation of measured to simulated illuminance values.

	R^2	MBE	CV(RMSD)
June 20, 2.00 pm	0.51	10%	21.1%
July 20, 11.00 am	0.67	20%	21.7%
July 20, 12.30 pm	0.78	20%	19.8%
July 20, 3.30 pm	0.71	55%	31.1%

4.2. Base Case Findings

This section is divided into 3 subsections displaying the results and explanations related to the analysis of task illuminance, uniformity at the workplane and luminance ratios within the observers' field of view and the interpretations within the frame of visual performance recommendations in libraries.

At first step, minimum dimensions between units were evaluated considering the library space planning instructions. Each dimension met the conditions of recommended values expressed by Neufert and Neufert (2002), but only the measured distances between bookshelves were found 1.16 m where a narrowest aisle should be minimum 1.6 m (See Figure 2.5 for the recommended minimum distances and See Figure 3.5 for the measured dimensions in the base case). This deficiency was taken into consideration along with the other deficiencies that were found in Subsection 4.2.1, Subsection 4.2.2 and Subsection 4.2.3 when the new layout arrangement is submitted in Section 4.3.

4.2.1. Task Illuminance and Uniformity at the Workplane

A total of 84 measurement points at the center of each study desk were analyzed to extract the horizontal illuminance values and the uniformity ratios. Note that the analyses were performed at 12:30 pm on solstice and equinox days under CIE intermediate sky with sun sky model.

Task Illuminance:

Overall, base case average illuminance values have been found out as 1500 lx, 459 lx, 1632 lx and 830 lx respectively on March 21st, June 21st, September 23rd and December 21st at 12:30 pm. As presented in Figure 4.2, illuminance in all cases shows an uneven distribution with a wide range of variation from very low levels to thousands. Peaks of horizontal illuminances occur at measurement points (SW1-SW12 in Figure 4.2) that were placed next to the south-west facing glazings. On the contrary, rapid decreases of illuminance are observed with the distance from the windows in the same zone (SW25-SW36 in Figure 4.2). Illuminance distribution of north-east oriented points (NE1-NE36 in Fig.7) appears relatively more uniform ranging from 46 lux to 1180 lux, which also partly decreases with the distance from the windows. Speaking of center zone measurement points (C1-C12 in Figure 4.2), we can conclude that the illuminance shows the lowest values, i.e. between 97 lux and 309 lux, because of being at the farthest locations from the windows.

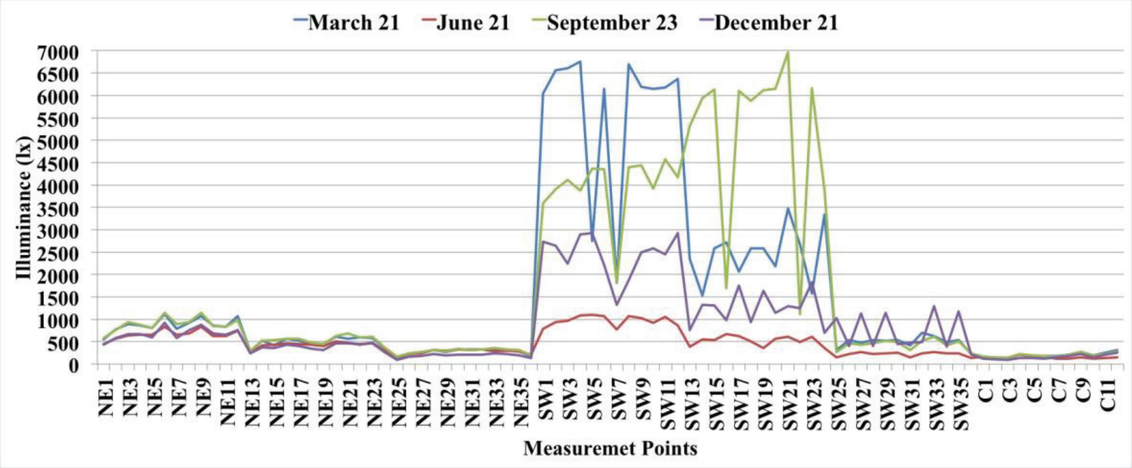

Figure 4.2. Horizontal illuminance (lux) of each measurement point at 12:30 pm on solstice and equinox days – Base Case.

Uniformity:

According to the summarized data shown in Table 4.2, illuminance values indicate a wide range for all cases which results as unsatisfactory uniformity ratios according to the standards. Except December 21, average illuminance values of the remaining three days were found beyond recommendations, which were ought to be between 500-1000 lux; however, at the same time, December 21 performed the worst uniformity performance. It is highly possible that dramatic changes in the amount of daylight over the working plane result as harsh indoor environment for the occupants and the findings above strongly support the need for a daylighting strategy in terms of improving visual performance of occupants. More detailed illuminance analysis of each measurement point for solstice and equinox days are given as tables that list task illuminance values on each point for four different days are presented in Appendix B.

Table 4.2. The lowest, highest and average illuminance values on working planes and the obtained uniformity ratios in the base case.

12:30 pm	E_{min}	E_{max}	E_{avg}	U (E_{min}/E_{avg})
March 21	137 lx	6750 lx	1500 lx	0,091
June 21	121 lx	1100 lx	459 lx	0,263
September 23	142 lx	6960 lx	1632 lx	0,087
December 21	94 lx	2930 lx	830 lx	0,11

4.2.2. Luminance Ratios within the Field of View

A total of 84 points were studied at a height of 0.76 m on the center of each study desk which was arranged with a computer screen and a white paper placed in front of the occupant. Figure 4.3 illustrates a representative view point with a fixed height of 1.40 m. The objective in this subsection was to identify the daylight distribution problem by measuring luminance pattern analysis in the visual field.

Figure 4.3. A representative view point of the renderings.

Luminance distribution of each view point was analyzed on solstice and equinox days at 12:30 pm. By reason of listing the numerical analysis and presenting renderings of 84 points for four different days may complicate the understanding, luminance-based analysis was limited and documented within the 21 March 12:30 pm simulations and the luminance map analysis for each case was presented for three view points with the least uniform luminance pattern (SW3, SW10, SW12).

Following the simulation results of 84 view points, the above-mentioned three points (SW3, SW10, SW12) were determined as holding the poorest luminance distribution performance within the context of recommended luminance ratio standards (IES, 1993). To achieve this, luminance values on screen, white paper, desk, wall, general surrounding and side wall adjacent to window were tabulated according to the luminance maps of each view. Table 4.3 lists in detail the luminance patterns of each view point in the reference case.

According to Table 4.3, south-west perimeter zone had the most critical luminance distribution within the field of view which ranged from 1,6 cd/m^2 to 2730 cd/m^2 on March 21 at 12:30 pm. In the case of view SW3, for example, the luminance ratio between the computer task and the side wall adjacent to window was found 1:120 on March 21 at 12:30 pm, which is excessively high comparing to the recommended 1:10 ratio. The case of view SW10 displayed the worst ratio between the paper task and desk (1:21.9) compared to view SW3 and SW12. A reasonably better version of luminous variability was observed in the north-east perimeter zone for not being affected by the high brightness as much as the southern zone; i.e. luminance on white paper ranger from 35 cd/m^2 to 343 cd/m^2 while the range was 99 cd/m^2 - 2620 cd/m^2 in the case of south-west perimeter zone; yet still, particularly on some dark surfaces, dramatic luminance decreases were observed as moving away from the window. The view points located at the center zone (C1-C12) displayed the most uniform luminous variability ranging from 1,4 cd/m^2 to 733 cd/m^2 considering the all surface luminances.

Yet, in all cases, the standards and recommendations (See in Table 2.3) could not been well corresponded; i.e. the luminance ratio between the paper task and computer task ranged from 1:12 to 1:158 –which ought to be between 1:2.5-1:3, and this case provoked a new layout proposal which may enhance the existing luminous conditions.

Table 4.3. Luminance within the field of view in the base case on March 21, 12:30 pm.

BASE CASE - MARCH 21, 12:30 pm						
Points	**Luminance (cd/m2)**					
	Dark Screen	**White Paper**	**Desk**	**Wall**	**Background**	**Side Wall Adjacent to Window**
SW1	13	2240	106	442	19,7	783
SW2	3,4	2520	146	351	9	1830
SW3	11	2380	115	419	x	1330
SW4	14,7	2480	120	371	x	909
SW5	15	872	108	450	18,8	640
SW6	5,25	2420	171	348	14	1100
SW7	27,8	734	136	454	17,5	1040
SW8	14,6	2520	182	343	87	1020
SW9	16,8	2620	135	476	x	1360
SW10	11,6	2520	115	336	x	1270
SW11	11	2480	140	630	15	982
SW12	9,7	2570	150	307	89	603
SW13	4,5	2010	64	439	23,5	885
SW14	6	2100	70	632	10	1180
SW15	6	2060	56	442	26	701
SW16	9	2010	102	405	101	750
SW17	7	2090	63	439	25	640
SW18	5	1980	59	334	8,2	807
SW19	5	2010	63,1	386	27	990
SW20	4,7	2080	74	x	128	855
SW21	10,6	2090	63	474	20,7	1090
SW22	11,6	1910	80	375	142	445
SW23	8,7	2730	67	x	20	1060
SW24	5	1950	74	303	127	675
SW25	3	95	47	235	25	453
SW26	3,15	182	149	106	5	x
SW27	4,5	184	49	515	28	744
SW28	5	210	72	187	11	1710
SW29	4	204	75	606	28	855
SW30	3,8	172	78	237	12	390
SW31	3,7	186	72	428	20	728
SW32	3,16	210	55	128	11,6	444
SW33	3,6	220	78	42	19,7	1580
SW34	5	154	134	x	107	488
SW35	3,4	210	58	11,5	21,5	x
SW36	1,6	99	45	390	121	392
NE1	6,3	210	108	196	18	700
NE2	6,7	256	128	187	10,8	771
NE3	7,3	279	150	203	x	782
NE4	7	208	176	224	x	630
NE5	7	217	135	250	x	945
NE6	8	310	217	263	x	463
NE7	8	230	145	285	x	724
NE8	7,5	245	181	253	79	970
NE9	11	317	230	252	x	852
NE10	7	209	171	218	x	551
NE11	8,3	237	148	270	17	776
NE12	7,8	343	190	240	71	742

(cont. on the next page)

Table 4.3. (cont.)

NE13	3,4	58	48	256	20	451
NE14	4	112	78,3	179	6,86	318
NE15	4	106	74	223	12	370
NE16	6	113	90	193	7	219
NE17	4,2	105	80	294	19	411
NE18	4,6	94	96	169	11	411
NE19	5,6	86	64	284	22	668
NE20	3,5	131	96	106	16	343
NE21	6	124	91	278	21	337
NE22	6	106	92	240	104	446
NE23	4	115	93	378	21	456
NE24	2	79	55	232	92,4	682
NE25	24	35	32	234	22,4	267
NE26	3	50	53	69	8,3	x
NE27	3	60	49	300	21,6	500
NE28	4,5	86	61	95,4	8,5	223
NE29	3	65	63	457	22,1	574
NE30	3,5	80	68	272	8	276
NE31	4	75	70	321	21	362
NE32	3,6	62,8	72,6	103	8,1	466
NE33	4,2	82	74	136	21	617
NE34	3,7	91	70	238	95	1050
NE35	3	71	72	22	5	x
NE36	2,5	46	35	456	98	478
C1	1,4	48	30	35	33	325
C2	1,6	36	25	38	46	293
C3	1,7	36	34	58	54	x
C4	2	64	51	45	65	733
C5	1,7	61	31	48	90	428
C6	1,7	54	35	24	36	x
C7	1,6	46	34	110	18	x
C8	2	44	33	x	46	x
C9	2	55	33	31	93	x
C10	1,7	64	40	62	34	x
C11	1,8	70	42	x	46	x
C12	2,6	90	47	46	64	352

Besides the numerical luminance distribution that was listed in Table 4.3, also luminance mapping results made it visually clear that particularly south-west perimeter zone had the most critical luminance distribution within the field of view. As mentioned above, to ease the comprehension of the effectiveness of the new layout and the daylighting system, three view points (SW3, SW10, SW12) with the least uniform luminance pattern were identified which were unsurprisingly located near the south-west facing window (See in Figure 4.4). Although their visual angles were reverse to each other, the identical problem with the case of view SW3 and the view SW10 was the interaction of the bright surfaces right in front of themselves and the other surfaces (i.e. desk partition, background) with relatively lower brightness which afterwards causes undesired luminous variability.

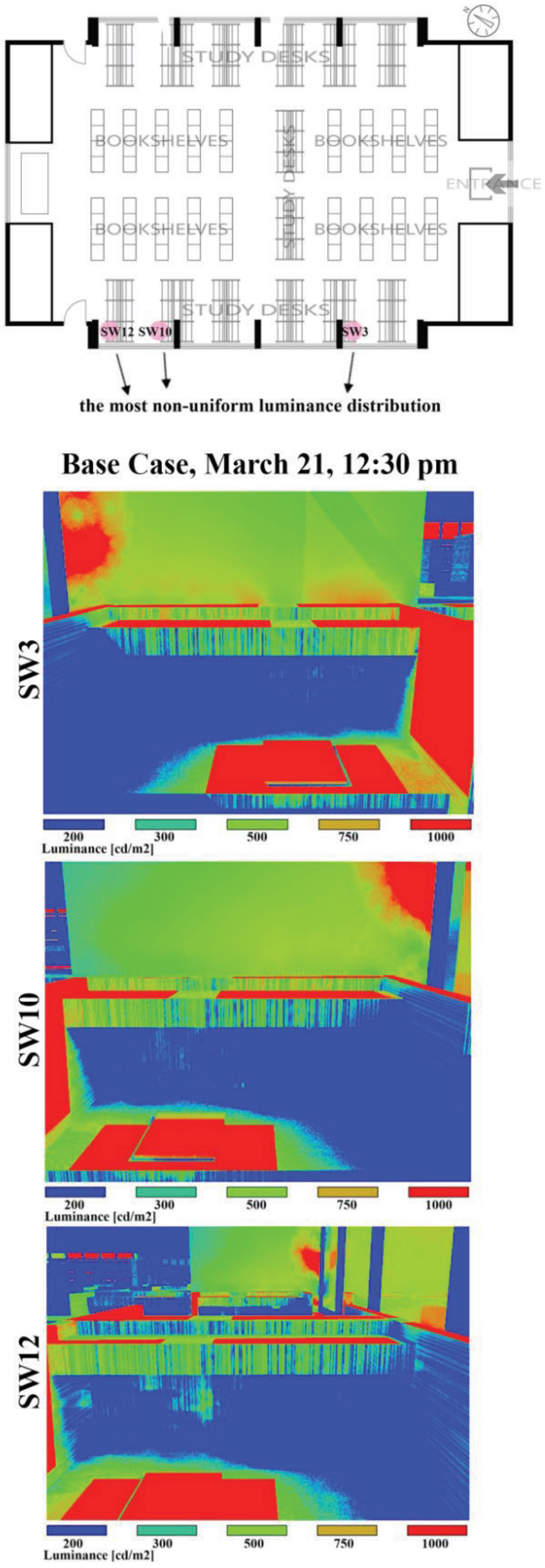

Figure 4.4. False colour luminance maps of the most problematic three view points on March 21 at 12:30 pm for the base and the second case.

