OPTIMIZING THE WINDOW SIZE AND DEPTH OF A SOUTH-FACING ROOM WITH PRISMATIC PANELS FOR A BETTER DAYLIGHT PERFORMANCE

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ABSTRACT

OPTIMIZING THE WINDOW SIZE AND DEPTH OF A SOUTH-FACING ROOM WITH PRISMATIC PANELS FOR A BETTER DAYLIGHT PERFORMANCE

In a conventional side-lit room, light levels decrease rapidly as room gets deeper, resulting in excessive daylight exposure near the perimeter zones and need for artificial lighting at the back of the room. Therefore, it is not possible to achieve good lighting performance throughout the room unless any daylight strategy is developed. Advanced daylighting systems are developed to figure out this problem. Prismatic daylight-redirecting panels, for instance, improve daylight distribution through sun shading and redirection.

This study mainly focuses on the performance of daylight redirecting prismatic panels attached in a south-facing, side-lit room with different room depths and window-to-wall-ratios (WWR). A deep-plan classroom was chosen as a reference case. The methodology is based on simulating the base model in Relux and testing it with alternative models composed of incrementally defined WWR and room depth values. The on-site measurements were performed to evaluate current daylight conditions and validate the simulation model. Illuminance values obtained throughout the room were evaluated in terms of the latest daylighting metrics and visual performance recommendations. Furthermore, simulation findings were used as inputs in constructing a multiple regression model to analyse the relation between room depth, window-to-wall-ratio and daylight illuminance.

The study presents the optimal window-to-wall ratios in relation with varying room depths when prismatic panels are attached. It is considered that the requirements mentioned in standards can be revised taking account of advanced daylighting systems. Besides, the prediction model estimating illuminance in such design alternatives would be integrated in the initial design phase.

ÖZET

DAHA İYİ BİR GÜN IŞIĞI PERFORMANSI İÇİN GÜNEYE BAKAN BİR ODANIN PENCERE BOYUTUNUN VE DERİNLİĞİNİN PRİZMATİK PANELLER İLE OPTİMİZASYONU

Geleneksel bir yandan aydınlatılan odada, pencereden uzaklaştıkça aydınlık seviyeleri hızla düşer, bu da pencereye yakın bölgelerde aşırı gün ışığına maruz kalınırken odanın arka kısmında yapay aydınlatma kullanılmasına sebep olur. Bu nedenle, herhangi bir doğal aydınlatma stratejisi geliştirilmediği sürece oda genelinde iyi bir aydınlatma performansı elde etmek mümkün değildir. Bu sorunu çözmek için inovatif doğal aydınlatma sistemleri geliştirilmiştir. Örneğin prizmatik paneller, aşırı gün ışığına karşı gölgeleme sağlarken, gün ışığını iç mekana yönlendirme yoluyla oda genelindeki aydınlatma dağılımını iyileştirir.

Bu çalışma temel olarak, görsel koşulların iyileştirilmesi açısından, farklı oda derinliklerine ve pencere-duvar oranlarına sahip, güneye bakan ve yandan aydınlatılan odaya yerleştirilmiş prizmatik panellerin gün ışığını yönlendirmedeki performansına odaklanmaktadır. Bu bağlamda, derin planlı bir sınıf örnek mekan olarak seçilmiştir. Araştırma yöntemi Relux aydınlatma programında örnek odanın modellenmesine ve aşamalı olarak tanımlanmış pencere-duvar oranı ve oda derinliği değerlerinden oluşan alternatif modellerle test edilmesine dayanır. Tasarım alternatifleri belirlenirken, mevcut doğal aydınlatma standartlarında belirtilen gereksinimler dikkate alınmıştır. Odada genelinde elde edilen aydınlık değerleri güncel doğal aydınlatma metriklerine ve görsel performans önerilerine göre değerlendirilmiştir. Ek olarak, simülasyon sonuçları oda derinliği, pencere-duvar oranı ve aydınlık değerleri arasındaki ilişkiyi analiz etmek için çoklu regresyon modelinin oluşturulmasında girdi olarak kullanılmıştır.

Çalışma, prizmatik paneller uygulandığında farklı oda derinliklerine bağlı olarak en uygun pencere-duvar oranlarını sunmaktadır. Daha iyi bir doğal aydınlatma performansı için, standartlarda belirtilen gereksinimlerin gelişmiş doğal aydınlatma sistemleri dikkate alınarak revize edilebileceği düşünülmektedir. Ayrıca, bu tür tasarım alternatiflerindeki aydınlık değerlerinin öngörülebildiği tahmin modeli tasarım sürecinde bilgisayar simülasyon programlarına alternatif olarak kullanılabilir.

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CHAPTER 1

INTRODUCTION

1.1. Argument

Natural light from the sun is one of the irreplaceable energy source for people's daily life. The significance of natural light in human life becomes more apparent when we are deprived of light or exposed excessive light. It has been proven that both lack of daylight and exposure to natural light in buildings have negative psychological and physiological effects on the health, well-being and performance of humans (Boyce, Hunter, and Howlett 2003). Excessive light explosion causes reflected glare, undesirable visual comfort and overheating. Consequently the deterioration of room atmosphere and energy balance causes occupants to be uncomfortable, the lack of concentration and to get tired easily. In the absence of sufficient daylight, artificial lighting is needed but studies proved that the typical symptoms such as headaches, fatigue and eyestrain increase in proportion to the use of artificial lighting (Brandi 2006). Therefore, people instinctively tend to prefer daylit areas instead of artificially lit areas.

In the design process of sustainable built environments, daylighting also plays a significant role in the energy savings since it allows the use of daylight to be maximized in an indoor environment and to reduce the energy consumption arising from lighting, cooling and heating of buildings. For a better daylight performance both quantitative and the qualitative parameters should be considered.

Various factors impact the interior daylight illuminance such as location, orientation, day and time, sky cover, room geometry, window size and presence of shading (Bellia, Fragliasso, and Pedace 2015). In particular, making the right decisions on room geometry and window size become crucial in the initial design phase since it is difficult to compensate later. Several countries have some standards and regulations concerning daylighting design in buildings. These standards are available in various forms based on illuminance, window size and daylight factor (Boubekri 2004). An example of window-size based standard can be found in The British Code BR 8206

(Part 2), which recommends a formula for calculating the maximum acceptable room depth of a side-lit room according to height of the upper edge of the window and also minimum acceptable window area according to room depth. More comprehensive approach can be found in *DIN 5034-4 Daylight in Interiors-Simplified regulation for minimum window sizes* that presents recommended minimum window width in relation to various room dimensions.

Besides such standards, there are studies to determine an optimum window area considering both daylight provision and energy consumption together. Grisi et. al. (2005) presented a methodology to determine the ideal window area of spaces in different climatic conditions and assessed the potential for electric energy savings using the ideal window concept. In the study, five different room ratios and ten different room dimensions were chosen and simulations were performed using VisualDOE with window areas ranging from 0% to 100% at increments of 10% for two cities (one in Brazil and one in the UK). The window area which energy consumption of the room is lowest was defined as the ideal window area. After determining the ideal window area for each room, the potential for lighting energy savings were calculated based on Daylight Factor. It was concluded that the potential for lightning energy savings ranged from 10.8% to 44.0% for all room ratios and room sizes in Leeds, UK and ranged from 20.6% to 86.2% in Florianopolis, Brazil. Reinhart et. al. (2013) carried out a study for south facing deep plan office located in Boston. The office with different window-to-wall ratios was assessed in terms of daylight availability, daylight glare probability and energy consumption using Radiance-based DAYSIM simulations combined with EnergyPlus. It was determined that the energy use arising from artificial lighting is increased due to reduced daylit area when the window-to-wall ratio is less than 20%. Energy usage was almost the same for larger windows but increasing glazing caused discomfort glare and occupants to close blinds more often which in turn prevent view to the outside. Hence, optimum window-to-wall ratio for south facing office in Boston was suggested as 40%. Another study conducted by Mehlika et. al. (2000) investigates optimum building aspect ratio and south window-to-wall ratio (WWR) in order to minimize the total annual heating and cooling loads of residential buildings located in five different cities in different climatic regions in Turkey. In accordance with results of parametric study performed in SUNCODE-PC software, increasing south window size in cold climates causes decrease in total annual load whereas it causes increase in warm climates. It was concluded that changing building aspect ratio does not notably affects the total energy loads in the studied locations and different window sizes are required for different climatic conditions.

As it can be deduced from the above mentioned studies, determining appropriate room and window ratio according to climatic conditions is very important both in terms of visual comfort and energy savings. However, geometric factors alone may not be sufficient for a good visual and thermal comfort especially in buildings mostly used in daytime. As a rule of thumb, conventional windows can adequately and effectively illuminate a room to a depth of 1.5 times the height of the window above the floor level (Ruck et al. 2000), rest of the room still need to be illuminated with additional artificial lighting. Applying large windows provides higher illuminance at the back of the room and thus reduces the use of artificial lighting, but this cause a disproportional amount of solar radiation into the front part of the room and resulting in an increase in cooling loads (Ochoa et al. 2012). In addition, the non-uniform illuminance distribution throughout the working plane can result visual problems associated with glare. Especially in hot climatic regions, uniform distribution is required to achieve the desired visual and thermal comfort.

Conventional daylighting design components partially control direct sunlight and glare near the perimeter zones but their characteristics are insufficient when it comes to illuminating deep spaces and providing adequately uniform lighting, therefore, variety of innovative daylighting systems have been developed to improve the usage of daylight. These systems rely on increasing illuminance further from windows to areas where it is required by redirecting incoming sunlight towards the ceiling plane. This proper handling of diffuse/direct daylight also prevents probability of glare for occupants seated near the window and distributes daylight evenly (Thanachareonkit, Lee, and McNeil 2014).

Prismatic elements are one of the advanced daylight redirecting systems that allow uniform daylight distribution and control direct sunlight. Multiple studies investigating performance of these systems focus mostly on deep plan office buildings where the lighting has a large proportion in electricity consumption. The study conducted by McNeil et. al. (2017) investigates performance of microstructured daylighting films in terms of potential lighting energy savings and occurrence of discomfort glare in a 12.2m deep, south-facing office for four different climates of the

U.S. Parametric simulations performed to evaluate annual lighting energy savings and visual comfort using the Radiance three-phase method. According to the simulation results, daylight redirecting system was produced 22-23% greater lighting energy savings compared to the conventional shading system but discomfort glare was occurred for views looking at the window during equinox to winter mid-day hour. The study also refers to various difficulties encountered during the modeling and simulation process and provides potential solutions. A similar study conducted by Mashaly et. al. (2017) aimed to find out a daylight redirecting prismatic system efficient at high solar altitudes. After determining the most suitable micro-prism angle, performance of proposed prism system was assessed in the 8.2m deep room with a 10% window-to-wall ratio using Radiance five-phase method. The proposed micro-prism design was succeeded in transmitting the daylight into deep spaces and the sDA value was increased from 29% to 41% at the back of the room while the total sDA came up to 78% with an 11% increase compared to traditional glazing. Another study carried out by Kazanasmaz et. al. (2016) presents three comparative approaches to determine smallest acceptable window area (WWR) that meet required sDA value of 75% and then necessary area for micro-prism film (FWR) applied on it. Simulations were run for south-facing classroom in Switzerland. Results show that micro prism films enable to improve the performance of windows with lower WWR. The best sDA value of 82.4% was obtained with the combination of WWR 75% and FWR 1/9.

This study differs from other studies in literature by examining the performance of attached prismatic panels which have shading capability, in a side lighted deep plan room to find out the least possible WWR value in relation to room depth satisfying the required daylight availability. The methodology is based on simulating a base model in Relux and testing it with alternative models composed of incrementally defined WWR and room depth values. The verification of the base model without any prismatic panel system is attained through field and measurement in an actual classroom. Moreover, a multiple regression model is developed to predict daylight illuminance in different room depth-WWR configurations when prismatic panels are installed. Resulted simplified equation can be used as an alternative way to computer simulation programs and integrated in the initial design phase.