4.3. Second Case Findings

Based on the assessment of the actual case findings, the south-west part of the room was observed as having the lowest daylighting performance which led to unbalanced task illuminance values and luminance ratios within the field of view among different measurement points. Thus, as the second step, a new layout was constituted with a purpose of minimizing these deficiencies. The highlights while attempting this new layout organization were first to pay attention for the minimum distances between units which did not completely meet the library space planning requirements in the base case, and to reorganize the room layout in such a way that distant from the problematic parts of the large south-west window. Therefore, four study desks with the poorest daylight conditions from the south-west part of the library were shifted from there to the north-east part in parallel with their previous positions and aligned next to the north-east facing seating desks (See Figure 3.6). Six of the bookshelves were moved in the place of the shifted study desks while the rest of them (twelve in total) were placed 2,05 m away from the other six bookshelves in a parallel direction.

Before giving the simulation based results, initially, minimum dimensions between units were evaluated considering the library space planning instructions. Each dimension that were measured at the site met the conditions of recommended values expressed by Neufert and Neufert (2002), but only the distances between bookshelves were found 1.16 m where a narrowest aisle should be minimum 1.6 m (See Figure 2.5 for the recommended minimum distances and See Figure 3.5 for the measured dimensions in the base case). This deficiency was taken into consideration along with the other deficiencies which were related to task illuminance and uniformity at the workplane and luminance ratio results when the new layout arrangement is submitted in Section 4.3.

4.3.1. Task Illuminance and Uniformity at the Workplane

Likewise, 84 measurement points at the center of each study desk were analyzed under the same time data, sky condition and orientation. Although the layout arrangement was different, the codes of the measurement points remained identical so that the point-based evaluation between the base and the second case would be comprehensible.

Task Illuminance:

The main results obtained for the second case are illustrated on Figure 4.5. They show the illuminance values of each point which lies within the range of 49-6610 lux. For this assessment, likewise the base case analysis, equinox and solstices were taken into account and 12:30 pm was chosen as the simulation time. The results indicated that illuminance within the range of 1200-6610 lux was particularly distributed in the remaining desks which are SW 5-8 and SW 17-20 (See in Figure 3.6).

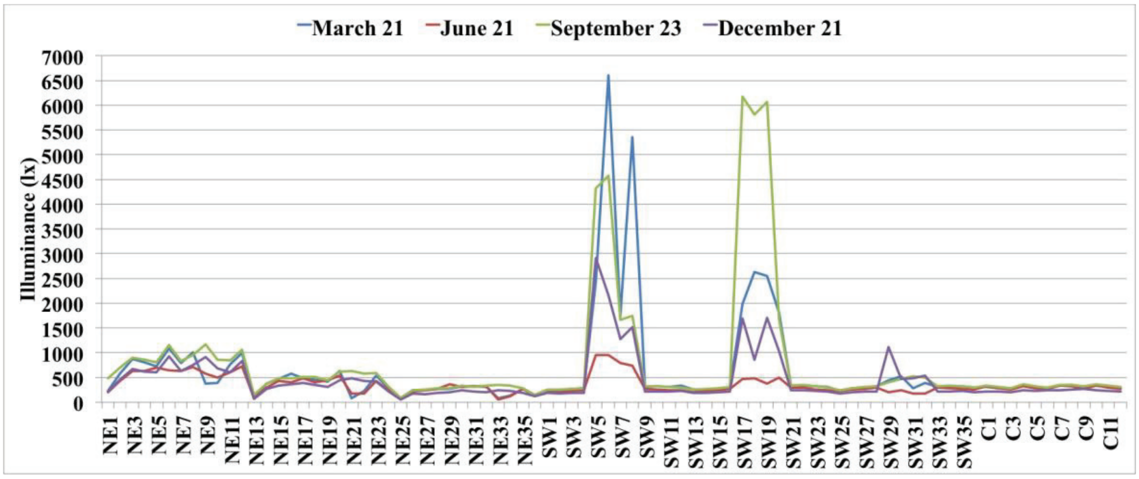

Figure 4.5. Horizontal illuminance (lux) of each measurement point at 12:30 pm on solstice and equinox days – Second Case.

A better performance of illuminance distribution was observed at the points that were moved from the southern part of the room to the northern part. As illustrated in Figure 4.6, on March 21st, fluctuation in illuminance among different measurement points in the base case was replaced by a more uniform illuminance distribution within an acceptable range of 241-339 lux. More figures including the results of each equinox and solstice day is found in Appendix C.

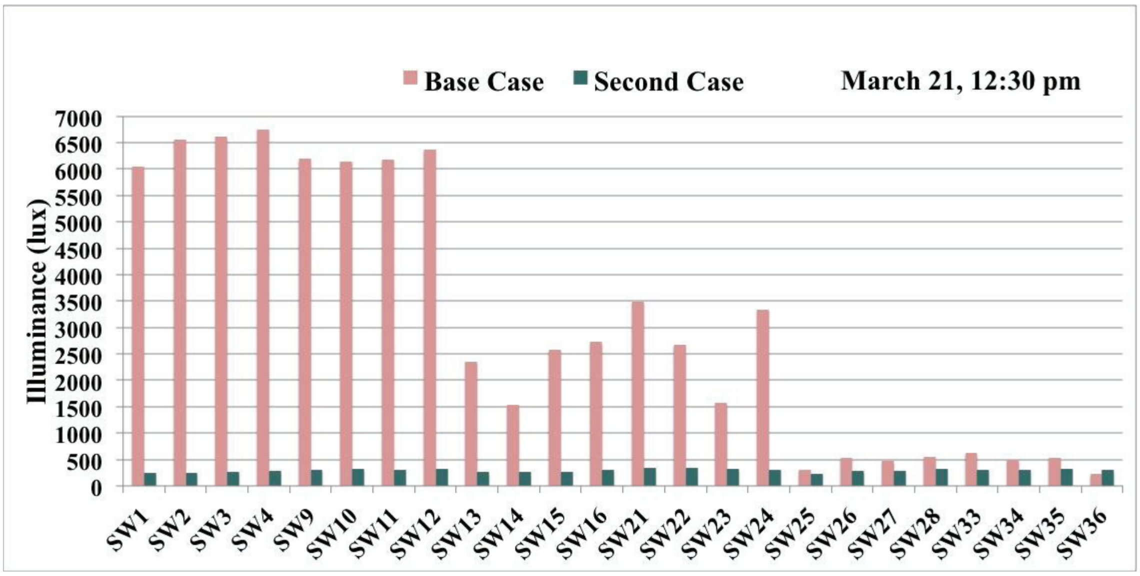

Figure 4.6. Comparison between illuminance distribution of the shifted south-west oriented points in the base case and the second case for March 21st 12:30 pm.

The general view on the comparison between illuminance distribution of each measurement point in the base case and the second case is presented in Figure 4.7. Likewise, the figure represents the analysis of the simulation carried out at 12:30 pm on March 21st and the remaining simulation results are presented in Appendix C. The graph at the first sight indicates that the illuminance values of the second case act more uniformly compared to the base case. Only still relatively fluctuating parts appear between SW5-SW8 and SW17-SW20 which remained at the same position as the base case. Apart from this, the overall illuminance distribution amongst 84 measurement points provides nearer values of illumination to the recommended range.

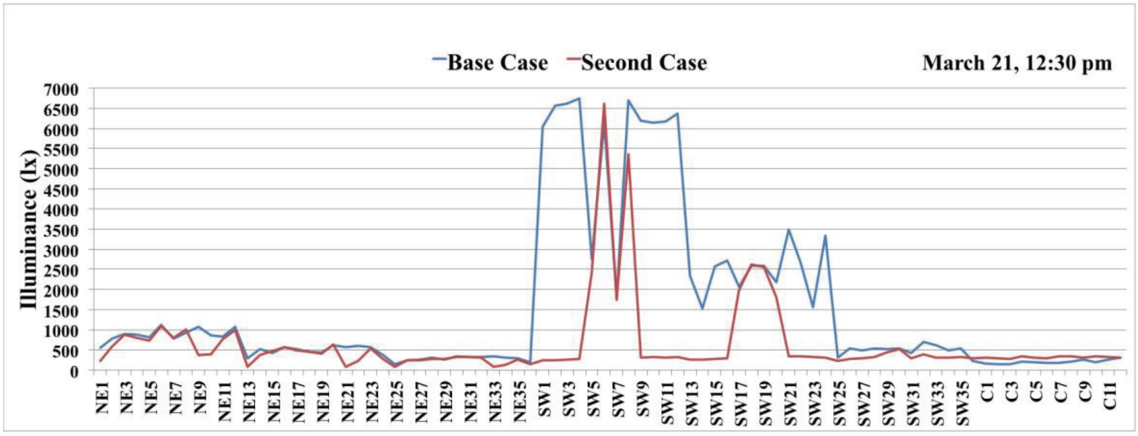

Figure 4.7. Illuminance of the measurement points indicating the change between the base case and the second case for March 21st 12:30 pm.

Uniformity:

Despite the fact that the number of measurements points whose illuminance values got nearer to the recommendations, not much change was observed in uniformity when compared to the base case. Below, Table 4.4 presents the overall assessment about uniformity considering March 21st, June 21st, September 23rd and December 21st, 12:30 pm. The reason of this circumstance is that the layout rearrangement was made in an attempt to decrease the peaks of illuminance values of the south-west oriented measurement points. This purpose was accomplished to a large extent; however, such seatings with relatively high illuminance values remained at the same position. Additionally, the lowest illuminance range did not show a big alteration since there was no implied attempt in this step of improvement. Therefore, except June 21st, a slight increasement in uniformity was achieved for each day which occured by means of the average illumination (E_{avg}) that got nearer to the recommended range.

Table 4.4. The lowest, highest and average illuminance values on working planes and the obtained uniformity ratios in the second case.

12:30 pm	E_{min}	E_{max}	E_{avg}	U (E_{min}/E_{avg})
March 21	75 lx	6610 lx	636 lx	0,118
June 21	49 lx	954 lx	350 lx	0,14
September 23	86 lx	6180 lx	769 lx	0,111
December 21	51 lx	2910 lx	450 lx	0,113

As result, four main graphs were generated highlighting the E_{max}, E_{min}, E_{avg} and uniformity (E_{min}/E_{avg}), change between the base case and the second case (Figure 4.8). E_{max}, E_{min} and E_{avg} values decreased for all solstice and equinox days as expected whereas the uniformity increased in three cases except June 21st. This might be due to position of the sun on the summer solstice which already led to maintained illuminance lower than March 21st, September 23rd and December 21st.

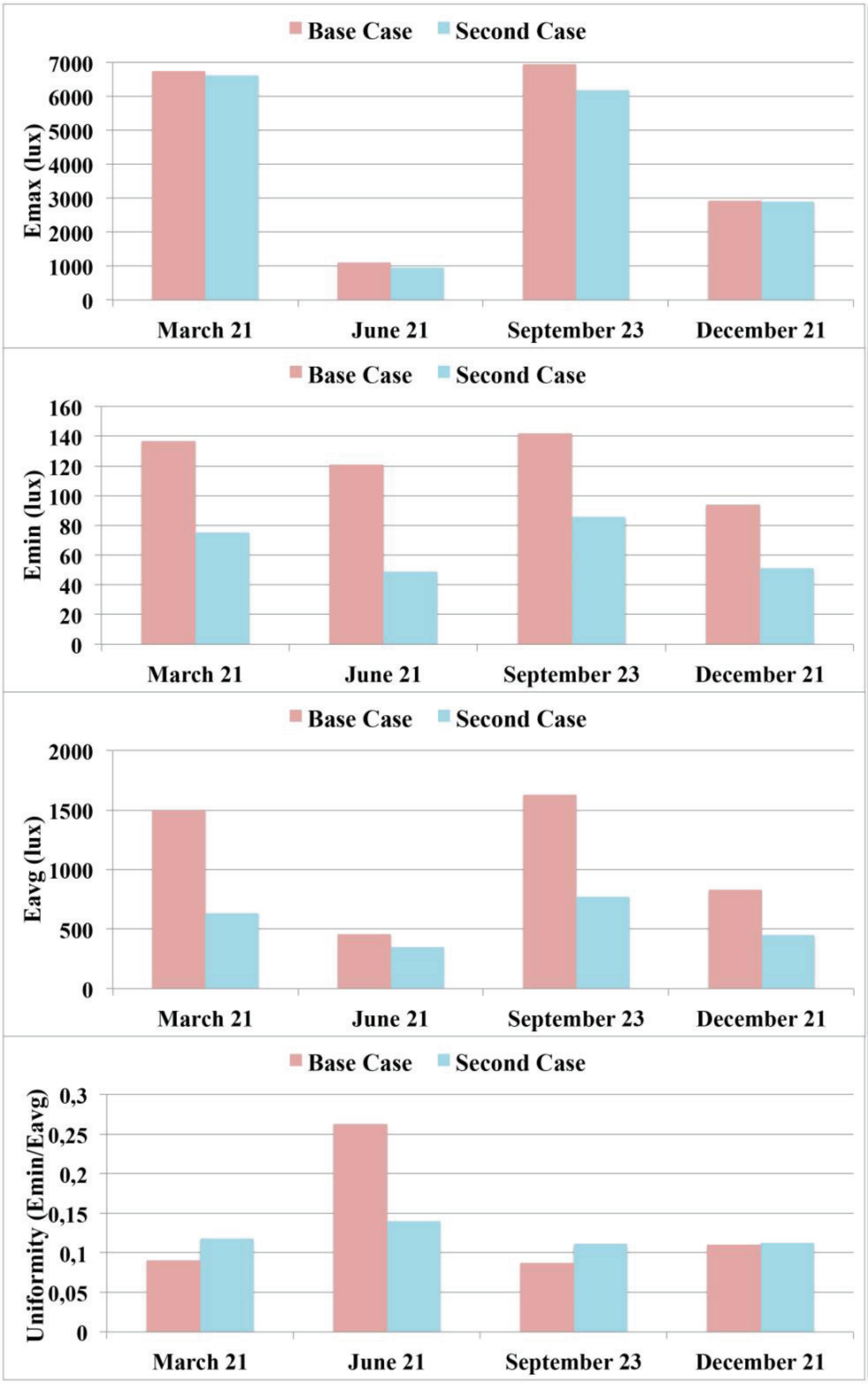

Figure 4.8. Overall E_{max}, E_{min}, E_{avg} and uniformity (E_{min}/E_{avg}) comparison of the base case and the second case on equinox and solstice days at 12:30 pm.

Nevertheless, the average illuminance values in the second case were found 636 lux, 350 lux, 767 lux and 450 lux respectively for March 21st, June 21st, September 23rd and December 21st. The results of average illuminance displayed around 58% decrease on 21 March, 24% decrease on 21 June, 53% decrease on 23 September and 46%

decrease on 21 December when compared to the average illuminance in the base case. Considering the target illuminance range for paper and computer tasks in work places (300-500 lux) (CIBSE, 1994), it can be concluded that there is a noticeable higher number of measurement points come close to the target range in comparison with the base case.

Uniformity also showed an enhancement when compared to the base case results. The results of the uniformity ratios (E_{min}/E_{avg}) indicated almost 30% increase on 21 March, 28% increase on 23 September, 3% increase on 21 December; but only showed an average 46% decrease on June 21.

4.3.2. Luminance Ratios within the Field of View

After the new layout arrangement, the locations of the corresponding view points (SW3, SW10, SW12) were moved to north-east perimeter zone. Below, in Table 4.5, luminance within the users' field of view in the base and the second case were compared. Note that only three most problematic points were listed here, in this section and the evaluation of the rest of the view points considering the base, second, and the final case will be listed within the final case findings.

Table 4.5. Base case-second case comparison of three view points (SW3-SW10-SW12) with the poorest luminance distribution.

	Date		**Luminance (cd/m2)**					
SW3			Dark Screen	White Paper	Desk	Wall	Background	Side Wall Adjacent to Window
	21 March	Base Case	11	2380	115	419	x	1330
		Second Case	4	72	50	166	21	574
	Date		**Luminance (cd/m2)**					
SW10			Dark Screen	White Paper	Desk	Wall	Background	Side Wall Adjacent to Window
	21 March	Base Case	11,6	2520	115	336	x	1270
		Second Case	2,9	91	60	134	35	600
	Date		**Luminance (cd/m2)**					
SW12			Dark Screen	White Paper	Desk	Wall	Background	Side Wall Adjacent to Window
	21 March	Base Case	9,7	2570	150	307	89	603
		Second Case	2,5	96	69	159	78	485

The results indicated here that a simple layout-based change could make a difference on the uniformity of luminance distribution. For instance, in the case of view SW3, the ratio between dark screen and white paper was 1:216 which can not be acceptable, then, following the new layout arrangement, converted into 1:18 which is 12 times better than the base case analysis. In the case of view SW10, the sharpest conversion is the white paper to desk ratio which was reduced from 21.9:1 to 1.5:1.

View SW12 also obtained similar improvements after the layout change except that the side wall adjacent to window to desk ratio which increased from 4.02:1 to 7:1 after the new layout.

In general, in Figure 4.9, the false colour luminance maps support the notion of improvement in the case of all three view points; i.e., after changing the positions of the view SW3 and SW10, excessively bright wall surfaces within the field of view were eliminated and replaced by more acceptable visual field in terms of luminous variability. Similarly, in the case of view SW12, false colour scale indicates that the luminous variability was excessively high within sight, for example, the ratio between the paper and the desk, or the computer screen and the paper was quite out of acceptable range. Likewise, in the case of the new position of view SW12, this problematic situation was eliminated as well by shifting the seating unit to the north-west part. Despite the layout-based luminosity improvements, yet still, some problematic surfaces were still found e.g. on the wall surfaces adjacent to windows, which will be strived to improve at the later stage.

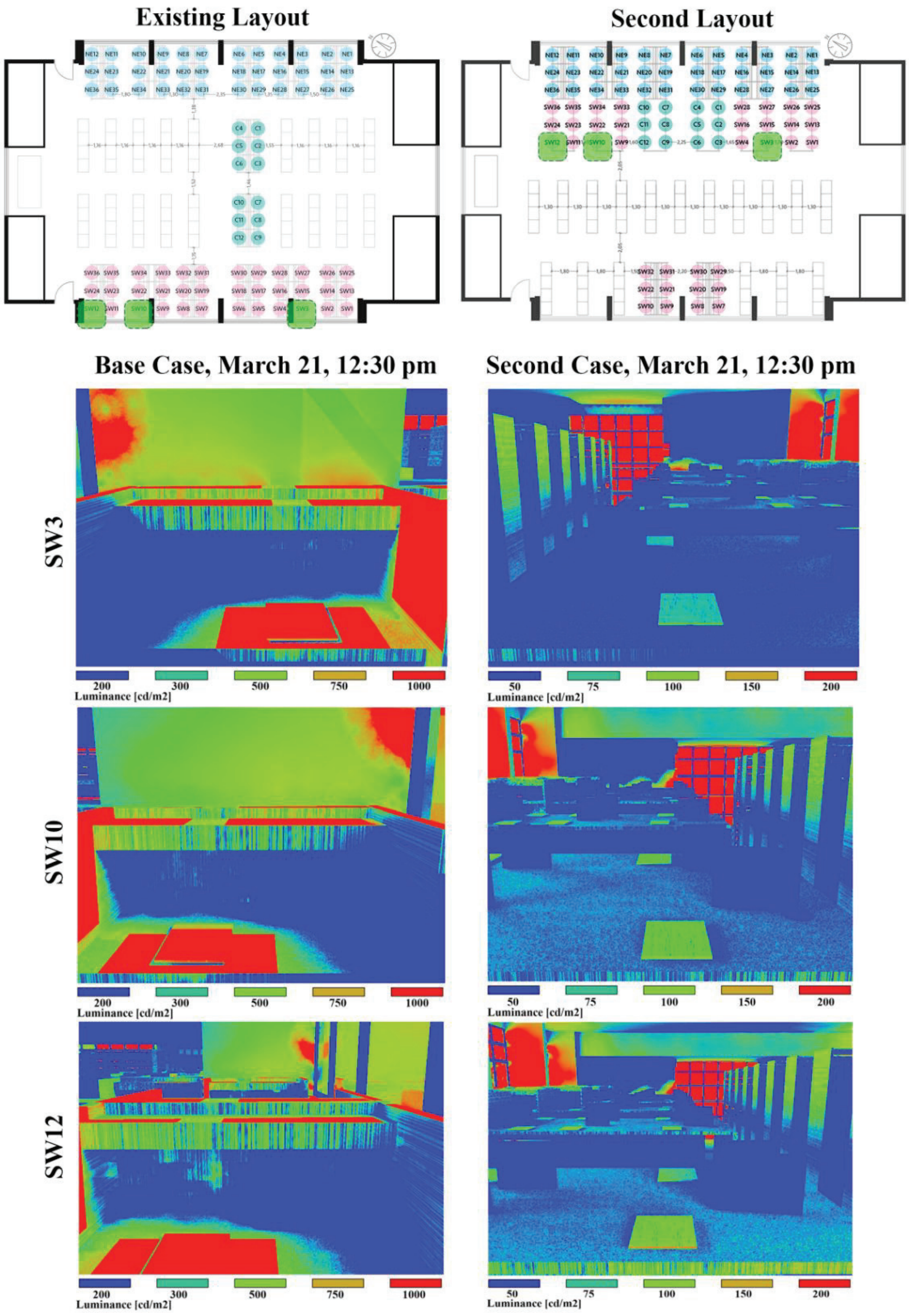

Figure 4.9. False colour luminance maps of the most problematic three view points (SW3, SW10, SW12) on March 21 at 12:30 pm for the base and the second case.

4.4. Final Case Finding

4.4.1. Task Illuminance and Uniformity at the Workplane

In the previous section, a better daylighting performance is achieved by the new layout arrangement according to the second case analysis results. However, at the south-west part of the room higher values of illuminance and unbalanced luminance ratios within the field of view were observed which led to unsatisfactory perception and visual performance conditions. Likewise, at the center of the room lower illuminance values were obtained due to the distance from the windows. Therefore, a new daylighting strategy was proposed since single glazing alone unfortunately was not in capable of boosting the daylighting performance of the room no matter how well the layout change was applied. As explained more detailed in Subsection 3.3.3, a new daylighting strategy consisting of a light shelf-reflective louver system was applied on the facade of the second case and the results were reinterpreted.

Task Illuminance:

Figure 4.10 illustrates the horizontal illuminance values on each measurement point of the final case on equinox and solstice days at 12:30 pm. The most noticeable achievement observed is the range of assessed illuminance which is approximately 100-1300 lux. Maximum illuminance (E_{max}) of the previous cases was up to 7000 lux while minimum illuminance (E_{min}) values were almost same with this case.

Meanwhile, the most problematic measurement points of the second case (SW5-SW8, SW17-SW20) that led to the design of a new light shelf-reflective louver on the south-west facade were exclusively focused on in order to determine the rate of improvement per each simulation time. Figure 4.10 shows the graph indicating the comparison of two cases in terms of illuminance distribution. Likewise, the comparison represents only March 21, 12:30 pm and the results of the rest of the simulation times are available in Appendix C.

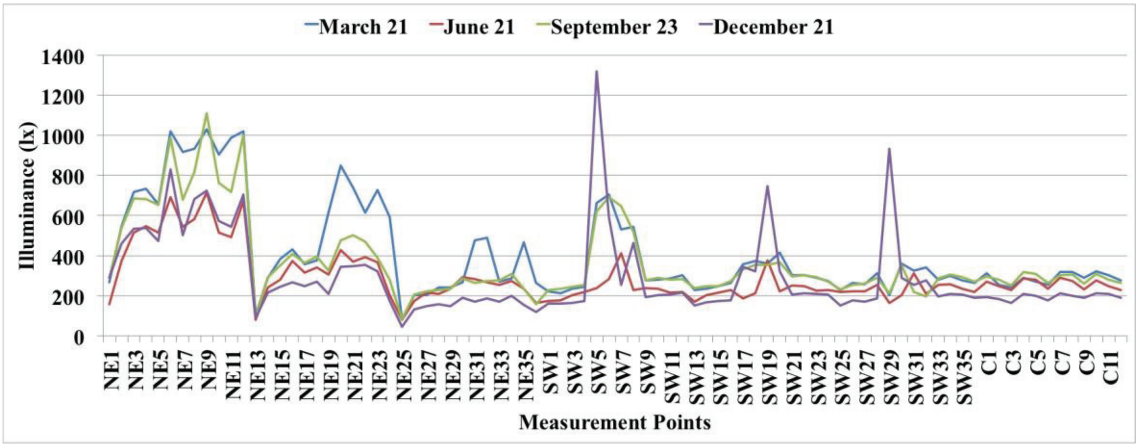

Figure 4.10. Horizontal illuminance (lux) of each measurement point at 12:30 pm on solstice and equinox days – Final Case.

In Figure 4.11 below, the target illuminance (300-500 lux) for each measurement point was almost 100% achieved whereas in the second case the minimum illuminance obtained was around 1700 lux among the corresponding measurement points. The average illuminance (E_{avg}) of these points was found to be 492 lux, which is highly satisfactory when compared to the average illuminance of the second case (3140 lux).

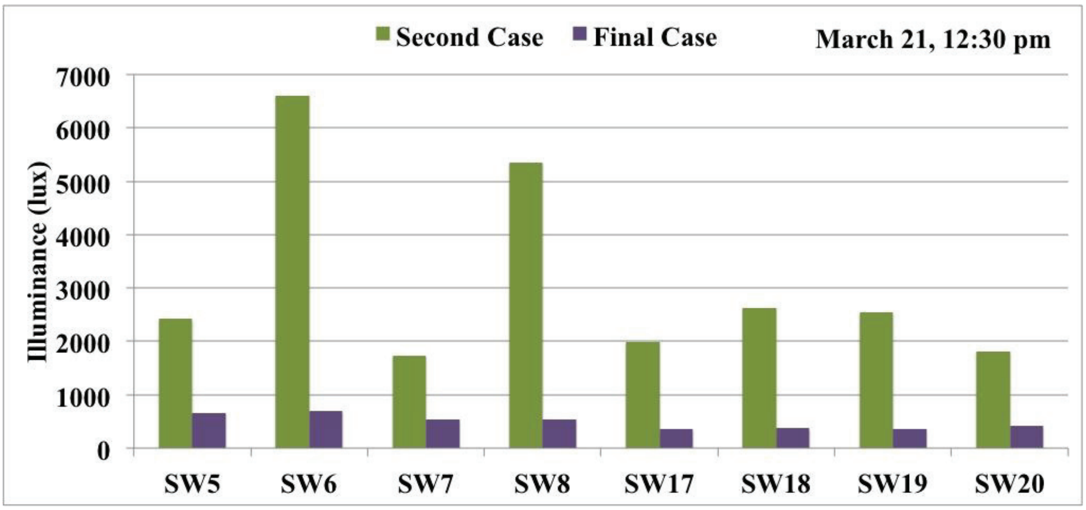

Figure 4.11. Comparison between illuminance distribution of the unshifted south-west oriented measurement points in the second case and the final case for March 21st 12:30.

Taking into consideration 84 measurement points, a comparison was made between the second case and the final case. Figure 4.12 illustrates the illuminance of each measurement point on work plane at 12:30 pm on March 21st. The big picture explicitly articulates that the peaks of horizontal illuminance found at the south-west part of the room in the second case disappeared in the final scenario by means of the light shelf-reflective louver system mounted on the corresponding facade. Another significant improvement is that such measurement points (i.e. NE19-NE24) that receive relatively low illuminance at the north-east part of the room came close to the target illuminance after the application of the reflective louver system on that corresponding facade.

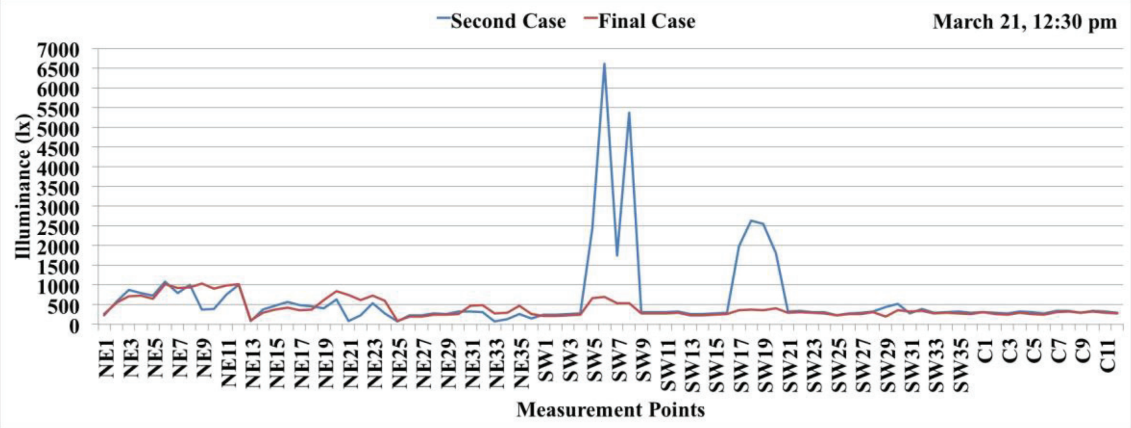

Figure 4.12. Illuminance of the measurement points indicating the change between the second case and the final case for March 21st 12:30 pm.

Uniformity:

The main values obtained from the final case are listed in Table 4.6. The most noticeable change compared to the identical main values of the first and second case is the highest horizontal illuminance (E_{max}) on work plane the showed a decrease within the range of 84% (March 21 and December 21) and 35% (June 21) which, consequently, improved the average illuminance (E_{avg}) and uniformity of daylight distribution over the horizontal plane. Hence, the improvement rate of the uniformity was appreciable. As mentioned in the previous section, layout change could not improve the uniformity ratio, moreover, in the case of June 21 analysis results, it showed a decrease. On the contrary, here, in this case, an improvement rate of 69% on March 21, 100% on June 21, 98% on September 23 and 32% on December 21 were observed in comparison with the second case. Comparing the final case with the base case, the overall improvement rates were found 119%, 6%, 152% and 36% for March 21, June 21, September 23 and December 21, respectively. Despite the huge rate improvements, yet, the uniformity at the work plane were still out of the recommendations which are 0.8 (E_{min}/E_{avg}) according to CIBSE (1987).

Table 4.6. The lowest, highest and average illuminance values on working planes and the obtained uniformity ratios in the final case.

12:30 pm	E_{min}	E_{max}	E_{avg}	U (E_{min}/E_{avg})
March 21	80 lx	1030 lx	408 lx	0,2
June 21	79 lx	715 lx	287 lx	0,28
September 23	82 lx	1110 lx	366 lx	0,22
December 21	45 lx	1320 lx	293 lx	0,15

The main illuminance based values and the uniformity ratios are illustrated on Figure 4.13. As mentioned before, the uniformity analysis results were adequate in the second case keeping in mind that there were no external application etc. to satisfy the lighting levels inside. Only decrease in the second case was observed on June 21 which in the final case was double times fixed. Considering the recommendations and the obtained illuminance and uniformity in the final case, it could be concluded that the illuminance based results were 100% satisfactory as taking E_{avg} findings into account. Uniformity based results were adequate as well when the improvement rate for each day below is analyzed.