1.2. Purpose of the Study

The purpose of the study is primarily to test and predict the performance of attached prismatic panels in defining optimum window size and room geometry when prismatic panels are installed in the side windows. The second aim is to provide sufficient daylight as deeply as possible into the space in every WWR-Room depth design alternatives and preventing excessive direct sunlight which may cause negative impacts on occupants. The climate of Izmir is another significance, meaning that, it would be possible to understand the applicability of a prismatic system in such a geographic and climatic location. This study presents a new approach with consideration of innovative daylight redirecting systems to propose revisions for the requirements mentioned in standards about daylight in buildings but based on conventional fenestration systems. The multiple regression model is useful in evaluating performance of the prismatic panel and the relations between room depth, window-to-wall-ratio (WWR) and daylight illuminance. Thus, study can be used as a guide in the design phase by all related professionals.

1.3. Structure of the Thesis

In this thesis, the study carried out in line with the above mentioned purposes is explained in 5 chapters. This first chapter comprises of the argument, the purpose of the study and the structure of the thesis summarizing the following chapters. Here, the research problem is identified, related previous studies and the deficiencies in these studies are explained and the importance of the study is stated.

The second chapter includes literature review on parameters affecting daylighting performance of side lighted rooms, current daylighting standards, detailed information about daylight redirecting prismatic panels and daylight performance metrics.

The third chapter provides a detailed description of the case room and the explanation of the on-site monitoring process. The simulation model of the case room and alternative rooms with varying window-to-wall ratios (WWR) and room depths are explained. The multiple regression model is developed according to simulation outputs.

The fourth chapter comprises of validation process of the simulation model, the results obtained from the computer and statistical analysis and their evaluation in terms of visual performance recommendations.

In the fifth chapter, conclusions of the study are stated by summarizing the analysis results; and recommendations for future studies and revisions to current daylighting standards are proposed.

CHAPTER 2

LITERATURE REVIEW

This section includes general information and related previous studies about daylighting in buildings. In the first part of this chapter, the importance of daylighting in terms of human health and sustainability is mentioned briefly and the parameters affecting the daylighting performance in interior are explained. Various daylighting standards established with the intention of providing good daylighting performance in buildings is mentioned. Section 2.2 includes technical properties, application types and researches of prismatic panels used to improve daylight quality in buildings. The last section describes daylight performance metrics and their pluses and minuses.

2.1. Daylight in Building Design

Today, the influence of built environment on people's health and well being cannot be ignored, as people spend vast majority of their time indoors (Boubekri 2014). The quality of the building environment from the thermal, biological and visual point of view can be significantly improved by a number of design considerations, including daylighting. Daylight has many significant contributions to human physical and psychological health; for example, it regulates the circadian rhythm of human, reduces the sadness regarding Seasonal Affective Disorder (SAD) by maintaining hormone balance and increases motivation and productivity in workplaces. However, lack of daylight, exposure to excessive sunlight, or prolonged exposure to artificial lighting has negative effects on health. For instance, several ailments such as fatigue, headaches, numbness etc. can appear depending on the increase in the use of artificial lighting, direct sun radiation can cause thermal discomfort, or glare arising from direct sunlight can impair visual performance and cause irritation to occupants' eyes, resulting in deterioration of well-being (Brandi 2006), (Boubekri 2014).

With the growing awareness about global warming, the effective utilization of daylight in spaces as a part of sustainable development has become even more important since daylighting has a share in the energy consumption and environmental costs of a building. With the judicious use of daylight, cooling and heating loads of the building can be managed by minimizing solar heat gain in summer while maximizing in winter and also energy consumption arising from artificial lighting can be reduced. As a consequence, it is crucial to ensure sufficient and evenly distributed daylight in the building design, bearing quantitative and qualitative requirements in mind (Boubekri 2014).

In the majority of buildings, daylighting, view and ventilation are provided through the facade openings in the building. Every room equipped with window, even facade is fully glazed, does not indicates a good daylighting performance, for this, occupants' comfort and energy saving need to be provided. Especially in side-lit rooms, as the majority of the rooms equipped with, daylighting performance should be addressed carefully and daylighting strategies may need to be developed. In the following section, parameters that affect daylighting performance and design strategies for side lighted room will be discussed.

2.1.1. Daylighting Strategies for Sidelighted Rooms

The parameters affecting the amount and distribution of daylight entering the interior space can be listed as follows: daylight availability (latitude, longitude, facade orientation), room design (location, geometry, optical properties), window design (size, configuration, orientation, optical properties), Obstructions (size, location, optical properties).

2.1.1.1. Daylight Availability

The luminance distribution from the sun and sky are the essential components of daylighting. Sunlight indicates the direct component while the skylight indicates the diffuse component of the daylight. The availability of daylight depends on geographical position (latitude and longitude) of the building site, climatic conditions and position of the sun (altitude and azimuth). The latitude of a specific geographic location determines the solar position for a certain time of day and year (Andersen and Foldbjerg 2012). Identification of the solar position in the sky leads daylighting design decisions such as orientation of building, determination of window type and area and selection of appropriate shading device (Li and Lam 2001). As moving away from the equator to the north or south, the difference between the summer and winter conditions vary depending on the change of latitude. Seasonal variations are lesser at low latitudes, and due to high daylight levels throughout the year in these regions, design strategies have been developed in order to prevent overheating, usually by limiting the amount of daylight entering the building. On the other hand, the difference between the summer and winter conditions are more apparent at higher latitudes and daylight levels are low in winter. In these latitudes, the purpose is usually to maximize the penetration of the daylight or redirection of daylight into the interiors.

The orientation of building facade is another significant factor in terms of daylight availability since direction to the sun affects the admission of daylight and solar gain in the building. In the northern hemisphere, a north-facing window receives a relatively small amount of solar radiation compared to windows facing other directions. The daylight from this direction consists of diffused lights and remains stable throughout the day. The daylight from the south, east and west directions often consists of direct sunlight, and the daylight levels vary considerably throughout the day. Especially for summer days, when the sun is high, south facing facades is protected from direct solar radiation using shading (Ruck et al. 2000), (Andersen and Foldbjerg 2012).

2.1.1.2. Obstructions

The obstacles at a construction site give the designers an idea of the daylight potential of the building facades and allow them to shape the building according to the availability of daylight. There are two types of obstacles affecting the amount and distribution of daylight in building interiors: Self-obstructing and surrounding obstructions. Overhangs, balconies, eaves etc. are self-obstructing elements in the building that prevents admission of daylight from the zenithal part of the sky. The surrounding obstructions include other buildings, vegetation, and terrain outside the window and so on. Self-obstructing elements mostly reduce the daylight levels in the area close to the window, while the surrounding obstructions affect the daylight levels with larger consequences. The effect of obstructions on the daylight levels in a building rely on the size of the obstacle and its distance to the building. The decrease in the amount of daylight entering from the window is proportional to the increase of the area blocking the sky. For instance, a high and thin obstruction opposite the window causes a further decrease in the interior daylight levels compared to a wider and lower building. Obstructions can also reflect sunlight, which can cause glare at street level or increase thermal loads of the buildings.

2.1.1.3. Room Design

In conventional side lighted rooms, the illuminance levels drops off rapidly as moving away from the window. As the depth of the room increases, the back of the room remains dark regardless of the window size; unless a daylighting system is applied (Apian-Bennewitz et al. 1998). Even if the building is designed appropriate for a particular site and climatic conditions, thermal and visual problems may still exist based on inadequate and uneven illuminance levels throughout the room (Arnesen, Kolås, and Matusiak 2011). Therefore, the proportions and optical properties of the room play an significant role in order to illuminate the room in good quality with adequate daylight. CIBSE (1999) proposes limitations on the overall plan depth if a side-lit room is to be illuminated by daylight only. The depth of the room depends on height of the upper edge of the window, window width and optical properties of the surfaces. The depth of the room depends on height of the upper edge of the window, window width and optical properties of the surfaces, and it is expressed by following formula (2.1):

$$\frac{\mathrm{L}}{\mathrm{W}} + \frac{\mathrm{L}}{\mathrm{H}_w} < \frac{2}{1-\mathrm{R}_b} \tag{2.1}$$

where L is the room depth, W is the room width, H_w the window head height above floor level and R_b the average reflectance of surfaces in the rear half of the room. It is pointed out that if the room depth exceeds this value, electrical lighting is required due to the low illuminance levels at the rear part of the room (CIBSE 1999).

The reflectance of the main surfaces in a room plays a significant role in the illumination of the interiors. Matt and high reflectance surfaces provide internal reflection and are especially recommended for workplaces. The reflectance of ceiling surface is recommended to be 0.8; however, it is favoured to be as high as practicable. The higher reflectance of wall surfaces allows the interior to be perceived as brighter.

The amount of light reaching the back of the room is mostly determined by the reflected light from the surfaces surrounding the window. In order to ensure a good contrast throughout the room, it is recommended that the surfaces surrounding the windows should not be less than 0.6. Likewise, an amount of light on the ceiling is reflected from the floor cavity; therefore, it is recommended that the average reflectance of the floor cavity is greater than 0.20 and less than 0.40 in order to maintain the luminance balance between the ceiling and the floor (CIBSE 1999).

2.1.1.4. Window Design

Windows are fundamental elements of daylighting. They also provide view to the outside, natural ventilation and solar heat gain for buildings. The quantity and distribution of daylight entering a room depends primarily on the window size, position and the glazing properties.

The challenge in the determining the optimum window design is to provide uniform daylight distribution throughout the room and adequate daylight to perform a task while minimizing energy consumption regarding excessive heat gains or losses and avoiding glare. Increasing the window area also means an increase in heat transfer through the envelope, which rising up heating loads due to heat loss during winter and cooling loads due to overheating in summer. Several studies have been carried out with the objective to find out an optimum window configuration that will provide good thermal performance while allowing sufficient daylight for a certain geographical location and climatic conditions, and significant energy savings regarding heating, cooling and lighting have been achieved (Ghisi and Tinker 2005), (Glassman and Reinhart 2013), (Reinhart, Jakubiec, and Ibarra 2013), (Mangkuto, Rohmah, and Asri 2016).

The position of the windows significantly affects the daylight distribution throughout the room (Figure 2.1). The high positioned windows result in more daylight at the back of the room and reduce the daylight levels close to window, thus providing a slightly more uniform illuminance distribution compared to a lower positioned window (Acosta, Campano, and Molina 2016).

Yet, the eye level of the occupants should also be taken into consideration while determining the size and position of the window since view through the window conveys information about time of the day, season, and weather conditions and contributes occupants' well-being (Brandi 2006).

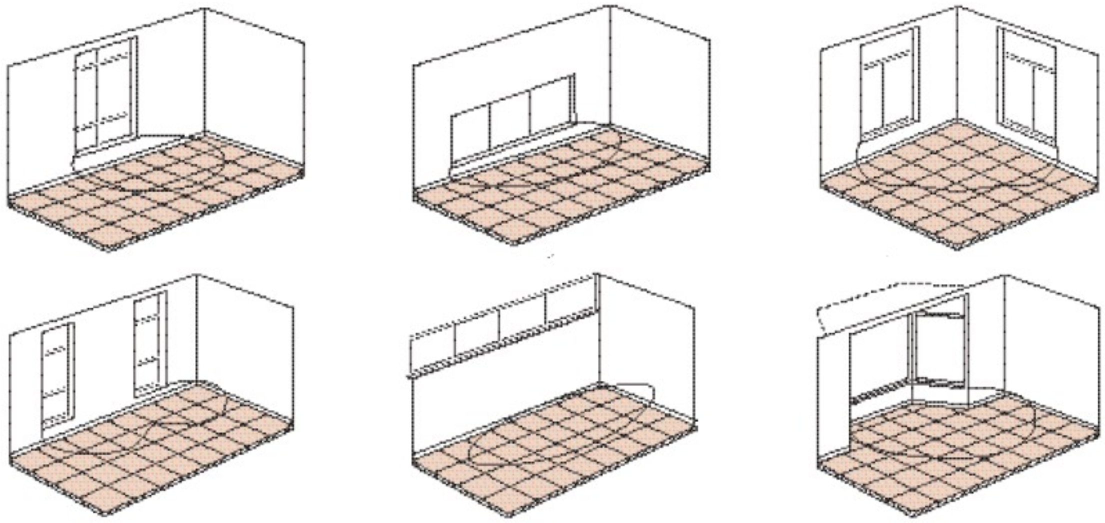


Figure 2.1. Illustration of daylight distribution in accordance with different window configurations (Source: CIBSE 1999).

The optimum number of windows and their configuration depends on the function of the room. For instance, offices are usually occupied working hours during daytime and require illuminance of 500 lx to perform a specific task. This means any change in daylight provision has a remarkable impact on the daylight autonomy and energy consumption. A sample study was carried out for a room with 4 m width, 6 m depth and 2.7 m height, and all daylighting scenarios were tested through a computer programme (Brandi 2006). Daylight autonomy of at least 30% for entire floor area is assumed to be a restriction criterion. Herewith, for a typical office space that has windows in one wall only, the following window-to-wall ratios (WWR) have been recommended, taking the daylight autonomy requirements and the energy demand for artificial lighting into account:

- The window-to-wall ratio of 50% determined as minimum requirement to meet desired daylight autonomy of 30%.
- 60% presents sufficiently bright rooms.

- 65% determined as optimum value with maximum degree of autonomy and energy saving.
- The window-to-wall ratio above 65% is considered unfavourable with respect to daylight autonomy and energy saving.

Since the frequency of use of residential buildings is more common in the evening hours, lower illuminance levels are acceptable for the visual tasks. In a similar way, the following window-to-wall ratios (WWR) have been recommended considering nominal illuminance of 100 lx for a typical residential space:

- The window-to-wall ratio of 30% meets desired daylight autonomy of 30%, minimum requirement.
- 40% presents sufficiently bright rooms.
- 50% provides maximum degree of autonomy and energy saving, optimum value.
- The window-to-wall ratio above 50% is considered unfavourable since problems may occur related to excessive heat gain.

Further study by Brandi (2006) for the same room was revealed the effect of the window position on the distribution of daylight throughout the room when the window area was kept constant. As a conclusion, room with low positioned window does not receive adequate daylight and has the worst daylight distribution since window does not provide daylight in the depth of the room (Figure 2.2.a). A mid-height window with equal dimensions provides much daylight to the front of the room, but does not provide enough daylight to the rear part of the room, resulting in uneven daylight distribution (Figure 2.2.b). A high ceiling extending to the ceiling transmits daylight deep into the room and provides the best daylighting distribution (Figure 2.2c). However, view to the outside is not possible in this position of the window. In Figure 2.2.d, window covers upper two thirds of the facade with ratio of 60% and presents standard solution for office space. A sufficient amount of daylight is transmitted to the depth of the room, but high illuminance levels can cause glare near the window perimeter. It has been indicated that, with a desired order of fenestration, a window positioned to the upper part of the facade with ratio of 50% is sufficient for best results in terms of daylight autonomy and energy saving.

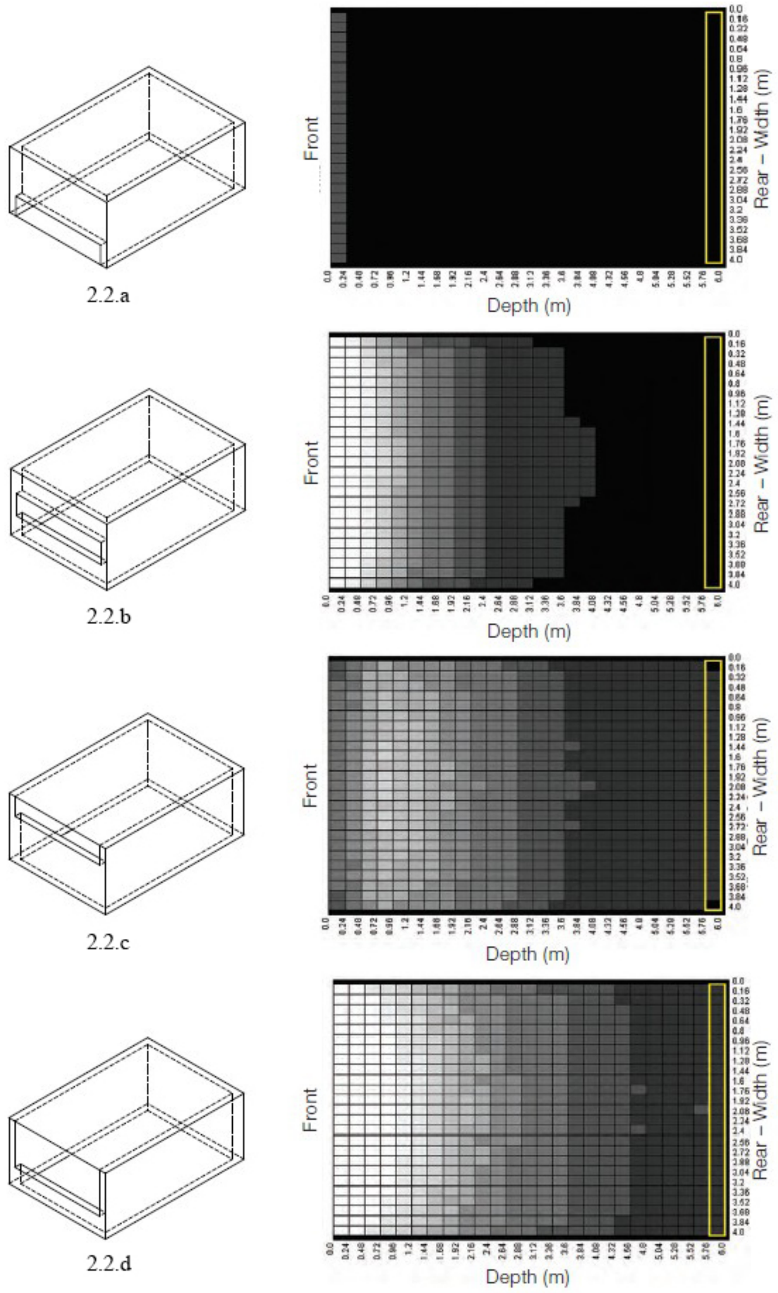


Figure 2.2. Daylight distribution throughout the room with a fixed ratio of window area (Source: Brandi 2006).

2.1.2. Daylighting Standards

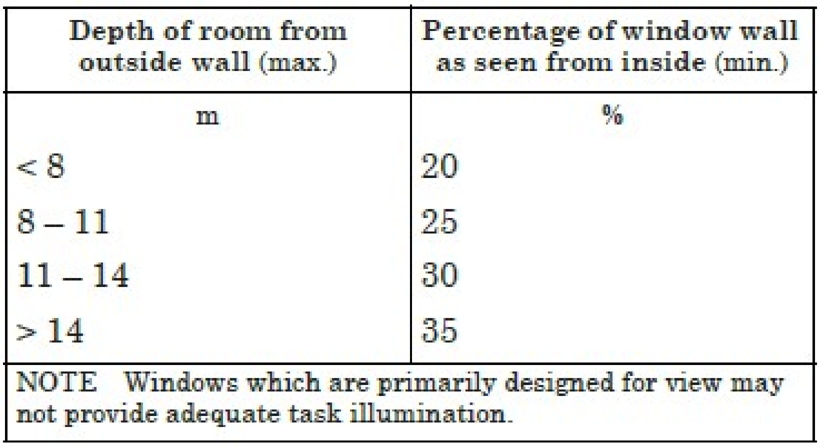
An interior which looks gloomy or does not have a view to outside is considered unsatisfactory by its users. The aim of the building standards regarding daylighting is to give guidance to building professionals to maintain the well-being, health and satisfaction of the building occupants. They present simple graphical and numerical methods to describe good practice in daylighting design (Boubekri 2004).

Daylighting is only matter that influences fenestration, which means that other environment performance issues such as thermal balance, energy use, noise etc. should also be considered. Even the best design for a building cannot provide the ideal solution for each individual function, therefore the intended use of the criteria given in the standard should be decided carefully (British Standards 1992).

There are various forms of legislations regarding daylighting varying from one country to another. These are only recommended practices for daylighting, not mandatory by law. For instance, according to the illuminance-based standard described by the Canadian Ministry of Public Works, an average daylight level of 200 lx should be supplied along the perimeter of the office space at a depth of 3 meters for a certain period of time. In Germany, the DIN 5034-4 standard recommends different daylight illuminance levels according to the difficulty of the visual task being carried out (i.e. 250-500 lx for normal task, 750-1000 lx for difficult task). According to The Chartered Institution of Building Services Engineers (CIBSE), the average recommended illuminance level for offices is minimum 300 lx; minimum 500 lx for auditorium, laboratory and lecture halls, minimum 200 lx for entrance halls, and minimum 100 lx for circulation areas (Boubekri 2014), (Erlalelitepe, Aral, and Kazanasmaz 2011).

An example of daylight factor-based standard can be found in France. Since outdoor conditions are constantly changing, such standards do not recommends a specific daylight illuminance level in the room; instead, percentage of horizontal indoor illuminance in relation to the outdoor illuminance is calculated under overcast sky conditions. Le Cahier des Recommendations Techniques de Construction of the French Ministère de l'Education, which contains building codes for educational buildings, recommends a minimum daylight factor of 1.5% for classrooms. Similarly in UK, a minimum Daylight Factor of 2% in classrooms was prescribed by the government during the post-war period (Boubekri 2004), (Erlalelitepe, Aral, and Kazanasmaz 2011).

As an example of a window-size based legislation, The British Code BR 8206 (Part 2) recommends different window-to-wall ratios (WWR) in relation with varying room depths (Figure 2.3). The German DIN 5034-4 standard is more comprehensive in terms of good daylighting practice since specific window sizes are described for various room dimensions (Boubekri 2004).



Depth of room from outside wall (max.)	Percentage of window wall as seen from inside (min.)
m	%
< 8	20
8 – 11	25
11 – 14	30
> 14	35

NOTE Windows which are primarily designed for view may not provide adequate task illumination.

Figure 2.3. Minimum glazed areas when windows are restricted to one wall (Source: The British Code BR 8206 (Part 2)).

2.2. Daylight Redirecting Prismatic Panels

In a conventional side lighted space with a vertical window, the effective daylit zone is limited to the window edge; areas further away from the perimeter zone receive considerably lower daylight (Reinhart 2005). Increasing window size to expand the effective daylit zone can contribute small gains in daylight levels at the rear part of the room but cause excessive solar radiation near the window (Kim and Wineman 2005). This disproportional distribution of daylight in space results in thermal and visual discomfort in front part of the room while additional support from artificial lighting is required at the back, which means undesirable lighting conditions for the occupants (Kontadakis et al. 2017).