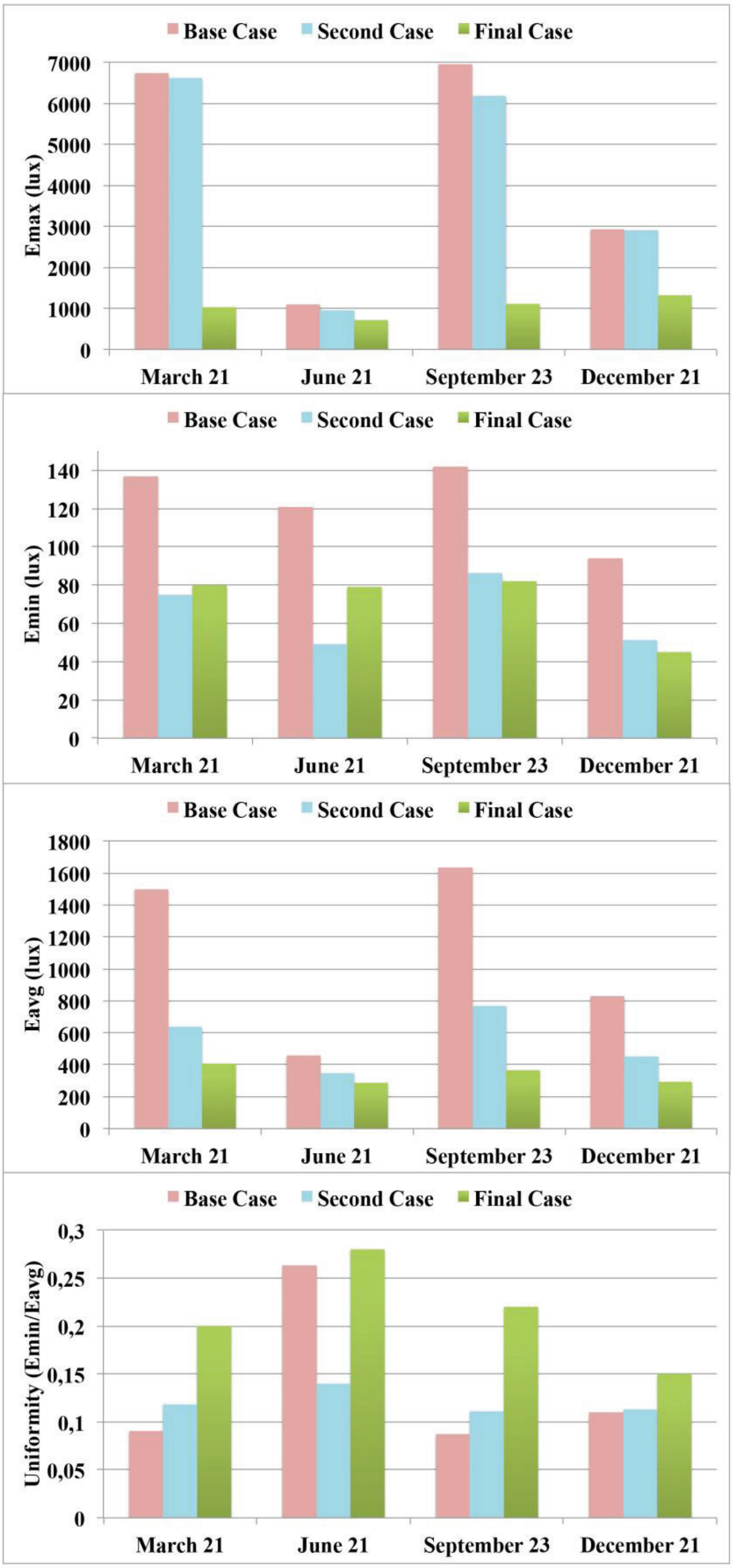

Figure 4.13. Overall E_{max}, E_{min}, E_{avg} and uniformity (E_{min}/E_{avg}) comparison of the base case, the second case and the final case on equinox and solstice days at 12:30 pm.

4.4.2. Luminance Ratios within the Field of View

Luminance of each field of view (84 in total) are listed in Table 4.7 including base case, second case and final case simulation results on March 21 at 12:30 pm. Also Figure 4.14 compares the reference case luminance distribution findings with the obtained findings after the application of the new layout and light shelf-reflective louver system. Three view points with the most non-uniform luminance pattern were taken as a basis and the luminance values of identical points with the actual case simulation results were identified. The results especially after the new daylighting strategy indicate that the luminance ratios within the field of view have substantially found the balance regarding visual performance standards. The shading function of these systems had played a strong role in that sense.

Particularly analyzed view points in regard of SW3 and SW10 were the worst ones not only because of being close location to side window but also because of the very bright side wall surfaces just in front of the viewers and which are fully covered by sun patches. The redirection effect of the system can be seen well in all three view points perceiving the wall surface lighter (Figure 4.14). In particular, the system functions as desired i.e. in September 23 for the view SW12 but not much for the view SW3 which observes sun patch traces on the wall surface. SW12 defines us a much more preferable seating location after the retrofitting application.

Luminous variability is higher in SW3 than the others, but still within the recommended values; i.e. desk-to-side wall luminance ratios are 1:4 in SW3, 1:2.7 in SW10 and 1:32.5 in SW12 in spring equinox. Or, desk-to-background ratios are found to be reasonably good indicators of sensation as respectively 2.1:1 in SW3, 1.6:1 in SW10 and 1:1.3 in SW12.

False colour luminance maps are also presented in Figure 4.15. Particularly in the case of view SW10 and SW12, following the application of the system, the bright wall surfaces adjacent to windows were softened whereas the remaining surface luminosity were kept in the almost same colour scale. Similar improvement was also observed within the field of view SW3 with a slight less amount; but still, considering the two steps from the base case to the final case, luminous variability in all view points were set at a range between 50-150 cd/m^2 in the colour scale whereas it was between 200-1000 cd/m^2 in the base case luminance maps.

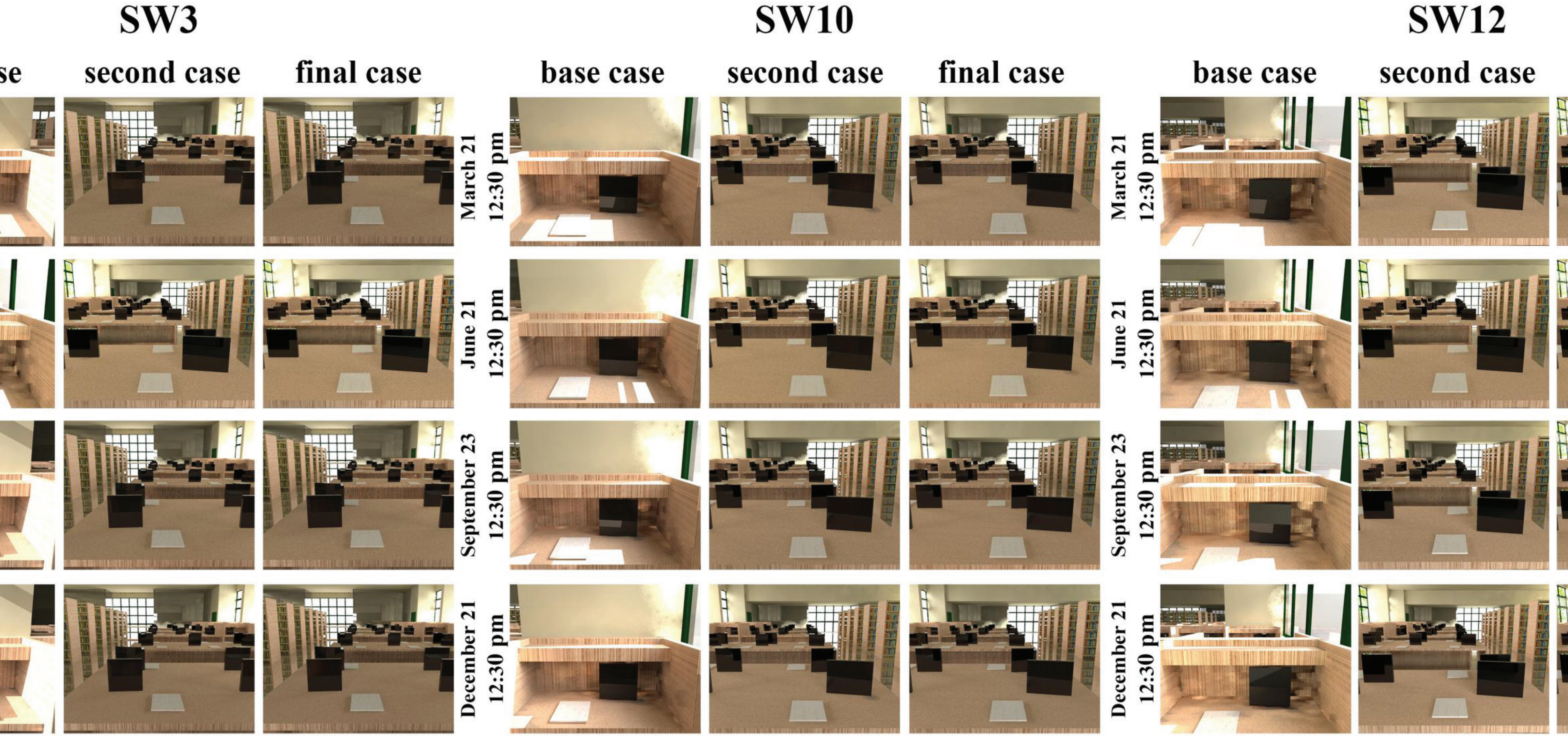

Figure 4.14. Renderings of the case view points on solstice and equinox days, at 12:30 pm.

Existing Layout

Final Layout

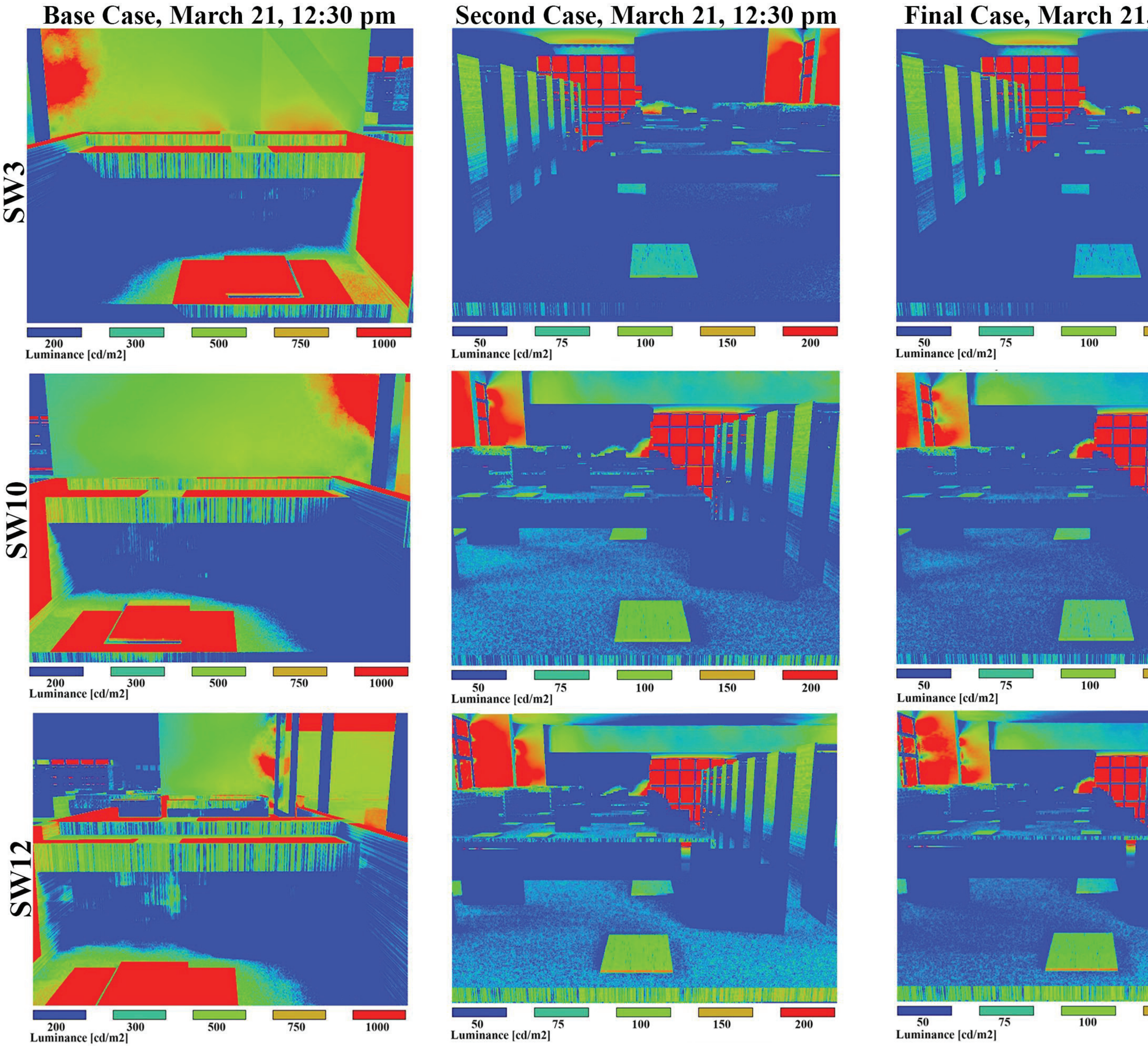

Table 4.7. Luminance within the field of view in all cases on March 21 12:30 pm.

Points	Date	Case	Luminance (cd/m2)					
			Dark Screen	White Paper	Desk	Wall	Background	Side Wall Adjacent to Window
SW1	21 March	Base Case	13	2240	106	442	19,7	783
		Second Case	2	64	49	213	20	563
		Final Case	2,4	64	47	180	22	584
SW2	21 March	Base Case	3,4	2520	146	351	9	1830
		Second Case	0,8	60	38	x	12	x
		Final Case	1,6	57	30	x	14	x
SW3	21 March	Base Case	11	2380	115	419	x	1330
		Second Case	4	72	50	166	21	574
		Final Case	2	64	45	199	21	584
SW4	21 March	Base Case	14,7	2480	120	371	x	909
		Second Case	3,8	58	47	x	38	x
		Final Case	2,2	62	48	x	58	x
SW5	21 March	Base Case	15	872	108	450	18,8	640
		Second Case	14,5	883	112	457	20	661
		Final Case	14	175	148	166	61	380
SW6	21 March	Base Case	5,25	2420	171	348	14	1100
		Second Case	5	2360	169	340	13,5	1125
		Final Case	17	223	208	x	72	x
SW7	21 March	Base Case	27,8	734	136	454	17,5	1040
		Second Case	26,5	722	130	450	17	1005
		Final Case	14,9	248	148	x	66	x
SW8	21 March	Base Case	14,6	2520	182	343	87	1020
		Second Case	14	2550	175	348	80	1034
		Final Case	15	202	111	154	71	339
SW9	21 March	Base Case	16,8	2620	135	476	x	1360
		Second Case	1	85	51	24	2250	x
		Final Case	2,6	78	45	24	2210	x
SW10	21 March	Base Case	11,6	2520	115	336	x	1270
		Second Case	2,9	91	60	134	35	600
		Final Case	2,6	80	55	153	33	475
SW11	21 March	Base Case	11	2480	140	630	15	982
		Second Case	2,4	66	45	16	18	x
		Final Case	2	69	44	24	20,4	x
SW12	21 March	Base Case	9,7	2570	150	307	89	603
		Second Case	2,5	96	69	159	78	485
		Final Case	3	83	60	150	78	393
SW13	21 March	Base Case	4,5	2010	64	439	23,5	885
		Second Case	1,6	65	43	237	20	358
		Final Case	2	65	36	151	19	486
SW14	21 March	Base Case	6	2100	70	632	10	1180
		Second Case	2,4	66	45	x	68	x
		Final Case	2,6	65	38	x	46	x
SW15	21 March	Base Case	6	2060	56	442	26	701
		Second Case	2,6	84	56	162	18	600
		Final Case	2,7	75	46	187	19,7	530
SW16	21 March	Base Case	9	2010	102	405	101	750
		Second Case	4,3	83	46	34	12,5	x
		Final Case	3,7	75	47	27	12	x
SW17	21 March	Base Case	7	2090	63	439	25	640
		Second Case	6,5	2083	66	423	24	664
		Final Case	3	110	72	150	17	241
SW18	21 March	Base Case	5	1980	59	334	8,2	807
		Second Case	5,5	2000	63	345	8	812
		Final Case	4,7	117	78	x	75	x
SW19	21 March	Base Case	5	2010	63,1	386	27	990
		Second Case	5,4	2024	67	390	25,5	985
		Final Case	3,5	103	63	x	82	x
SW20	21 March	Base Case	4,7	2080	74	x	128	855
		Second Case	4	2072	77	x	120	884
		Final Case	2,5	99	69	155	93	312
SW21	21 March	Base Case	10,6	2090	63	474	20,7	1090
		Second Case	3	91	50	24	2550	x
		Final Case	3	85	58	23	2490	
SW22	21 March	Base Case	11,6	1910	80	375	142	445
		Second Case	3	105	69	145	44	389
		Final Case	3	91	59	155	64	372

(cont. on the next page)

Table 4.7. (cont.)