Furthermore, using conventional solar shading devices, such as roller shades or venetian blinds (Littlefair 1999), reduce the amount of daylight entering into room and worsen the daylight distribution across the space (Bellia et al. 2014). Innovative daylighting systems have been proposed to overcome shortcomings of conventional daylighting techniques. By means of the reflective or refractive components incorporated into the glazing system, these systems improve the daylighting performance throughout the area (Kolås 2013). For instance, they can be used to transfer daylight deeper inside the room than is possible with conventional design, to increase usage of daylight for predominantly overcast skies or provide direct sunlight control for very sunny climates, to increase daylight availability for spaces blocked by external obstructions, or to transport daylight to spaces without window (Ruck et al. 2000).

Over the years, various daylighting systems have been developed (Littlefair 1990), (Köster 2004). The classifications made according to their operation types, position within the building envelope, shading capabilities or daylighting conditions (diffuse or direct skylight) are presented in several articles and review papers (Kischkoweit-Lopin 2002), (Nair, Ramamurthy, and Ganesan 2014), (Freewan 2015) (Tsangrassoulis 2008). One of the most comprehensive classifications can be found in the IEA Task 21, where a detailed matrix of daylighting systems is divided into two main groups based on their shading capability to help building professionals in choosing a right system (Ruck et al. 2000). Daylighting systems with shading basically allow diffuse sunlight into the space and block direct sunlight, or use direct sunlight and redirect to the ceiling/above eye level. While their location in the building can vary (window or skylight), light shelves, laser cut panels, louvers and blinds, prismatic panels, turnable lamellas, anidolic solar blinds are examples of this category. On the other hand, the principle of daylight systems without shading is based on redirecting sunlight to areas further away from the facade openings. This category includes anidolic integrated systems, anidolic ceilings, holographic optical elements (HOEs), light scattering systems and light transporting systems (heliostats, light pipes, fibres, solar tubes) and so on (Ruck et al. 2000), (Köster 2004), (Littlefair 1990).

There are several parameters that should be considered while choosing the daylighting system for desired place: daylighting conditions of given site (location, climate, obstructions), window properties, objectives (visual comfort or energy saving), operational preferences (fixed or movable), limitations regarding architectural integration, economic limitations (Ruck et al. 2000). Taking these parameters into account, movable prismatic panels which provide both solar protection and daylight control were selected in order to examine their performance in the case room determined within the scope of the thesis. The physical characteristics of prismatic systems, their application types and case studies are explained in detail in the following sections.

2.2.1. Technical Properties

Prismatic panels are thin, planar elements made of highly transparent acrylic glass with a flat surface on one side and an array of prisms on the other side. There are various types differ mainly based on prism angles: these are available either as square panels about 1 cm thick or as flexible films less than 1 mm thick (Baker and Steemers 2014). Prismatic panels are produced in four different configurations using injection moulding method. Some panels are covered with a reflective aluminium film on one of the surfaces of the prism in order to provide sunlight reflection (Ruck et al. 2000). Figure 2.4 shows the prismatic panels with various angles designed for different applications produced by the injection molding method. Prismatic films are produced using specialised etching method. The resulting acrylic film can be applied on window pane or integrated into a double glazed unit. Although the acrylic film is very thin and lightweight, it has good optical properties (Ruck et al. 2000).

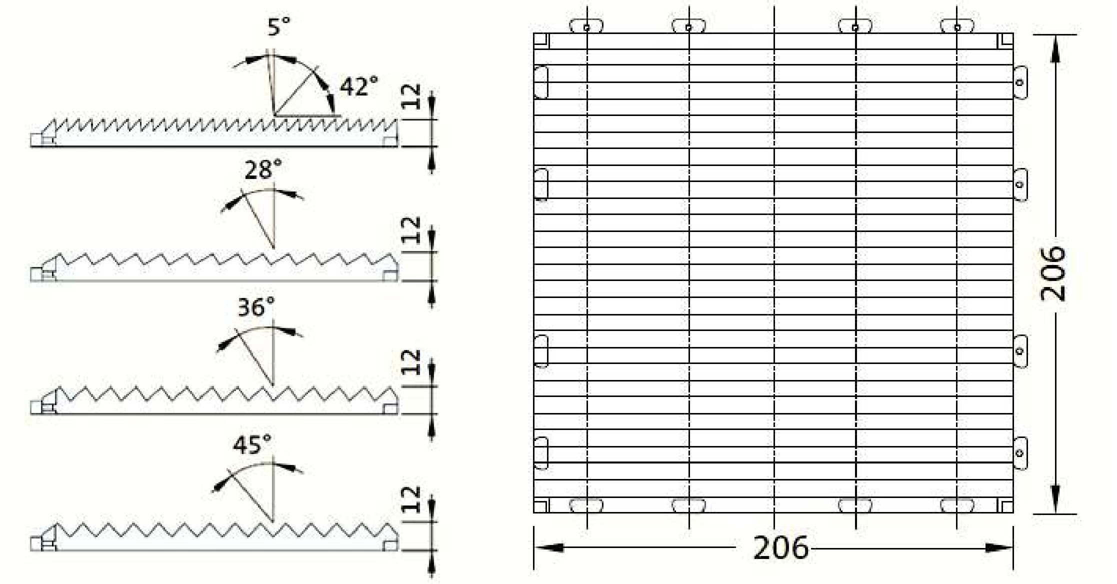


Figure 2.4. Four types of prismatic panels with different angles available on market (Source: Ruck et al. 2000).

The main principle of prismatic panels is to change direction of incoming daylight by reflection or refraction, thus offering controlled use of daylight in buildings. The system can be designed to reflect the sunlight coming upright, while directing the daylight coming from other angles to the room, typically through the ceiling (Littlefair

1990), (Ruck et al. 2000). This reduces excessive luminance near the windows; create ergonomic illumination across the room. The performance of the panels depends on the determination of the appropriate prismatic profile for different geometric and geographical conditions (Baker and Steemers 2014). Furthermore, the ceiling with highly reflective optical properties is required in order to increase illuminance levels at the rear part of a room (Ruck et al. 2000).

The optical properties of the prismatic panels enable very high light transmission and redirect the skylight with low losses. But they prevent totally clear view to the outside. Therefore, prismatic panels are usually installed to the upper part of the vertical window, above the eye level (Ruck et al. 2000), (Baker and Steemers 2014).

Prismatic panels show better performance in sunny conditions rather than overcast sky conditions. Owing to their large blockage range that allows systems shading, they slightly decrease illuminance levels, and thus they have a limited applications in climates with frequent overcast sky conditions. However, in a heavily obstructed room, prismatic panels increase illuminance further from windows by redirecting skylight to the upper half of the room. (Littlefair 1990), (Baker and Steemers 2014), (Ruck et al. 2000).

2.2.2. Application Types

The two main functions of prismatic elements are solar shading and daylight redirection. When used for daylight redirection purpose, prismatic panels are placed in vertical windows to redirect incident sunlight or diffuse light on the prismatic structure towards the ceiling plane, and thus transmit daylight deeper inside the room. The panels also work as an anti-glare system by reducing the brightness of the window. However, at some times of the year unwanted downward light beams may occur and cause glare. In order to avoid this, additional sun shading is required in front of the panels in direct sunlight conditions. Prismatic panels can be used in static and movable configurations for solar shading purposes. They can be applied to facades or skylights in many different ways depending on daylighting design objectives (Ruck et al. 2000), (Littlefair 1990), (Baker and Steemers 2014).

Static Prism Systems

The exterior surface of the static prismatic panels is flat and the interior surface consists of triangular prisms. One prism edge is coated with specular ultra-pure aluminium. The aluminium coating functions as a mirror, and the sun rays that strike the exterior surface of panel at right angle reflected back by the oblique prism edges. This structure of static prismatic panels enables the larger reflection range and completely eliminates direct sunlight, thus particularly suited for use in inclined facades and skylights. Deflection prisms distribute the daylight evenly throughout the room and ensure glare free illumination. Since system reflect hot sunlight, and only allows cool diffuse daylight to penetrate, the rooms are prevented from heating up. The prismatic structure is designed depending on some significant factors such as inclination of the glass, geographic location and orientation of the building, and then mounted between panes of double glazing unit in order to protect from moisture and impurities, as shown in Figure 2.5 (Littlefair 1990), (Ruck et al. 2000). Due to double glazing unit contains reflective coating, colour dispersion may arise.

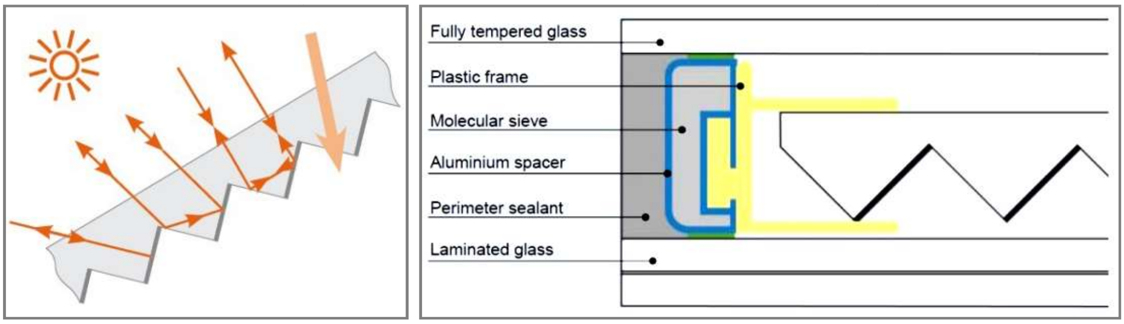


Figure 2.5. The path of the sun rays that strike the static prism system (left) and installation detail of partially coated prismatic panel into double glazing units (right) (Source: Siteco 2017).

An application example of static prismatic panels can be found in the Bavarian Parliament Building, Munich (Figure 2.6). After refurbishment, Plenary Hall in the building is designed with a completely glazed roof and static prismatic panels are installed on 470 square meter-large surface. The prismatic insert oriented to the south prevents excessive ingression of sunlight and overheating of the space. By means of static prism systems, the space, which was formerly illuminated only by artificial lighting, now illuminated by daylighting. Innovative technologies used for lighting and air conditioning provide energy savings of 60 percent (Siteco 2017).

Figure 2.6. An exterior (left) and interior (right) view of the Plenary Hall in the Bavarian Parliament Building (Source: Siteco 2017).

Movable Prism System

The movable prism system consists of translucent, uncoated acrylic glass panels with an extremely precise prism structure. Prismatic panels are always arranged to ensure that the sun rays always strike the rear of the prism at a 45^0 angle, so that direct sunlight can be reflected while daylight from other angles is guided into the room (Figure 2.7). This sun protecting panels can be mounted either vertically in front of or behind the facade opening in a louver form or horizontally upon glass enclosed courtyards or glazed roofs (Figure 2.7). They are resistant to bad weather conditions and ultraviolet rays. The alignment of the prismatic panels are controlled by microprocessors according to the position of the sun in order to provide always the correct angle of reflection in clear sky conditions and maximum light transmission and view in cloudy sky conditions (Ruck et al. 2000), (Boubekri 2014), (Baker and Steemers 2014).

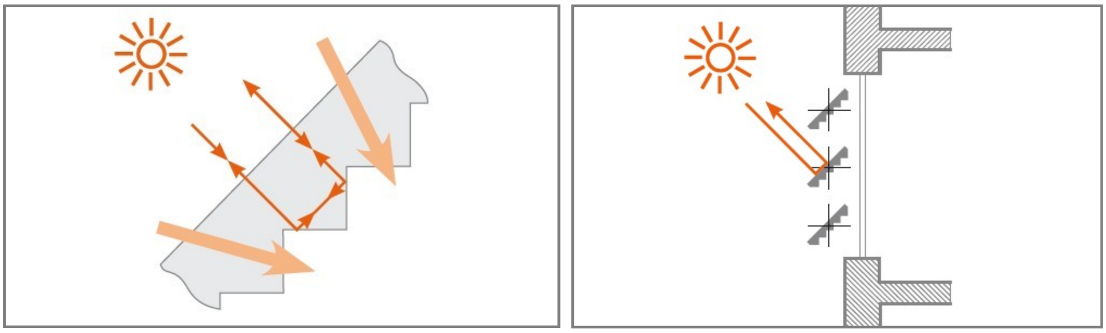


Figure 2.7. The path of the sun rays that strike the movable prism system (left) and the prismatic panels implemented vertically to facade (right) (Source: Siteco 2017).

An example of movable prism system application can be found in hospital building in Linz, Austria. The hospital rooms facing southwest direction have fully glazed facade and sun protection is provided by movable prismatic panels mounted upper area of the balconies in front of the rooms (Figure 2.8). The prismatic panels placed along the window in the louver form protect the room from overheating in summer, whereas the slanting rays of the sun penetrates deeper into the patients' rooms below the prismatic panels in winter. On cloudy days the prismatic panels are rotated to a horizontal position so that daylight redirection function of the panels can also be used to illuminate interiors.

Figure 2.8. An example of movable prism system application in hospital building in Linz, Austria (Source: Siteco 2017)

2.2.3. Researches and Case Studies

Several studies have been carried out on different aspects of prismatic systems with the objective of achieving effective daylight redirection for a wide range of incident angles without creating discomfort glare.

In a research carried out by Christoffers (1996), it was demonstrated that using prismatic panels, seasonal shading that is responsive to the position of the Sun can be achieved. The refractive angles of the prismatic panel which applied to the south-facing vertical window have been designed considering Sun's path for 52º northern latitude. Depending on two essential path of the Sun rays: incident light rays at low altitude angles that strike the surfaces tilted upwards or downwards are transmitted, while light rays at altitude angles higher than 48º are reflected. The light rays at high solar altitude angles do not strike the surfaces tilted downwards. The performance of the defined prism was tested in an experimental set-up. Consequently, the direct sunlight that strikes a vertical south facing window is diminished by 10% on a clear day in summer, while it is transmitted by 90% on clear day in winter. Owing to the prismatic panels, the solar gains from the south facing facade meet the annual heating energy needs of the building. Owing to the prismatic panels, the solar gains from the south facing facade correspond to the annual heating energy needs of the building. Such a system is recommended for spaces which do not need clear view since prismatic glazing distort the view outside (Christoffers 1996).

In the study conducted at Berlin Technical University, Germany, the performance of the Siteco 45/45 prismatic panel is tested with the combination of semi-perforated blinds. The system consisting one layer with prismatic panel for sun shading and other layer with semi-perforated blinds for diffuse light redirection is installed inside the window (Figure 2.9). The system covers entire window area in the test room. Owing to the microcontroller unit pre-set based on location and orientation of the room, the slat angle of the prismatic panels is automatically changed according to the sun position. On the other hand, the reference room had a clear glazing without any shading system in the overcast sky conditions, while a standard venetian blind with the slat angle of 45⁰ installed outside the window for clear sky conditions (Ruck et al. 2000).

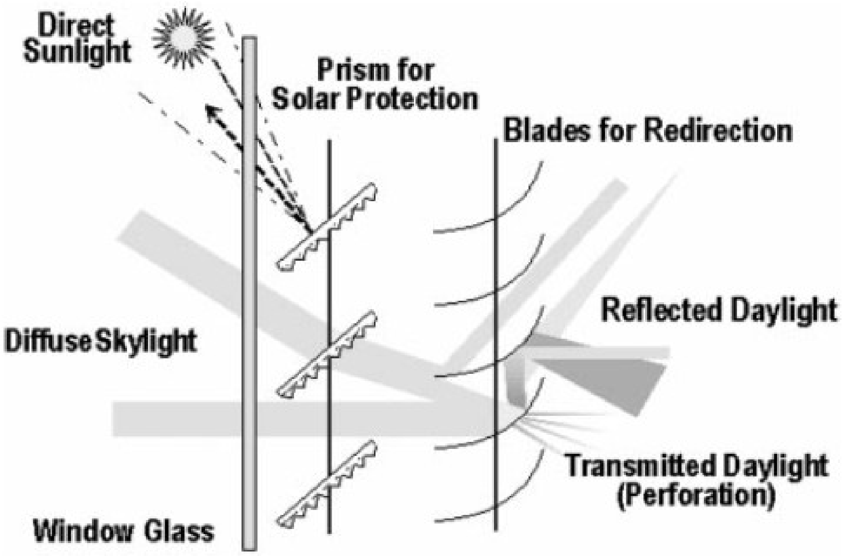


Figure 2.9. The section of proposed daylighting system consisting of prismatic panels and semi-perforated blinds (Source: Ruck et al. 2000).

According to measurement results, under overcast sky conditions, illuminance levels in the test room were the same with those in reference room. Under clear sky conditions, the illuminance levels in test room with proposed daylighting system were higher compared to reference room with venetian blinds (Ruck et al. 2000).

An experimental study on performance of prismatic panel and prismatic film is carried out by Aizlewood (1993) in two identical south-facing mock offices. One office is equipped with innovative daylighting system, while other office has conventional clear glazing. Since they distort the clear view to the outside, both daylighting systems were applied on the upper half of the window in test room. The prismatic panel that used in the study was installed between panes of a double glazing unit and one side of the each prism was coated with reflective material. The prismatic film system consists of a prism structure etched onto a thin film and then adhered to the surface of the window. The prism angles of prismatic panel and prismatic film are shown in Figure 2.10.

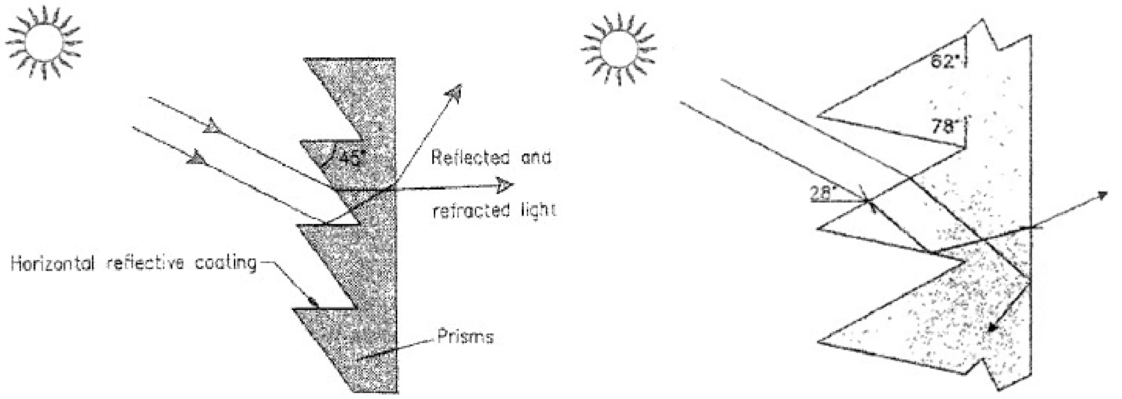


Figure 2.10. The prismatic panel (left) and the prismatic film (right)
(Source: Aiziewood 1993).

Under overcast sky conditions, the prismatic panel reduced the illuminance levels across the room by 35-40% compared to reference room with clear glazing. Under clear sky in summer, the panel shaded the area near the window by excluding direct sunlight while part of the sunlight redirected onto ceiling illuminated the rear part of the room; however, the overall illuminance levels in the room was reduced. On clear equinox days, the illuminance levels at the rear part of the room were increased by more than 100%. The illuminance levels at the rear part of the room were reduced by

50% on clear winter days, because the sun rays that come at lower angle were not penetrated deep into the room but redirected to the ceiling by the system.

In the test room with prismatic film, illuminance levels were reduced by 10-30% under overcast sky conditions. On clear summer and equinox days, incoming sunlight was refracted to the ceiling by the prismatic film and illuminance levels at the back of the room were increased by up to 20% compared to reference room. The performance of the prismatic film was similar to the prismatic panel on clear winter days, illuminance level at the rear part reduced by 30-40% but glare control was provided at the front (Aiziewood 1993).

The majority of the prismatic daylighting systems have been designed and performed for northern skies, namely, low solar altitudes. However, Mashaly et al. (2017) have been investigated the performance of a daylight redirecting prismatic system which is designed to work efficiently at high solar altitudes, especially in Egypt. First, prism angles of single-sided prismatic panel were determined taking solar altitude range in Egypt into account and most applicable prism angles were found to be (α) 25^{0} and 35^{0} (Figure 2.11). The performance of proposed prism systems was assessed in a 3.6m wide x 8.2m deep x 2.8m high room with 10% window-to-wall ratio, using RADIANCE simulation tool.

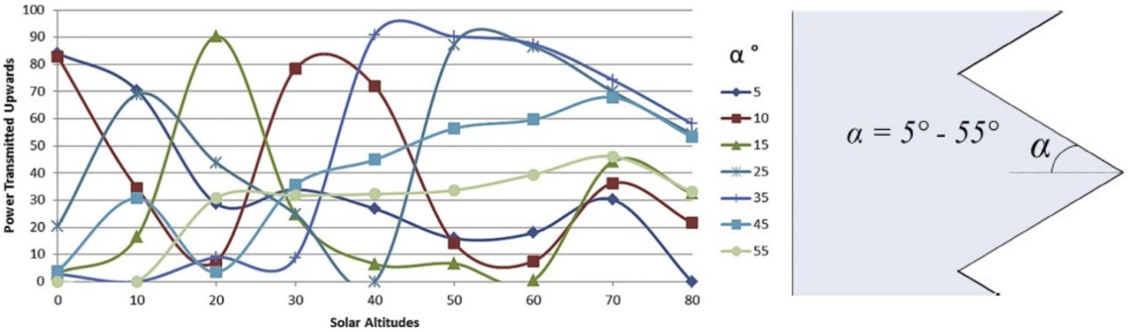


Figure 2.11. Light redirected upwards according to different prism angles at different solar altitudes (Source: Mashaly et al. 2017).

The proposed single-sided prism design achieved to direct daylight to the back of the room without glare. For the proposed system with (α) 25^{0} prism angle, illuminance levels across the room were increased by 53%, 205% and 106% in summer, autumn and winter, respectively. For the proposed system with (α) 35^{0} prism angle, increase in illuminance levels was 22%, 179% and 63% in summer, autumn and winter, respectively. The results were also evaluated based on Daylight Autonomy: the proposed prism system increased the sDA value at the back of the room from 29% to 41% and the overall sDA rose by 11%, in comparison to the room with clear glazing (Mashaly et al. 2017).

An empirical assessment of a microstructured multi-sided prismatic film was performed at the Lawrence Berkeley National Laboratory, California. Three identical rooms, two of which are test rooms and one is reference room, were built. First test room consists of daylight redirecting system with prismatic film adhered to inner surface of the window. Second test room consists of daylight redirecting system which uses the same prismatic panel but also a light diffusing film in a double glazing unit. The reference room had a Venetian blind in a completely lowered position. Both daylighting systems and Venetian blind were placed in the upper clerestory of the window wall and lower windows were covered with blackout shade. As a result, the first system with only the prismatic film was succeeded to redirect sunlight effectively to the ceiling plane but perceptible levels of discomfort glare were occurred during winter. The second system in which prismatic film combined with diffusing layer was extended the redirected daylight evenly to a larger area and reduced the discomfort glare to imperceptible levels. On clear summer and equinox days, when the sunlight was redirected to the back of the room, the work plane illuminance levels of the rooms with daylighting systems were remarkably higher than the reference room with a traditional interior shade. Under overcast sky conditions, discomfort glare in the both test rooms was imperceptible (Thanachareonkit, Lee, and McNeil 2014)

2.3. Daylight Performance Metrics

The main requirement of daylighting a building is that there are openings in the building envelope where daylight can penetrate. The amount of daylight entering a building is determined by the outside conditions and the building fenestration design. Due to its transmittable, absorbable, diffusible, refractive, reflective dynamic nature of daylight, illuminance levels vary from near facade openings to deep inside the building. The word "daylit" can be used to identify areas with sufficient or adequate daylight. Thereby, areas that do not provide this condition are automatically being "non-daylit"

(Reinhart 2014). However, a quantitative approach is required to separate the daylit areas from the non-daylit areas numerically.