SW23	21 March	Base Case	8,7	2730	67	x	20	1060
		Second Case	3	77	53	22	2000	x
		Final Case	2,3	75	57	23	2070	x
SW24	21 March	Base Case	5	1950	74	303	127	675
		Second Case	2,4	85	63	130	26	606
		Final Case	2,7	79	54	144	24	547
SW25	21 March	Base Case	3	95	47	235	25	453
		Second Case	1,2	49	38	170	19	531
		Final Case	1,3	43	36	181	21	474
SW26	21 March	Base Case	3,15	182	149	x	5	x
		Second Case	1,48	57	35	x	12	x
		Final Case	1,4	52	37	x	12	x
SW27	21 March	Base Case	4,5	184	49	515	28	744
		Second Case	2,4	63	39	158	19	543
		Final Case	1,6	61	47	163	18	618
SW28	21 March	Base Case	5	210	72	187	11	1710
		Second Case	2,4	75	46	188	26	x
		Final Case	2,2	72	47	169	42	x
SW29	21 March	Base Case	4	204	75	606	28	855
		Second Case	4,7	214	79	612	26	861
		Final Case	1,6	54	37	228	61	208
SW30	21 March	Base Case	3,8	172	78	237	12	390
		Second Case	4	165	73	231	11,5	384
		Final Case	2,4	74	67	75	40	x
SW31	21 March	Base Case	3,7	186	72	428	20	728
		Second Case	4	197	84	437	22	735
		Final Case	3	92	74	x	46	x
SW32	21 March	Base Case	3,16	210	55	128	11,6	444
		Second Case	4	225	58	137	13	439
		Final Case	2,2	55	48	158	95	205
SW33	21 March	Base Case	3,6	220	78	42	19,7	1580
		Second Case	2,5	80	46	23,8	2530	x
		Final Case	2,6	77	57	20,8	2410	x
SW34	21 March	Base Case	5	154	134	x	107	488
		Second Case	2	84	52	163	83	488
		Final Case	2,3	76	47	143	79	484
SW35	21 March	Base Case	3,4	210	58	11,5	21,5	x
		Second Case	2	85	53	24	490	x
		Final Case	2	81	48	22	421	x
SW36	21 March	Base Case	1,6	99	45	390	121	392
		Second Case	1,5	63,7	42,4	217	20	463
		Final Case	1,5	62	42	198	23	379
NE1	21 March	Base Case	6,3	210	108	196	18	700
		Second Case	6	206	103	192	15,7	686
		Final Case	6,7	150	104	198	20	569
NE2	21 March	Base Case	6,7	256	128	187	10,8	771
		Second Case	6,5	215	94	189	13,2	780
		Final Case	6,4	165	126	154	12	732
NE3	21 March	Base Case	7,3	279	150	203	x	782
		Second Case	6,7	275	158	214	x	776
		Final Case	6	252	128	182	x	601
NE4	21 March	Base Case	7	208	176	224	x	630
		Second Case	8	238	132	218	x	506
		Final Case	7,2	181	110	184	x	575
NE5	21 March	Base Case	7	217	135	250	x	945
		Second Case	6,4	224	124	261	x	956
		Final Case	5	180	120	230	x	1100
NE6	21 March	Base Case	8	310	217	263	29	463
		Second Case	9	293	160	232	25	538
		Final Case	10	251	193	187	14	457
NE7	21 March	Base Case	8	230	145	285	14,6	724
		Second Case	7,4	224	142	280	15	742
		Final Case	4	209	126	261	18	916
NE8	21 March	Base Case	7,5	245	181	253	79	970
		Second Case	6,7	260	120	232	80	879
		Final Case	6,3	204	142	214	74	567
NE9	21 March	Base Case	11	317	230	252	x	852
		Second Case	10	308	224	268	x	887
		Final Case	7,6	290	179	276	x	805

(cont. on the next page)

Table 4.7. (cont.)

NE10	21 March	Base Case	7	209	171	218	72	551
		Second Case	6	250	133	221	69	628
		Final Case	6,6	215	142	208	68	597
NE11	21 March	Base Case	8,3	237	148	270	17	776
		Second Case	8	224	133	254	16	808
		Final Case	8	217	136	235	18	750
NE12	21 March	Base Case	7,8	343	190	240	71	742
		Second Case	7,4	321	178	230	73	659
		Final Case	10	306	191	217	73	495
NE13	21 March	Base Case	3,4	58	48	256	20	451
		Second Case	3	47	44	272	18,5	466
		Final Case	2,7	71	61	250	20	422
NE14	21 March	Base Case	4	112	78,3	179	6,86	318
		Second Case	4	122	77	168	6	305
		Final Case	3	78	65	163	7	206
NE15	21 March	Base Case	4	106	74	223	12	370
		Second Case	3,6	102	71	225	11	376
		Final Case	3	46	64	184	17	419
NE16	21 March	Base Case	6	113	90	193	7	219
		Second Case	5,5	74	89	193	9	227
		Final Case	3,8	63	79	170	9	181
NE17	21 March	Base Case	4,2	105	80	294	19	411
		Second Case	4	102	88	303	16	428
		Final Case	2,6	65	64	301	17	465
NE18	21 March	Base Case	4,6	94	96	169	11	411
		Second Case	3,5	67	61	227	9	389
		Final Case	3	67	74	193	14	412
NE19	21 March	Base Case	5,6	86	64	284	22	668
		Second Case	5	80	61	276	20	661
		Final Case	3	66	51	253	18	710
NE20	21 March	Base Case	3,5	131	96	106	16	343
		Second Case	5	79	86	242	9	341
		Final Case	3,4	72	82	216	8	324
NE21	21 March	Base Case	6	124	91	278	21	337
		Second Case	5,5	114	94	260	19	368
		Final Case	4	54	74	265	20	331
NE22	21 March	Base Case	6	106	92	240	104	446
		Second Case	5,4	75,5	75	218	85	432
		Final Case	4,2	66	78	224	88	365
NE23	21 March	Base Case	4	115	93	378	21	456
		Second Case	3,2	113	102	350	26	469
		Final Case	4,3	64	70	233	20	476
NE24	21 March	Base Case	2	79	55	232	92,4	682
		Second Case	2,1	74,2	62	224	84	610
		Final Case	3,7	61	54	214	82	596
NE25	21 March	Base Case	2,4	35	32	234	22,4	267
		Second Case	2,2	33	34	205	21	284
		Final Case	2,7	30	34	225	21	263
NE26	21 March	Base Case	3	50	53	69	8,3	x
		Second Case	3	71	42	46,5	10	x
		Final Case	3	70	45	32	9,5	x
NE27	21 March	Base Case	3	60	49	300	21,6	500
		Second Case	3,4	65	46	312	25	512
		Final Case	3	48	52	197	19	678
NE28	21 March	Base Case	4,5	86	61	95,4	8,5	223
		Second Case	3,2	71	46	190	10	486
		Final Case	3,2	62	59	161	10	450
NE29	21 March	Base Case	3	65	63	457	22	574
		Second Case	3,5	74	69	468	23	593
		Final Case	2,3	49	47	280	20	587
NE30	21 March	Base Case	3,5	80	68	272	8	276
		Second Case	3	77	55	157	10	243
		Final Case	2,8	63	52	154	10	215
NE31	21 March	Base Case	4	75	70	321	21	362
		Second Case	4,6	84	74	335	19	378
		Final Case	2,4	61	50	176	19	382
NE32	21 March	Base Case	3,6	62,8	72,6	103	8,1	466
		Second Case	4	86	54	168	10	439
		Final Case	3,3	68	57	180	11	404

(cont. on the next page)

Table 4.7. (cont.)

NE33	21 March	Base Case	4,2	82	74	136	21	617
		Second Case	4	86	69	128	25	602
		Final Case	2,6	45	47	256	22	659
NE34	21 March	Base Case	3,7	91	70	238	95	1050
		Second Case	3,7	79	52	259	92	805
		Final Case	4,3	72	51	208	80	620
NE35	21 March	Base Case	3	71	72	22	5	x
		Second Case	3,5	79	74	17	4,4	x
		Final Case	2,5	58	45	24	14	x
NE36	21 March	Base Case	2,5	46	35	456	98	478
		Second Case	2,45	50	43	219	71	450
		Final Case	2,7	48	37	214	65	368
C1	21 March	Base Case	1,4	48	30	35	33	325
		Second Case	2	73	48	197	20	511
		Final Case	1,8	60	41	176	18	472
C2	21 March	Base Case	1,6	36	25	38	46	293
		Second Case	3	78	53	205	20	700
		Final Case	2,3	76	54	140	19	613
C3	21 March	Base Case	1,7	36	34	58	54	x
		Second Case	2,6	76	53	186	20	641
		Final Case	2,4	70	46	156	21	551
C4	21 March	Base Case	2	64	51	45	65	733
		Second Case	2,4	77	48,6	157	11	437
		Final Case	2,5	68	49	176	11	349
C5	21 March	Base Case	1,7	61	31	48	90	428
		Second Case	2,8	85	61	204	15	x
		Final Case	3	79	57	179	13	x
C6	21 March	Base Case	1,7	54	35	24	36	x
		Second Case	2,2	77	51	33	15,2	x
		Final Case	2,5	70	49	29	21	x
C7	21 March	Base Case	1,6	46	34	110	18	x
		Second Case	2,3	82	54	246	22	723
		Final Case	2	71	46	183	22	708
C8	21 March	Base Case	2	44	33	x	46	x
		Second Case	3	92	60	25	2550	x
		Final Case	2,5	84	57	20	2490	
C9	21 March	Base Case	2	55	33	31	93	x
		Second Case	2,7	81	51	22,7	2430	x
		Final Case	2,3	80	45	22	2200	x
C10	21 March	Base Case	1,7	64	40	62	34	x
		Second Case	2,3	78	44,5	246	13	508
		Final Case	2	66	47	194	11,5	300
C11	21 March	Base Case	1,8	70	42	x	46	x
		Second Case	3	93	56	141	10	429
		Final Case	2,9	89	61	153	12	424
C12	21 March	Base Case	2,6	90	47	46	64	352
		Second Case	8	83	53	85	13	362
		Final Case	3	76	55	97	13	343

CHAPTER 5

DISCUSSIONS AND CONCLUSIONS

This study dealt with the improving visual conditions of a library reading room with a focus on the assessment of visual performance criterias, namely task illuminance, luminance ratios within the field of view, and uniformity at a workplane. The library of Izmir Institute of Technology was chosen as the reference case for having large floor area and three facade covered with single glazing with no sun protection. In a climate type which is sunny most of the year, that can be assumed as a model for library buildings with highly glazed facades and large floor areas, visual performance assessments can not result satisfactorily with no daylighting strategy, thus can not hold an adequate indoor environment for library users which results with a decrease in well-being and productivity of them.

The main contribution of this study was evaluating the effect of a new layout arrangement and a light shelf-reflective louver system in terms of enhancing visual performance assessment of a library reading room. The determination of the new layout and daylighting system was dependent on running a considerable amount of simulations by taking into consideration the physical characteristics of the building and the related previous studies. The evaluation process of the study was split into three sections: the overview of the base case building and its actual visual performance assessment, the second case with the new layout arrangement with reference to library space planning recommendations and the physical characteristics of the existing building and its visual performance assessment, and the final case with a light shelf-reflective louver system applied on the facade of the second case building.

In the first step, the base case was investigated in terms of actual visual performance and library space planning criterias. According to the base case analysis results, following deficiencies were defined as follows:

(i) Window size and glazing types were designed independently of the building specifications such as orientation, size, function etc.

(ii) The space organization of the library was designed with a conventional thinking in a manner that seating units were adjacent to windows and the bookshelves were at the center part.

(iii) Without concerning physical attributes of the building, placement of the seating units adjacent to windows that have no sun protection led to an unsatisfactory daylight distribution among different parts of the space.

(iv) Therefore it should be no surprise that the daylighting performance of the base case was poor due to the highly unbalanced illuminance distribution across the work plane and the extremely non-uniform luminance distribution within the different fields of view.

Discussions indicated above showed that the reference case was in need of a better space planning and a strategy that transmit daylight more uniformly into the space. Therefore, as a first step, the second case was formed in consideration of these deficiencies. A new layout arrangement was designed after running several layout variation simulations, and this one, as yielding the best daylighting performance, was chosen as the second case. The results were quite satisfactory to find out how a simple layout change can make an positive impact on the visual performance assessment when the building specifications and space planning recommendations are considered carefully. Yet, when evaluated within the scope of visual performance criterias, there were still low daylighting performance at the south part due to excessive daylight exposure and at the center part due to the distance from windows. Hence, to distribute daylight into space more efficiently, a light shelf-reflective louver system was proposed for the south-west and north-east facing facade. Likewise, based upon the physical characteristics of the building and the related previous research, various simulations were run in order to find the optimum characteristics of the system.

Following the application of this new daylighting strategy, the final analysis results showed that the visual performance criterias were ~100% completely fulfilled except the uniformity at the work plane. Although it was also improved between 35%-84% compared to the base case, due to the large floor area and the high number of evaluation points, the uniformity ratio could not meet the criterias of recommendations (CIBSE, 1987) which are 0.2 (E_{min}/E_{max}) and 0.8 (E_{min}/E_{avg}). Apart from this, the most critical illuminance-related change was observed in E_{max} values especially after the retrofitting application. The fluctuations among equinox and solstice days (1000-7000 lux) were improved and the average E_{max} for four days was set at a fixed range around 1000 lux when the final step was applied. Another illuminance-related significant improvement was that the E_{avg} which was set at a range around 300-400 lux whereas in the base case, for example, it was found above 1600 lux on 21 September at 12:30 pm.

Additively, concerning UDI (Useful Daylight Illuminance), high incidence of adequate results were obtained for all solstice and equinox days. To define briefly, UDI is the annual representation of illuminances across the work plane where all the illuminance values are within the range 100-2000 lux (Nabil and Mardaljevic, 2005). Here, in this study, the range of UDI was found between 75%-100% at 12:30 pm for the base case and afterwards calculated within the range of 98%-100% in the final case considering all four days that represent the whole year.