Defining a well-daylit space is not an easy task because, according to the study by Reinhart, different professions focus on different aspects of daylighting within the scope of sustainable building design. In a survey in which the other options were definitions of daylighting regarding building energy consumption, load management, and operating costs, participants from different professions mostly voted for the architectural and lighting energy savings definitions, which they found the most relevant to their work. While architectural definition focuses on providing the visually stimulating, healthy and productive interior environment, the energy saving definition focuses on reducing annual energy consumption by using daylighting instead of artificial lighting. Researchers have sought to determine how well-daylit space should be in terms of these two most favored definitions (Reinhart, Mardaljevic, and Rogers 2006).

Several methods have been proposed including static metrics as well as dynamic metrics in order to describe the parameters of a well-daylit space. The illuminance-based daylight performance metrics will be discussed in later sections. Other factors that are important for daylight quality in buildings such as luminance distribution, glare, and directionality of light will not be elaborated on here.

2.3.1. Static Daylight Performance Metrics: Daylight Factor

The daylight factor is defined as the ratio between the internal illuminance at a given point inside a room and unobstructed, external horizontal illuminance under CIE overcast sky (Moon and Spencer 1943). The main reason for using rates rather than absolute values is to avoid the difficulty of dealing with variabilities in the intensity of daylight. Regardless of time, the ratio between internal and external illuminance remains constant under overcast sky conditions. Hence, the daylight factor is easy to calculate and usually expressed as a percentage (Boubekri 2014).

Due to its simplicity, the daylight factor is the most common quantitative performance measure for daylighting used in actual practice and guidelines. Given the fact that 500 lx on the work plane is usually recommended for workplaces and there is about 10000 lx of outdoor illuminance under an overcast sky, the daylight factor requirement can be found as 500 lx / 10000 lx = 2 percent, which corresponds to the CIBSE threshold level. In accordance with CIBSE, if the average daylight factor is less than 2%, electric lighting is to be used during daytime. In case electric lighting not to be used, daylight factor shouldn't be less than 5% (CIBSE 2002).

However, the daylight factor is used as a minimum legal lighting requirement rather than a measure of good daylighting design since it has several shortcomings. As remarked by Reinhart et al. (2006), the daylight factor does not consider the seasonal variations, time variations, direct solar ingress, or different sky conditions, and thus, the recommended daylight factor is the same for all facade orientations and building locations. One of the significant consequences of this is that the daylight factor cannot determine if there is a glare problem in a room, and it cannot help to develop glare protection strategies for different facade orientations and geographical location. In other words, the recommended daylight factor would be the same for North-facing building in Stornoway and South-facing building in Brighton, as stated by Mardaljevic et al. (2009). In addition, since the shading devices are not operated under overcast sky conditions, daylight factor is not affected by any design strategies based on solar angle, solar intensity, or redirection of sunlight (Boubekri 2014).

The daylight factor is classified as static daylight performance metrics due to it is limited to one sky condition (CIE overcast sky) only. Several dynamic daylight performance metrics have been proposed as an alternative to daylight factor-based approach to overcome some of its shortcomings. These are also defined as 'climate-based' performance metrics since they allow hourly assessment of illuminance levels within an area during the entire year considering regional climatic conditions, and discussed in following section.

2.3.2. Dynamic Daylight Performance Metrics

The dynamic daylight performance metrics present the time series of illuminance based on quantity and character of daily and seasonal variations of daylight for the location of the building. While a single number is obtained as a percentage in the conventional static approach, the climate-based approaches makes an illuminance prediction for every working hour of the year for each calculation point considering numerous different sky conditions. Due to the fact that it is not possible to realistically measure illuminance levels in a space throughout the year and the complexity of the calculation, computer-based simulation tools are required for dynamic performance metrics. By means of dynamic simulations, it is possible to establish the percentage of calculation points that provide the minimum illuminance levels required by the regulations and the amount of artificial lighting to be used; or to calculate the percentage of time in a year to determine the most suitable solar shading system in order to restrict discomfort conditions caused by daylight related glare.

Useful Daylight Illuminance (UDI), is a dynamic daylight performance metric based on work plane illuminance, proposed by Nabil and Mardaljevic (2005). UDI deals with the large range of naturally occurring, time-varying daylight illuminance levels and suggests the classification of these values according to the threshold (target) illuminances in order to inform both useful levels of daylight illuminance for occupants and also excessive daylight levels that are associated with occupant discomfort and undesirable solar gain. The absolute range of illuminance levels based on threshold values have been defined according to comprehensive review of field study regarding occupant behavior in daylit office environments under a wide range of illumination conditions (Nabil and Mardaljevic 2006). According to occupant preferences and behavior, illuminance levels less than 100 lx are generally considered insufficient; illuminance levels in the range 100–500 lx are considered effective either as a single lighting source or in integration with artificial lighting; illuminance levels in the range 500–2000 lx are considered as desirable or at least tolerable; and illuminance levels higher than 2000 lx are likely to produce visual or/and thermal discomfort. Consequently, daylight illuminance on work plane that falls within the range 100-2000 lx defined as “useful” for the occupants of space. Based on the lower and upper thresholds of 100 lx and 2000 lx, three metrics are used, that is, the percentages of the occupied times of the year when the UDI is within the useful range (100-2000 lx), fall short of the useful range (less than 100 lx), and exceed the useful range (greater than 2000 lx) (Nabil and Mardaljevic 2006).

Daylight Autonomy (DA) is another daylight performance metric proposed by Reinhart and Walkenhorst (2001) as an annual percentage of the occupied time when the minimum illuminance indicated by standards on a work plane is met by daylight alone. The minimum illuminance level indicates the minimum daylight illuminance requirement that must be kept at all times so that a certain task can be carried out without tiring the occupants. Using the DA method, the potential electrical lighting energy savings can be easily determined by calculating the percentage of time that specific illumination threshold provided by daylighting.

Continuous Daylight Autonomy (DA_{con}) and Maximum Daylight Autonomy (DA_{max}) introduced by Rogers and Goldman (2006), based on a research on evaluation of the in classrooms. In DA_{con}, partial credit is based upon time steps when the work plane illuminance falls below the minimum daylight illuminance requirement. It is calculated as the ratio between daylight illuminance at a point and the minimum daylight illuminance required by the standards. For instance, when the daylight illuminance requirement is 500 lx and actual illuminance provided by daylight at a given time step is 400 lx, a partial credit found as 0.8 (400 lx/500 lx) for that time step. *Maximum Daylight Autonomy (DA_{max})* is reported together with DA_{con}, to consider visual discomfort risks arising from direct sunlight. It is defined as the percentage of the occupied hours when excessive daylight conditions occur. The threshold for DA_{max} is set at ten times the minimum required daylight illuminance of a space. For instance, assuming that the required illuminance for a classroom is 300 lx, the threshold value for DA_{max} will be 3000 lx. The upper threshold indicates the likely appearance of direct sunlight and, therefore, informs how often and where large illuminance contrasts may occur in a space (Reinhart, Mardaljevic, and Rogers 2006).

Currently, Illuminating Engineering Society of North America (IESNA) promotes the concept of two metric, namely, Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). While sDA focuses on sufficiency of daylight illuminance for a given area, ASE considers the potential risk of excessive sunlight penetration that may cause visual discomfort. These two metrics should be reported together to contribute daylighting design evaluation process as design solutions are developed.

Spatial Daylight Autonomy (sDA) indicates the percentage of analysis area in which the target illuminance achieved only with daylight for specified fraction of working hours per year. This metric uses the illuminance threshold of 300 lx on a work plane and the analysis time period of 10 hours per day from (8 am to 6 pm). Thus, sDA_{300lx} [50%] presents the percentage of the analysis area that meets or exceeds the target daylight illuminance of 300 lx for at least 50% of analysis period per year. Two sDA performance criteria is recommended with regard to daylight sufficieny; the

sDA_{300lx} [50%] that meets or exceeds 75% of the analysis area is rated as "preferred" and the sDA_{300lx} [50%] that meets or exceeds 55% of the analysis area is rated as "nominally acceptable".

Annual Sunlight Exposure (ASE) indicates the percentage of analysis area in which a specific direct sunlight illuminance level is exceeded for more than specified number of working hours per year. This metric takes the analysis points into account that are exposed to direct sunlight exceeding 1000 lx for more than 250 hours per year. The analysis areas that have more than 10% $ASE_{100lx,\ 250h}$ are reported as “unsatisfactory” in terms of visual comfort. The analysis areas with less than 7% $ASE_{100lx,\ 250h}$ are reported as “neutral/nominally acceptable” and finally space with less than 2% $ASE_{100lx,\ 250h}$ are reported “clearly acceptable”.

Furthermore, these metrics are included in some regulations and green building rating systems such as LEED in order to describe acceptable occupant comfort for daylit spaces.

CHAPTER 3

THE PROCEDURE

In this study, a quantitative approach is adopted to assess the performance of prismatic panels in improving the daylighting conditions of side-lit rooms with different room geometry-window size configurations. The computational tools and techniques were used to predict illuminance levels throughout the work plane for each determined alternative WWR-Room Depth design. This chapter involves detailed explanation of the case room, actual measurements, simulation and regression modeling process under four sections.

3.1. Case Building Explanation

In this study, a deep plan, side-lit classroom was chosen as a reference room to enhance indoor daylighting quality by applying prismatic panels. The reference room is located on the second floor of an educational building of Izmir Institute of Technology, Izmir. The building named as block A is one of the 5 blocks of the Faculty of Architecture, situated in the highest level of campus, coordinates at 38° 19’ N, 26°37’ E and at an altitude of approximately 76 m over sea-level. The reference room is located on 2nd floor of the building. It is facing north, total area is 72 m^2 and internal dimensions are W 6.00 m x L 12.00 x H 3.80 m. The reason for selection and evaluation of such a deep room is to examine the prismatic panels’ ability to deliver daylight beyond the typical effective daylight zone and provide uniform daylight distribution. A double glazed window is located on the short side, sill height from the floor level is 1.00 m, and upper facade is fully glazed. Window dimensions are 5.50 m wide by 2.80 m height and there is no solar shading. The room has unobstructed, clear view to the outside. The detailed geometrical properties of the room and window are given in Table 3.1.

Table 3.1. Geometrical properties of the case room.

ROOM	**Type**	**Length**	**Depth**	**Height**	**Area**
	Classroom	12.00 m	6.00 m	3.80 m	72.00 m^2
WINDOW	**Orientation**	**Width**	**Height**	**Window Area**	**WWR**
	North	5.50 m	2.80 m	15.40 m^2	67%

The classroom is used as a computer laboratory where theoretical and practical courses are given to architecture students. The space is occupied on weekdays, from 8:00 to 17:00 h local time. There is a white board and projection screen on the rear wall of the room where the lessons are explained and students mostly occupy seats close to white board. Since rear part of the room where students occupy relatively darker than perimeter zone, artificial lighting is frequently used during lectures. On the other hand, students sitting next to the window are exposed to excessive daylight and discomfort glare. Figure 3.1 presents interior picture of the classroom.