In the case of luminance-based improvement, it can be concluded that the layout change made a positive impact on the luminous variety of displaced south-western seating units, but still the view points located at the north-west part of the library remained the same in terms of luminance distribution. The most striking improvement was observed after the application of the system not only for blocking the excessive daylight filtering inside the space, but also for redirecting daylight to the deeper parts of the library. By this way, the system distributed the light more homogenously inside the room and this resulted in more acceptable luminance values on bright surfaces i.e. white paper, wall.

The significant point to take into consideration is that the steps applied are not the expressions of comparison; rather, these steps are applied to emphasize the amount of improvement in each case and to provide the optimum visual performance in the end.

In overall, the big picture gives the clues on how a proper design of a layout and a daylighting system together provide a noticeable improvement in visual performance of a library having these building specifications. In addition to this, recommendations for future work may be given on the basis of these findings as follows:

- In this study, the material characteristics of the furnitures inside the evaluated space were kept identical in an attempt to observe the amount of improvement in each related step, most particularly in the layout-based one. It can be further recommended that different variations of features (e.g., reflectance of materials, colour of surfaces) may be applied in order to find the optimal combinations.

- This study was limited with the use of natural light as to see the effects of light shelf-reflective louver system in the assessment of final case. In such a further study dealing with the visual performance assessment of various layout types, artificial lighting may be also added for cases in which library is in use during both daytime and nighttime.
- 1st floor of the library of Izmir Institute of Technology was chosen as the base case because of the fact that the ground floor was surrounded by cars, small trees etc. that led to a necessarily unlit environment. However, in a further study, both the ground and the first floor can be analyzed to observe the effects of external obstructions on daylight availability and visual performance.
- Simulation tests were carried out on solstice and equinox days at 12:30 pm throughout the study. Time variations representing the whole daytime (e.g., 09:30 am, 12:30 pm, 15:30 pm) can be further implemented for providing more accurate results of illuminance and luminance distribution.
- In this study representative occupants were excluded of simulations performed in all three cases. However, daylight availability also depends on the presence of occupants who may block the transmitting daylight to the evaluated surfaces. Another further study may investigate the visual performance of the same simulations performed which also considers the occupant presence in the model; and hence the effect of representative occupants in Relux simulation tool can be discovered.

There has not been conducted sufficient number of research regarding layout related improvements in educational spaces. Therefore, initially, this thesis would make a contribution to the literature establishing such simple layout changes can make differences in terms of improving visual performance, accordingly, learning performance and alertness of academic library users.

Second of all, this thesis emphasized on the inefficiency of a single glazing with no daylighting system that could not completely meet the visual performance requirements of an educational building in which reading, writing and computer tasks were performed during the daytime. Thus, an applicable daylighting system is needed in such educational spaces like this in order to control and use daylight efficiently. Moreover, the layout arrangement of interior environments is much better to be considered simultaneously with the facade of buildings at the early-design phases to avoid from daylight quality and distribution related problems.

In future, this study may be a guide for architects, designers and researchers by providing knowledge about practices in terms of satisfying visual conditions of educational buildings, most particularly academic libraries. No matter new or retrofitted cases, both layout design and daylighting systems can make significant visual performance improvements at any design stage of a building. The proposed layout and the daylighting system in this study would be an infrastructure for future research and applications to accelerate the design process of buildings.

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APPENDIX A

LUMINANCE BASED ON-SITE MEASUREMENTS AND RENDERINGS OF IDENTICAL VIEWS

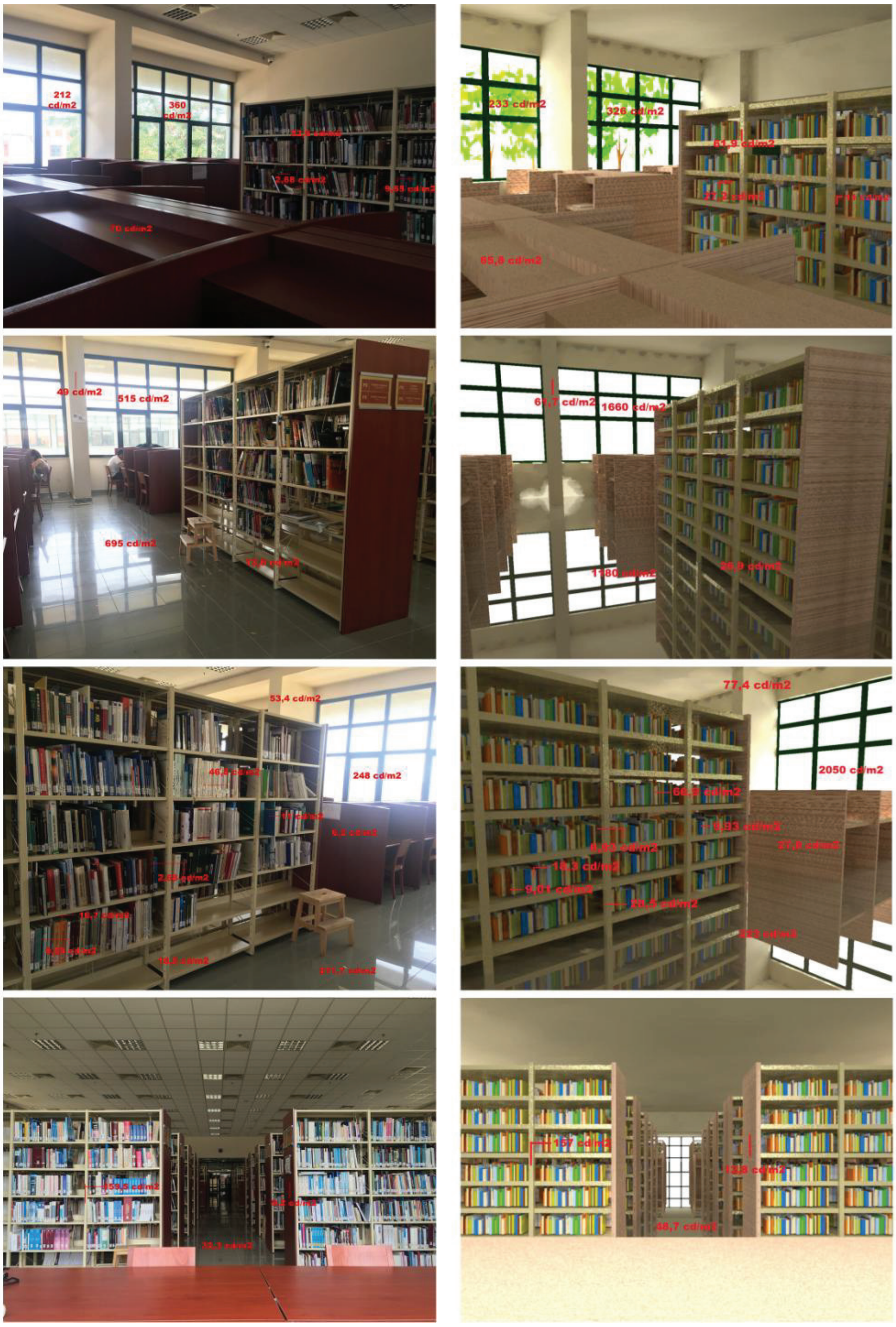

Figure A.1. Luminance values on surfaces while monitoring and the simulation phases on June 20, 15:30 pm.

APPENDIX B

ILLUMINANCE AND UNIFORMITY BASED RESULTS ON SOLSTICE AND EQUINOX DAYS

Table B.1. Illuminance and uniformity results of the base case, March 21, 12:30 pm.

March 21, 12:30 pm			
Point	Task Illuminance (lux)	Point	Task Illuminance (lux)
NE1	553	SW7	1810
NE2	772	SW8	6690
NE3	894	SW9	6190
NE4	870	SW10	6150
NE5	807	SW11	6170
NE6	1120	SW12	6370
NE7	785	SW13	2350
NE8	919	SW14	1530
NE9	1070	SW15	2580
NE10	869	SW16	2720
NE11	827	SW17	2060
NE12	1070	SW18	2590
NE13	290	SW19	2590
NE14	524	SW20	2180
NE15	424	SW21	3480
NE16	570	SW22	2670
NE17	523	SW23	1570
NE18	451	SW24	3340
NE19	442	SW25	311
NE20	611	SW26	530
NE21	572	SW27	481
NE22	594	SW28	541
NE23	575	SW29	519
NE24	365	SW30	529
NE25	142	SW31	417
NE26	246	SW32	705
NE27	258	SW33	624
NE28	315	SW34	485
NE29	264	SW35	534
NE30	335	SW36	227
NE31	329	C1	163
NE32	321	C2	139
NE33	333	C3	137
NE34	310	C4	208
NE35	291	C5	186
NE36	187	C6	173
SW1	6040	C7	174
SW2	6560	C8	214
SW3	6610	C9	264
SW4	6750	C10	200
SW5	2750	C11	260
SW6	6140	C12	309

Illuminance (lux)			Uniformity	
Eavg	Emin	Emax	U1(Emin/Eavg)	U2(Emin/Emax)
1500	137	6750	0,091	0,020

Table B.2. Illuminance and uniformity results of the base case, June 21, 12:30 pm.

June 21, 12:30 pm			
Point	Task Illuminance (lux)	Point	Task Illuminance (lux)
NE1	445	SW7	777
NE2	567	SW8	1070
NE3	638	SW9	1020
NE4	659	SW10	925
NE5	654	SW11	1060
NE6	834	SW12	862
NE7	648	SW13	385
NE8	678	SW14	547
NE9	828	SW15	537
NE10	629	SW16	665
NE11	631	SW17	624
NE12	739	SW18	504
NE13	254	SW19	357
NE14	414	SW20	562
NE15	431	SW21	607
NE16	458	SW22	487
NE17	442	SW23	611
NE18	431	SW24	363
NE19	402	SW25	147
NE20	502	SW26	230
NE21	472	SW27	263
NE22	435	SW28	229
NE23	484	SW29	244
NE24	300	SW30	248
NE25	153	SW31	151
NE26	228	SW32	237
NE27	244	SW33	274
NE28	310	SW34	241
NE29	295	SW35	234
NE30	323	SW36	133
NE31	315	C1	168
NE32	327	C2	134
NE33	281	C3	129
NE34	295	C4	216
NE35	285	C5	178
NE36	205	C6	159
SW1	783	C7	121
SW2	943	C8	128
SW3	961	C9	143
SW4	1090	C10	128
SW5	1100	C11	134
SW6	1070	C12	153

Illuminance (lux)			Uniformity	
Eavg	Emin	Emax	U1(Emin/Eavg)	U2(Emin/Emax)
459	121	1100	0,263	0,11

Table B.3. Illuminance and uniformity results of the base case, September 23, 12:30 pm.

September 23, 12:30 pm			
Point	Task Illuminance (lux)	Point	Task Illuminance (lux)
NE1	588	SW7	1830
NE2	762	SW8	4390
NE3	930	SW9	4440
NE4	872	SW10	3920
NE5	796	SW11	4580
NE6	1150	SW12	4170
NE7	898	SW13	5320
NE8	938	SW14	5940
NE9	1140	SW15	6130
NE10	852	SW16	1700
NE11	837	SW17	6100
NE12	985	SW18	5880
NE13	296	SW19	6120
NE14	518	SW20	6150
NE15	534	SW21	6960
NE16	562	SW22	1120
NE17	564	SW23	6160
NE18	473	SW24	3870
NE19	445	SW25	275
NE20	623	SW26	465
NE21	681	SW27	437
NE22	596	SW28	465
NE23	603	SW29	521
NE24	366	SW30	492
NE25	171	SW31	311
NE26	243	SW32	516
NE27	263	SW33	617
NE28	310	SW34	412
NE29	281	SW35	512
NE30	345	SW36	235
NE31	314	C1	169
NE32	329	C2	156
NE33	351	C3	142
NE34	335	C4	221
NE35	315	C5	191
NE36	198	C6	184
SW1	3600	C7	171
SW2	3900	C8	208
SW3	4110	C9	269
SW4	3870	C10	196
SW5	4370	C11	224
SW6	4350	C12	285

Illuminance (lux)			Uniformity	
Eavg	Emin	Emax	U1(Emin/Eavg)	U2(Emin/Emax)
1632	142	6960	0,087	0,020

Table B.4. Illuminance and uniformity results of the base case, December 21, 12:30 pm.

December 21, 12:30 pm			
Point	Task Illuminance (lux)	Point	Task Illuminance (lux)
NE1	426	SW7	1330
NE2	581	SW8	1870
NE3	664	SW9	2490
NE4	668	SW10	2580
NE5	600	SW11	2450
NE6	921	SW12	2930
NE7	588	SW13	762
NE8	762	SW14	1330
NE9	874	SW15	1310
NE10	685	SW16	983
NE11	653	SW17	1750
NE12	755	SW18	937
NE13	232	SW19	1640
NE14	372	SW20	1140
NE15	361	SW21	1290
NE16	427	SW22	1250
NE17	402	SW23	1830
NE18	348	SW24	692
NE19	315	SW25	1030
NE20	458	SW26	406
NE21	461	SW27	1130
NE22	446	SW28	405
NE23	461	SW29	1140
NE24	264	SW30	448
NE25	94	SW31	473
NE26	160	SW32	492
NE27	181	SW33	1300
NE28	230	SW34	387
NE29	193	SW35	1180
NE30	215	SW36	207
NE31	208	C1	117
NE32	212	C2	103
NE33	234	C3	97
NE34	222	C4	138
NE35	198	C5	132
NE36	131	C6	122
SW1	2740	C7	149
SW2	2650	C8	181
SW3	2240	C9	219
SW4	2890	C10	157
SW5	2930	C11	210
SW6	2220	C12	253

Illuminance (lux)			Uniformity	
Eavg	Emin	Emax	U1(Emin/Eavg)	U2(Emin/Emax)
830	94	2930	0,11	0,032

Table B.5. Illuminance and uniformity results of the second case, March 21, 12:30 pm.

March 21, 12:30 pm			
Point	Task Illuminance (lux)	Point	Task Illuminance (lux)
NE1	232	SW7	1740
NE2	577	SW8	5360
NE3	875	SW9	311
NE4	799	SW10	318
NE5	728	SW11	310
NE6	1090	SW12	331
NE7	793	SW13	256
NE8	1010	SW14	257
NE9	379	SW15	274
NE10	384	SW16	299
NE11	769	SW17	1990
NE12	997	SW18	2630
NE13	81	SW19	2550
NE14	378	SW20	1810
NE15	468	SW21	333
NE16	576	SW22	339
NE17	489	SW23	318
NE18	453	SW24	312
NE19	412	SW25	233
NE20	635	SW26	276
NE21	87	SW27	290
NE22	229	SW28	321
NE23	541	SW29	445
NE24	278	SW30	527
NE25	75	SW31	283
NE26	237	SW32	391
NE27	236	SW33	302
NE28	275	SW34	304
NE29	267	SW35	327
NE30	326	SW36	298
NE31	321	C1	304
NE32	308	C2	288
NE33	77	C3	271
NE34	135	C4	333
NE35	264	C5	313
NE36	145	C6	285
SW1	241	C7	342
SW2	246	C8	346
SW3	262	C9	302
SW4	281	C10	337
SW5	2430	C11	324
SW6	6610	C12	301

Illuminance (lux)			Uniformity	
Eavg	Emin	Emax	U1(Emin/Eavg)	U2(Emin/Emax)
636	75	6610	0,118	0,011

Table B.6. Illuminance and uniformity results of the second case, June 21, 12:30 pm.