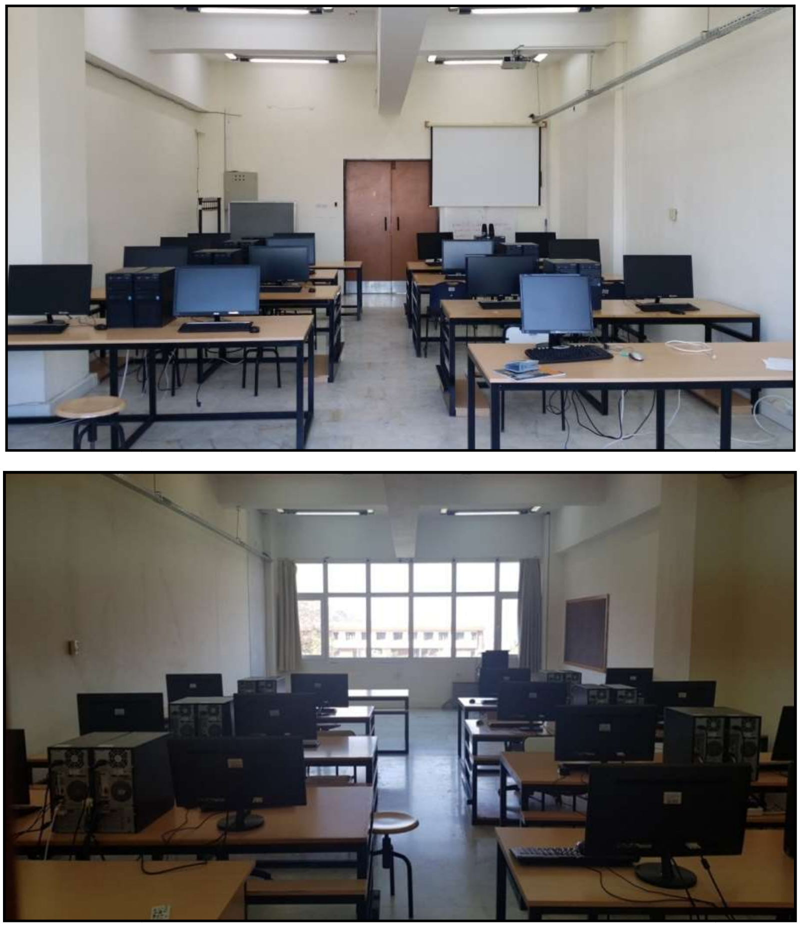


Figure 3.1. Interior view of the classroom from window towards back of the room (above) and view from back of the room towards the window (below).

3.2. Daylight On-site Monitoring

In order to evaluate current daylight condition of the room and validate the simulation model, illuminance levels were measured at certain points of the room for certain days and times. The number of measurement points and their location were determined considering recommendations in IES: Daylighting Monitoring Protocols & Procedures for Buildings. In a classroom with sidelit window, measurement points should represent both daylight and dark areas. Thereby, to measure daylight illuminance variations across the room, measurement points were aligned along the room depth. The distance of measurement points to both sidewalls are equal and 3.00 m. In order to increase accuracy, spacing between each point set to be 0.60 m as IES suggests “two-foot analysis grid” and total 19 measurement points are defined (Heschong et al. 2012). The constant height of the measurement plane was determined to be 0.75 m above the floor considering the desk-height inside the room. Figure 3.2 presents the position of the on-site measurement points in classroom.

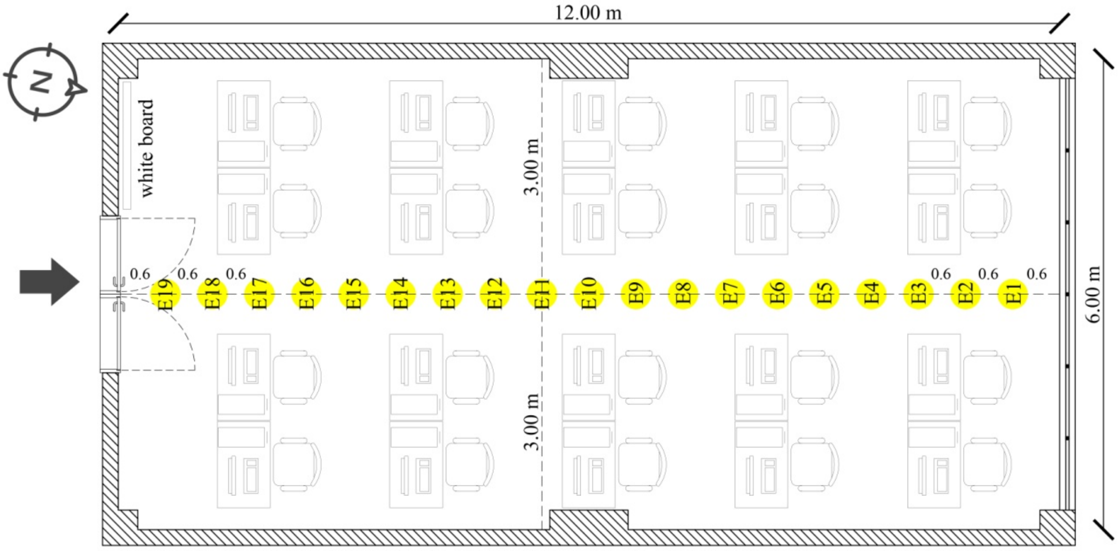


Figure 3.2. The position of the measurement points on plan.

The on-site measurements were taken on November 23, 2017, under clear sky condition and December 21 (winter solstice), 2017, under overcast sky condition. The measurement times were 9:30, 12:30 and 15:30 for both days. A digital illuminance meter, which is an instrument for measuring the amount of light falling upon a surface in lux, was used during the measurements. The reflective properties of opaque materials such as wall, ceiling and floor were also measured on-site. There are 7 methods described by Gradillas (2015) to define surface reflectance properties accurately. These are spectrophotometer, luminance/illuminance, up/down illuminance, Macbethcal, Benchmark, CIBSE color chart and RAL color fan. The luminance/illuminance based method with 20% accuracy rate was used in this study (Jakubiec 2016). After finding the illuminance (lux) at a specific point of related surface, luminance (cd/m^2) of the same point also measured in a single direction using luminance meter. The reflectance of monitoring walls, ceiling and floor was calculated using equation of Lambertian reflectance (3.1) given below:

$$L = \frac{E \, x \, \rho}{\pi} \tag{3.1}$$

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

The transmittance of clear glazing was determined in a similar way. The luminance of an object behind the glazing was measured in a direction perpendicular to the glazing surface once with the window closed and once with the window open. The transmittance clear glazing was found using following equation (3.2):

$$\tau = \frac{\mathrm{L}_{in}}{\mathrm{L}_{out}} \tag{3.2}$$

where L_{in} is the luminance of a specific point measured with glazing, L_{out} is the luminance of the same point measured without glazing. The optical properties of the materials are given in Table 3.2.

Table 3.2. Optical material properties of the case room calculated on-site.

Walls	Ceiling	Floor	Glazing
90% reflectance	85% reflectance	60% reflectance	80% transmittance

3.3. Simulation Models in Relux

Computer simulations were carried out to find the work plane illuminance levels in different WWR-Room depth alternatives. Simulation is defined as a tool used to build a prototype of processes and events that will actually take place. Simulation models can be operated several times under various conditions to observe the model results, make comparisons and to interpret. In this sense, simulations are similar to virtual experiments because with a simulation, the researcher is experimenting using the model instead of the real scene (Gilbert and Troitzsch 2005). Simulation is more advantageous than traditional mathematical modeling in terms of process and operation. With real data, it is quite hard to know utterly the real world processes that cause specific measured values to take place. But in a simulation, researchers can directly intervene in the model and experiment with events to see how the outcomes change and how the analysis is affected (Davis, Eisenhardt, and Bingham 2007), (Gilbert and Troitzsch 2005).

Computer simulation programs can process a large number of design parameters and perform detailed and scenario-based daylight performance analysis. Lighting simulation programs that are widely used today can accurately predict daylighting performance in buildings and have photo-realistic rendering features that can give information about how the actual building may perform (Wong 2017), (Çelebi 2007). Relux Pro which offers both daylighting and artificial lighting simulations was used throughout this study. The program developed by Relux Informatik AG in Switzerland uses radiocity method for basic calculations and Radiance-based raytracing method for renderings (Acosta et al. 2015), (Yu, Su, and Chen 2014). In a study conducted by Maamari et al. (2006), 32 different scenarios were tested and the results showed that Relux can predict indoor illuminances with high accuracy. It is suitable for the architects' use as it is a simple tool that supports various phases of the architectural project (Ochoa, Aries, and Hensen 2012), (Bhavani and Khan 2011).

3.3.1. The Base Case Model

The simulation model of the reference room was generated in Relux Pro to compare the actual data obtained during on-site measurement with simulation outputs. It is important that the simulation data is close to the measured data in terms of the accuracy and usability of the virtual model. In order to achieve more realistic results, the virtual model was generated as close to the actual room characteristics as possible using measurement results collected on-site. The interior material properties such as reflectance/transmittance of wall, ceiling, floor and glazing of the simulation model were assigned as 0.90, 0.85, 0.60 and 0.80 respectively, identical to the on-site measured values. The base case model also includes basic models of the furniture, columns and beams inside the room as shown in Figure 3.3. The IWEC.epw weather file was imported to the Relux Pro to make simulations according to location and climatic conditions of Izmir. Just as in on-site measurement, total 19 measurement points were determined with 0,6 m spacing between each point on the measurement plane 0,75 m above the floor (see Figure 3.2). Simulations were carried out at the time 9:30, 12:30 and 15:30, under CIE clear and overcast sky conditions on 23th November and 21th December, respectively.

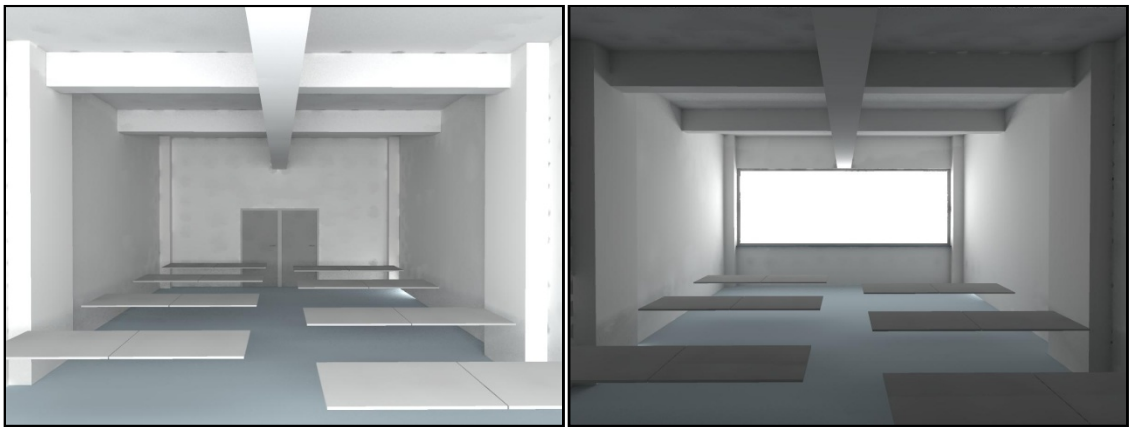


Figure 3.3. Interior renderings of the case room for 23th November at 12:30; view from front to back (left) and view from back to front (right).

3.3.2. Determination of Design Alternatives

Alternative room depths and window sizes were determined following standards and recommendations in literature and modeled in Relux Pro.

First, limiting room depth for the reference room was determined according to window width, reflectance of surfaces and window head height. The equation (3.3) is described by *The British Code BR 8206(Part 2)* as:

$$\frac{L}{W} + \frac{L}{H_w} < \frac{2}{1-R_b} \tag{3.3}$$

where L is the room depth, W is the room width, H_w the window head height above floor level and R_b the average reflectance of surfaces in the rear half of the room.