June 21, 12:30 pm			
Point	Task Illuminance (lux)	Point	Task Illuminance (lux)
NE1	196	SW7	797
NE2	435	SW8	742
NE3	636	SW9	262
NE4	636	SW10	260
NE5	695	SW11	241
NE6	644	SW12	238
NE7	629	SW13	205
NE8	709	SW14	225
NE9	580	SW15	242
NE10	493	SW16	265
NE11	608	SW17	468
NE12	721	SW18	479
NE13	84	SW19	382
NE14	291	SW20	493
NE15	427	SW21	291
NE16	401	SW22	297
NE17	482	SW23	258
NE18	406	SW24	239
NE19	446	SW25	226
NE20	539	SW26	254
NE21	172	SW27	268
NE22	176	SW28	292
NE23	433	SW29	207
NE24	236	SW30	235
NE25	79	SW31	169
NE26	220	SW32	176
NE27	235	SW33	289
NE28	271	SW34	285
NE29	357	SW35	274
NE30	313	SW36	253
NE31	326	C1	319
NE32	322	C2	278
NE33	49	C3	252
NE34	119	C4	327
NE35	267	C5	287
NE36	137	C6	262
SW1	199	C7	334
SW2	203	C8	325
SW3	231	C9	269
SW4	240	C10	334
SW5	952	C11	300
SW6	954	C12	275

Illuminance (lux)			Uniformity	
Eavg	Emin	Emax	U1(Emin/Eavg)	U2(Emin/Emax)
350	49	954	0,14	0,051

Table B.7. Illuminance and uniformity results of the second case, September 21, 12:30 pm.

September 23, 12:30 pm			
Point	Task Illuminance (lux)	Point	Task Illuminance (lux)
NE1	479	SW7	1660
NE2	704	SW8	1750
NE3	899	SW9	325
NE4	855	SW10	328
NE5	806	SW11	304
NE6	1150	SW12	301
NE7	838	SW13	256
NE8	947	SW14	275
NE9	1170	SW15	283
NE10	859	SW16	304
NE11	839	SW17	6180
NE12	1060	SW18	5810
NE13	149	SW19	6070
NE14	382	SW20	1680
NE15	478	SW21	341
NE16	485	SW22	348
NE17	512	SW23	323
NE18	513	SW24	295
NE19	449	SW25	243
NE20	619	SW26	285
NE21	633	SW27	302
NE22	574	SW28	326
NE23	588	SW29	404
NE24	303	SW30	474
NE25	86	SW31	526
NE26	241	SW32	495
NE27	259	SW33	316
NE28	287	SW34	331
NE29	280	SW35	327
NE30	334	SW36	291
NE31	313	C1	342
NE32	335	C2	303
NE33	346	C3	287
NE34	342	C4	361
NE35	287	C5	322
NE36	144	C6	298
SW1	260	C7	348
SW2	253	C8	347
SW3	272	C9	317
SW4	284	C10	362
SW5	4320	C11	342
SW6	4580	C12	302

Illuminance (lux)			Uniformity	
Eavg	Emin	Emax	U1(Emin/Eavg)	U2(Emin/Emax)
769	86	6180	0,111	0,013

Table B.8. Illuminance and uniformity results of the second case, December 21, 12:30 pm.

December 21, 12:30 pm			
Point	Task Illuminance (lux)	Point	Task Illuminance (lux)
NE1	210	SW7	1280
NE2	454	SW8	1520
NE3	672	SW9	220
NE4	623	SW10	219
NE5	606	SW11	220
NE6	923	SW12	227
NE7	632	SW13	185
NE8	755	SW14	188
NE9	913	SW15	202
NE10	688	SW16	212
NE11	606	SW17	1690
NE12	836	SW18	864
NE13	70	SW19	1700
NE14	272	SW20	1030
NE15	337	SW21	242
NE16	364	SW22	244
NE17	390	SW23	230
NE18	352	SW24	217
NE19	313	SW25	176
NE20	439	SW26	203
NE21	482	SW27	214
NE22	435	SW28	218
NE23	412	SW29	1120
NE24	213	SW30	464
NE25	51	SW31	486
NE26	176	SW32	541
NE27	161	SW33	220
NE28	193	SW34	220
NE29	196	SW35	233
NE30	242	SW36	205
NE31	208	C1	215
NE32	205	C2	216
NE33	242	C3	203
NE34	234	C4	235
NE35	188	C5	231
NE36	115	C6	245
SW1	182	C7	243
SW2	180	C8	250
SW3	189	C9	262
SW4	189	C10	248
SW5	2910	C11	228
SW6	2160	C12	211

Illuminance (lux)			Uniformity	
Eavg	Emin	Emax	U1(Emin/Eavg)	U2(Emin/Emax)
450	51	2910	0,113	0,017

Table B.9. Illuminance and uniformity results of the final case, March 21, 12:30 pm.

March 21, 12:30 pm			
Point	Task Illuminance (lux)	Point	Task Illuminance (lux)
NE1	266	SW7	529
NE2	545	SW8	544
NE3	718	SW9	277
NE4	734	SW10	279
NE5	656	SW11	285
NE6	1020	SW12	302
NE7	917	SW13	228
NE8	932	SW14	236
NE9	1030	SW15	247
NE10	904	SW16	263
NE11	986	SW17	356
NE12	1020	SW18	374
NE13	102	SW19	360
NE14	288	SW20	414
NE15	382	SW21	302
NE16	431	SW22	303
NE17	357	SW23	290
NE18	375	SW24	273
NE19	615	SW25	229
NE20	848	SW26	262
NE21	739	SW27	258
NE22	614	SW28	311
NE23	727	SW29	202
NE24	593	SW30	361
NE25	80	SW31	326
NE26	204	SW32	340
NE27	203	SW33	281
NE28	241	SW34	299
NE29	241	SW35	277
NE30	266	SW36	264
NE31	475	C1	312
NE32	490	C2	255
NE33	271	C3	242
NE34	287	C4	288
NE35	467	C5	269
NE36	262	C6	254
SW1	221	C7	318
SW2	213	C8	319
SW3	234	C9	290
SW4	245	C10	321
SW5	663	C11	302
SW6	703	C12	275

Illuminance (lux)			Uniformity	
Eavg	Emin	Emax	U1(Emin/Eavg)	U2(Emin/Emax)
408	80	1030	0,2	0,008

Table B.10. Illuminance and uniformity results of the final case, June 21, 12:30 pm.

June 21, 12:30 pm			
Point	Task Illuminance (lux)	Point	Task Illuminance (lux)
NE1	158	SW7	412
NE2	372	SW8	227
NE3	516	SW9	237
NE4	547	SW10	234
NE5	513	SW11	215
NE6	692	SW12	219
NE7	542	SW13	171
NE8	582	SW14	204
NE9	715	SW15	215
NE10	515	SW16	228
NE11	493	SW17	185
NE12	673	SW18	213
NE13	79	SW19	376
NE14	241	SW20	222
NE15	278	SW21	251
NE16	374	SW22	247
NE17	315	SW23	226
NE18	340	SW24	229
NE19	304	SW25	219
NE20	428	SW26	222
NE21	369	SW27	223
NE22	392	SW28	253
NE23	366	SW29	165
NE24	202	SW30	203
NE25	81	SW31	311
NE26	174	SW32	208
NE27	215	SW33	254
NE28	210	SW34	258
NE29	236	SW35	235
NE30	292	SW36	219
NE31	283	C1	269
NE32	268	C2	246
NE33	255	C3	227
NE34	273	C4	287
NE35	234	C5	279
NE36	165	C6	235
SW1	172	C7	288
SW2	177	C8	272
SW3	204	C9	232
SW4	220	C10	275
SW5	239	C11	249
SW6	284	C12	228

Illuminance (lux)			Uniformity	
Eavg	Emin	Emax	U1(Emin/Eavg)	U2(Emin/Emax)
287	79	715	0,28	0,11

Table B.11. Illuminance and uniformity results of the final case, March 21, 12:30 pm.

September 23, 12:30 pm			
Point	Task Illuminance (lux)	Point	Task Illuminance (lux)
NE1	290	SW7	645
NE2	538	SW8	519
NE3	686	SW9	275
NE4	681	SW10	289
NE5	652	SW11	279
NE6	987	SW12	284
NE7	678	SW13	238
NE8	816	SW14	247
NE9	1110	SW15	247
NE10	763	SW16	274
NE11	717	SW17	332
NE12	1000	SW18	355
NE13	93	SW19	353
NE14	293	SW20	366
NE15	350	SW21	295
NE16	408	SW22	301
NE17	363	SW23	292
NE18	394	SW24	270
NE19	325	SW25	232
NE20	476	SW26	253
NE21	500	SW27	259
NE22	469	SW28	289
NE23	390	SW29	213
NE24	280	SW30	350
NE25	82	SW31	219
NE26	207	SW32	195
NE27	221	SW33	286
NE28	229	SW34	304
NE29	236	SW35	294
NE30	285	SW36	271
NE31	264	C1	297
NE32	273	C2	280
NE33	275	C3	251
NE34	307	C4	317
NE35	234	C5	307
NE36	157	C6	264
SW1	229	C7	301
SW2	233	C8	304
SW3	243	C9	260
SW4	255	C10	309
SW5	622	C11	279
SW6	690	C12	262

Illuminance (lux)			Uniformity	
Eavg	Emin	Emax	U1(Emin/Eavg)	U2(Emin/Emax)
366	82	1110	0,22	0,07

Table B.12. Illuminance and uniformity results of the final case, March 21, 12:30 pm.

December 21, 12:30 pm			
Point	Task Illuminance (lux)	Point	Task Illuminance (lux)
NE1	290	SW7	255
NE2	460	SW8	463
NE3	535	SW9	194
NE4	536	SW10	202
NE5	474	SW11	206
NE6	830	SW12	214
NE7	500	SW13	152
NE8	681	SW14	166
NE9	723	SW15	172
NE10	573	SW16	178
NE11	544	SW17	345
NE12	703	SW18	323
NE13	90	SW19	746
NE14	215	SW20	322
NE15	245	SW21	206
NE16	268	SW22	211
NE17	249	SW23	210
NE18	270	SW24	205
NE19	209	SW25	150
NE20	343	SW26	176
NE21	348	SW27	170
NE22	354	SW28	185
NE23	322	SW29	932
NE24	172	SW30	288
NE25	45	SW31	253
NE26	131	SW32	275
NE27	147	SW33	197
NE28	158	SW34	208
NE29	148	SW35	207
NE30	188	SW36	190
NE31	171	C1	193
NE32	187	C2	182
NE33	169	C3	165
NE34	198	C4	209
NE35	155	C5	198
NE36	120	C6	177
SW1	159	C7	212
SW2	159	C8	198
SW3	165	C9	189
SW4	174	C10	211
SW5	1320	C11	209
SW6	591	C12	188

Illuminance (lux)			Uniformity	
Eavg	Emin	Emax	U1(Emin/Eavg)	U2(Emin/Emax)
293	45	1320	0,15	0,034

APPENDIX C

COMPARISON OF CASES IN TERMS OF DAYLIGHT DISTRIBUTION PERFORMANCE

June 21:

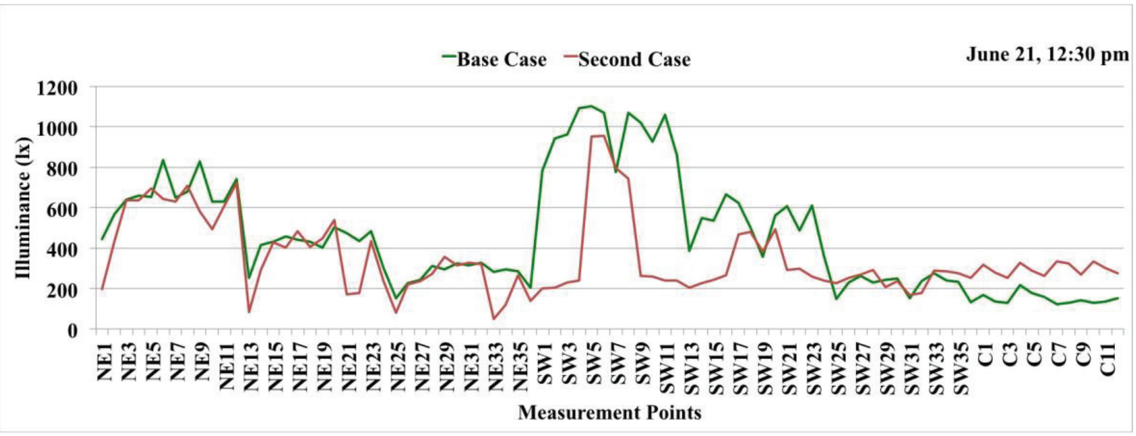

Figure C.1. Comparison of the base and second case on June 21 at 12:30 pm in terms of received light levels.

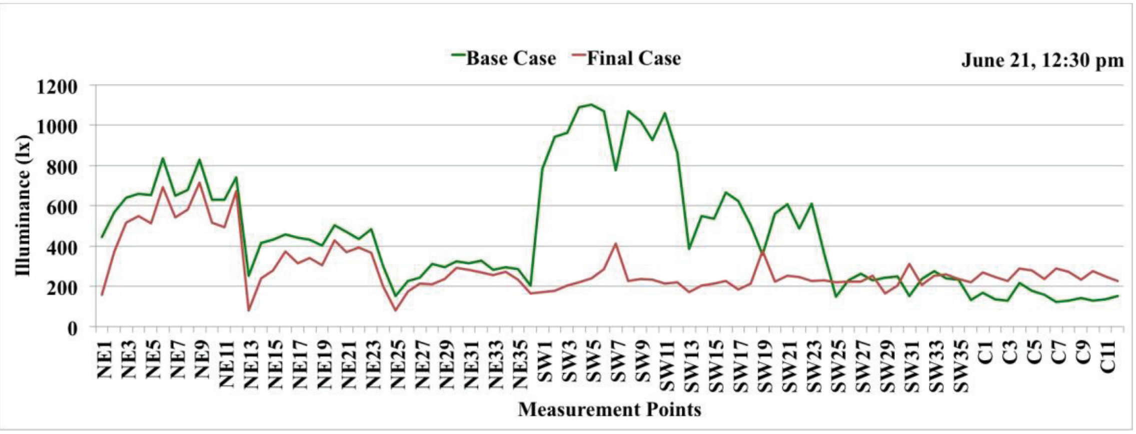

Figure C.2. Comparison of the base and final case on June 21 at 12:30 pm in terms of received light levels.

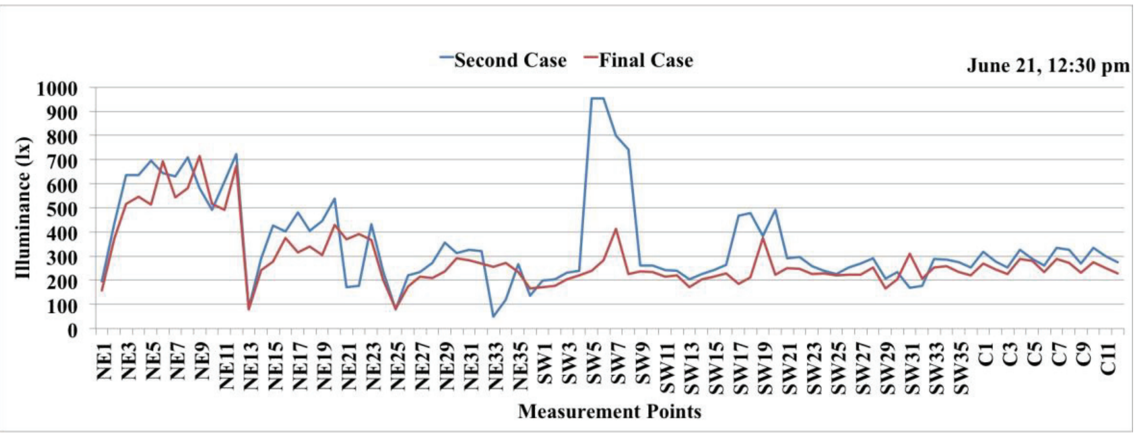

Figure C.3. Comparison of the second and final case on June 21 at 12:30 pm in terms of received light levels.

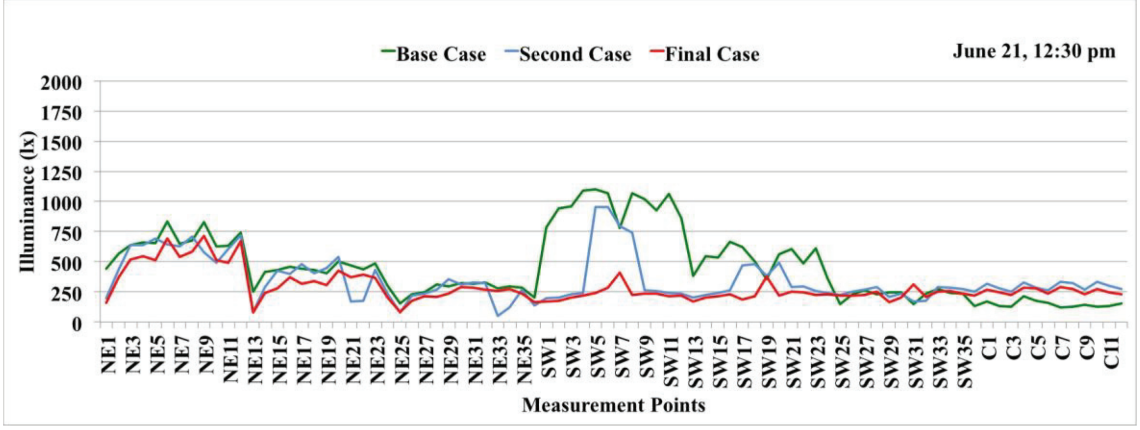

Figure C.4. Comparison of the base, second, and final cases on June 21 at 12:30 pm in terms of received light levels.

September 23:

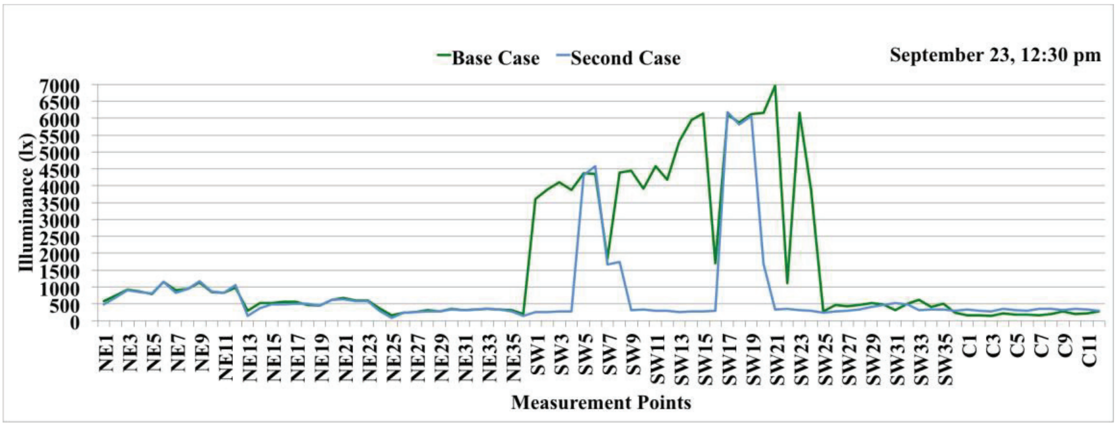

Figure C.5. Comparison of the base and second case on September 23 at 12:30 pm in terms of received light levels.

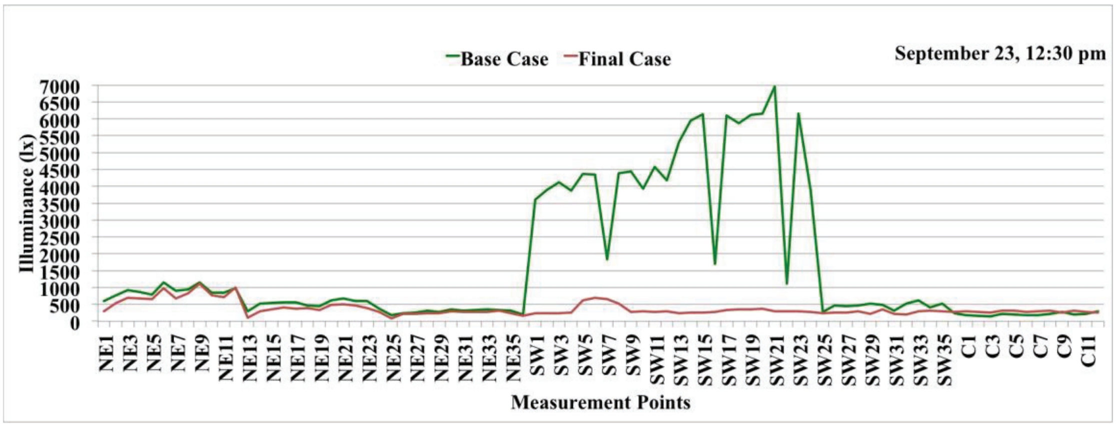

Figure C.6. Comparison of the base and final case on September 23 at 12:30 pm in terms of received light levels.

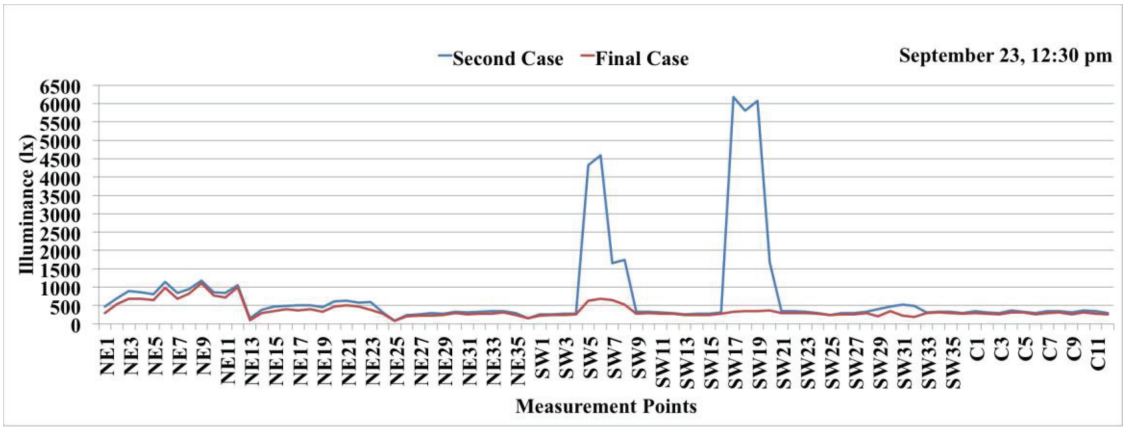

Figure C.7. Comparison of the second and final case on September 23 at 12:30 pm in terms of received light levels.

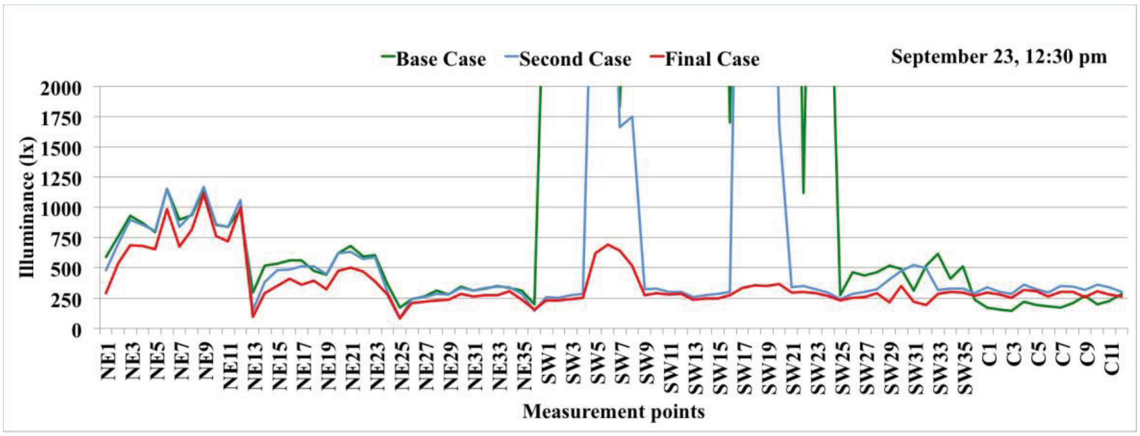

Figure C.8. Comparison of the base, second, and final cases on September 23 at 12:30 pm in terms of received light levels.

December 21:

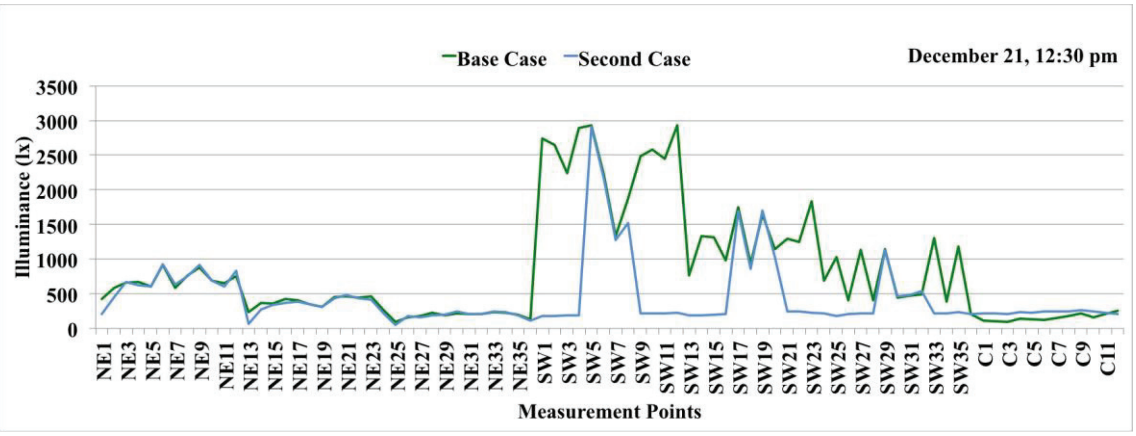

Figure C.9. Comparison of the base and second case on December 21 at 12:30 pm in terms of received light levels.

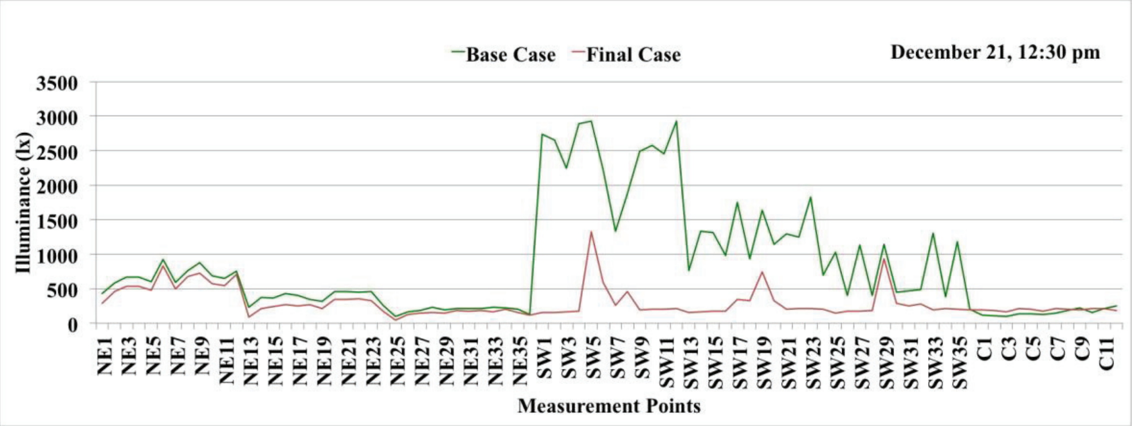

Figure C.10. Comparison of the base and final case on December 21 at 12:30 pm in terms of received light levels.

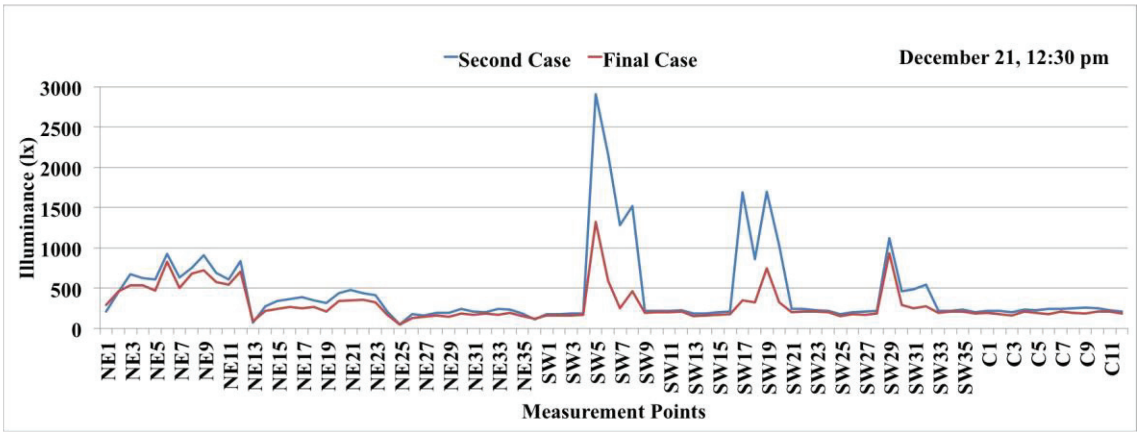

Figure C.11. Comparison of the second and final case on December 21 at 12:30 pm in terms of received light levels.

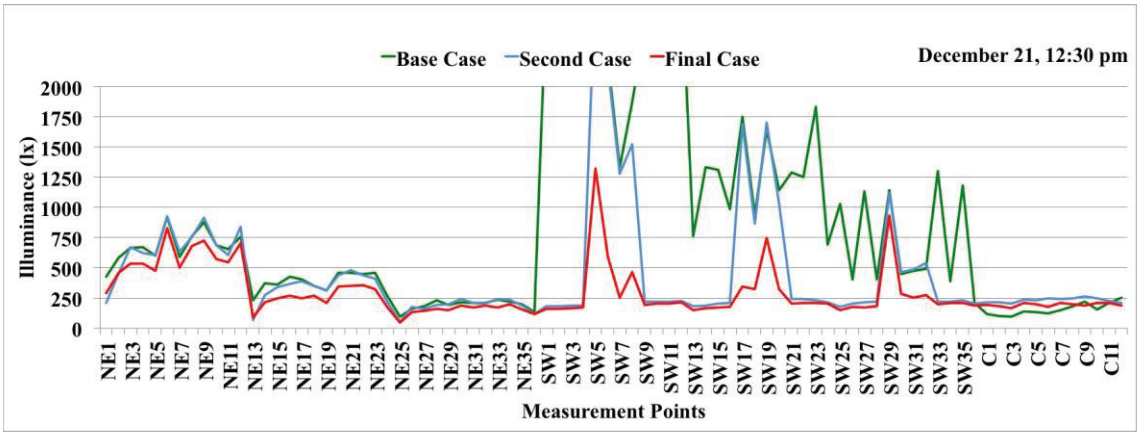

Figure C.12. Comparison of the base, second, and final cases on December 21 at 12:30 pm in terms of received light levels.