According to this equation, minimum acceptable room depth of the reference room was found as 9 m, indicating that room depth should not exceed this value in order to avoid gloomy looking and additional electric lighting in the rear half of the room. Taking limiting value into account, three different floor aspect ratios (Figure 3.4) of room depth to width were determined as follows:

A.R.= 1 (when room depth is 6 m, less than limiting value)
A.R. = 1.5 (when room depth is 9 m, equal to limiting value)
A.R. = 2 (when room depth is 12 m, greater than limiting value)

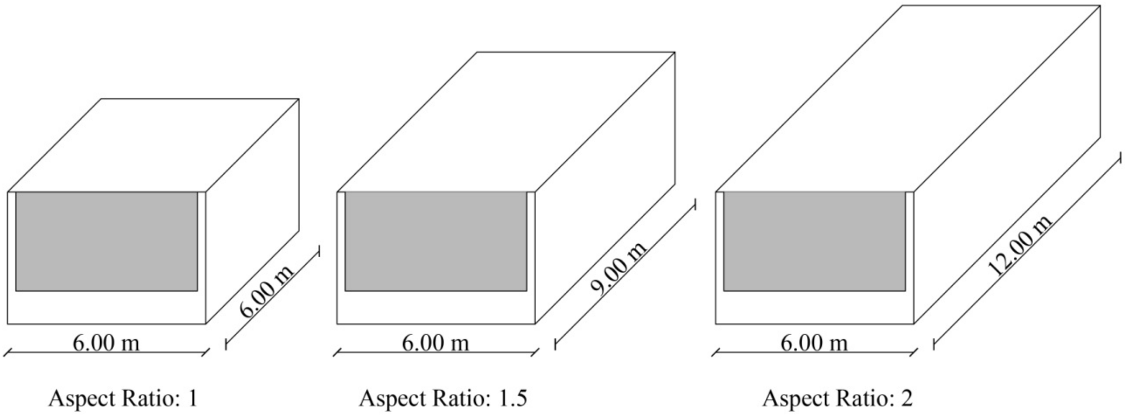


Figure 3.4. Isometric view presents three different floor aspect ratios.

Since large windows increases exposure to sun and thus may cause excessive heat gain and visual discomfort, the window area of each determined aspect ratio was incrementally reduced as shown in Figure 3.5. *The British Code BR 8206(Part 2)* presents minimum window area based on room depth when room is illuminated by window in one wall only. For rooms ranging from 11-14 meters in depth, minimum window-to-wall ratio should be 30%. Due to its significant impact on room depth, the window head height was kept constant and starting from the reference case with WWR of 67%, the window width was reduced by 50 cm from both sides at each stage until minimum acceptable WWR of 30% was achieved.

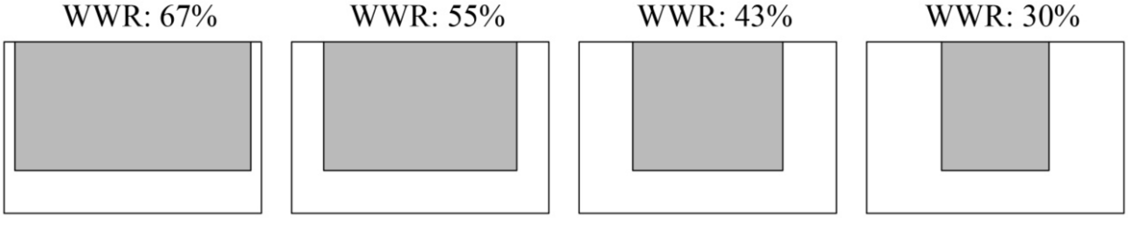


Figure 3.5. Schematic view of glazing areas determined for each floor aspect ratio.

3.3.3. Modeling of Prismatic Panels

In a room with conventional windows, as also observed during the on-site measurement, illuminance levels are higher near the window and decrease rapidly with increasing distance from window. Therefore, it is not possible to achieve good lighting performance throughout the room unless any daylight strategy is developed. Movable prismatic panels (Siteco 45/45) manufactured by company Siteco were chosen to enhance the daylight quality in interior space due to its capability to transmit daylight to the rear part of the room and provide uniform daylight distribution.

The selected prismatic panel was modeled in Relux according to real scale samples obtained directly from the manufacturers. First, the prismatic panel was drawn two-dimensional with flat surface on one side and the array of 45-degree prisms on the other side. Resulting shape was extruded by 30 cm and rotated 60 degrees in the vertical plane with saw tooth patterns facing downwards, thereby forming a three-dimensional prismatic panel (Figure 3.6). Several identical panels were duplicated and grouped to create an array along the window. A specific material was defined and assigned to prismatic panels to perform the refraction of light. The properties of assigned material are given in Figure 3.7.

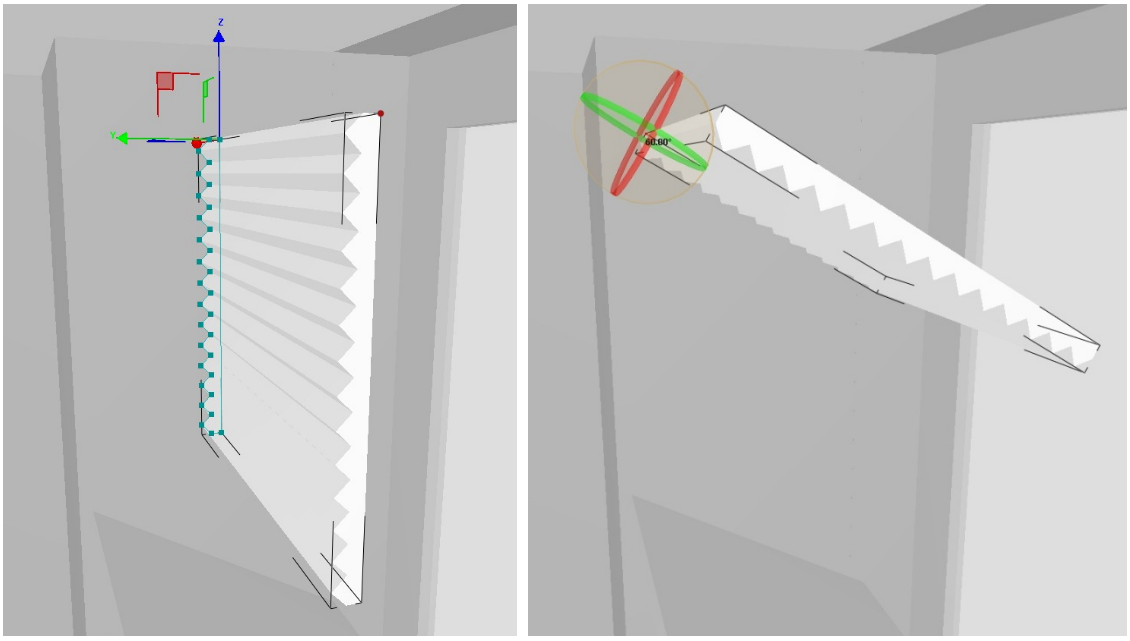
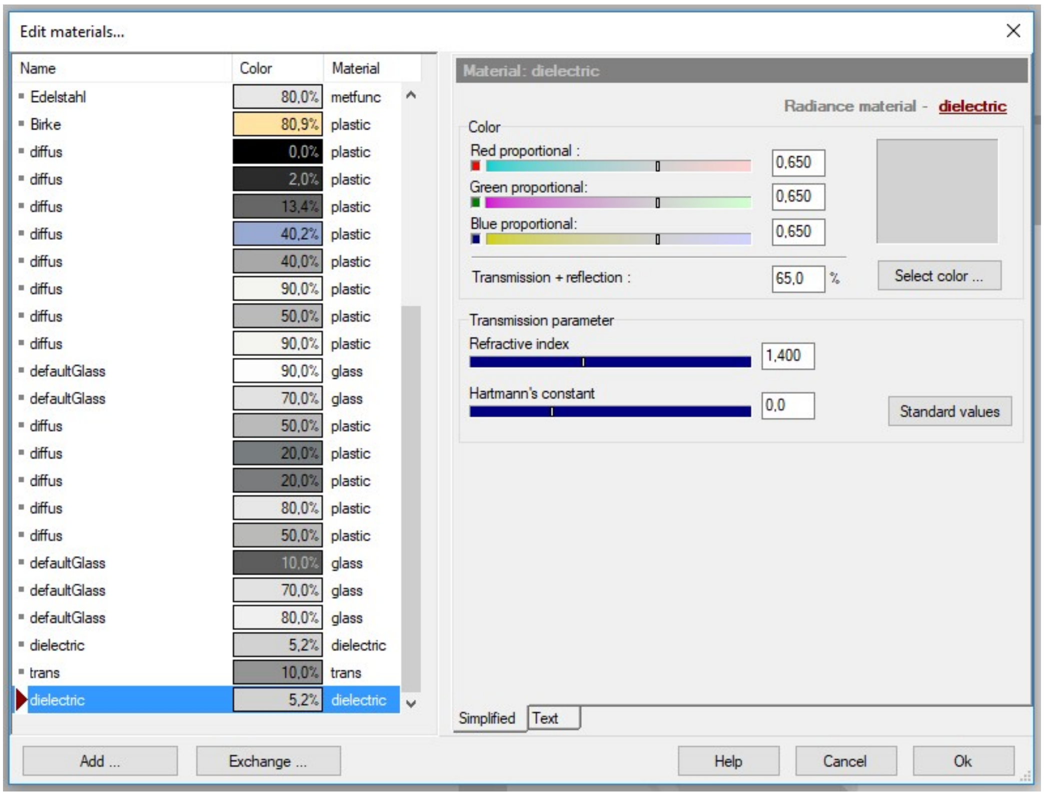


Figure 3.6. Modeling process of the prismatic panels in Relux.



Name	Color	Material
Edelstahl	80,0%	metfunc
Birke	80,9%	plastic
diffus	0,0%	plastic
diffus	2,0%	plastic
diffus	13,4%	plastic
diffus	40,2%	plastic
diffus	40,0%	plastic
diffus	90,0%	plastic
diffus	50,0%	plastic
diffus	90,0%	plastic
defaultGlass	90,0%	glass
defaultGlass	70,0%	glass
diffus	50,0%	plastic
diffus	20,0%	plastic
diffus	20,0%	plastic
diffus	80,0%	plastic
diffus	50,0%	plastic
defaultGlass	10,0%	glass
defaultGlass	70,0%	glass
defaultGlass	80,0%	glass
dielectric	5,2%	dielectric
trans	10,0%	trans
dielectric	5,2%	dielectric

Material: dielectric

Radiance material - dielectric

Color
Red proportional : 0,650
Green proportional: 0,650
Blue proportional: 0,650
Transmission + reflection : 65,0 %

Transmission parameter
Refractive index 1,400
Hartmann's constant 0,0

Figure 3.7. Material properties of the prismatic panels in Relux.

The prismatic panels were used in louver form and placed inside the window at slat angle of 30°, in this way it can also act as a sun-shading device and control glare from the sun. Prismatic panels were installed upper part of the window, between 2.00 m and 3.80 m above the floor. This position above the eye level prevents potential glare arising from daylight redirection through prismatic panels. The lower part of the window allows view outside. The distance between each panel group set to be 0.30 m. Physical properties of the prismatic panels are given in Table 3.3. The identical prismatic panels were applied to all room depth-WWR configurations. Schematic illustration of prismatic panel principle and application in this study are shown in Figure 3.8.

Table 3.3. Physical properties of the prismatic panel.

System	**Length**	**Width**	**Thickness**	**Transmission**	**Prism angle**
Prismatic Panel	Along the window	300 mm	12 mm	65 %	45°

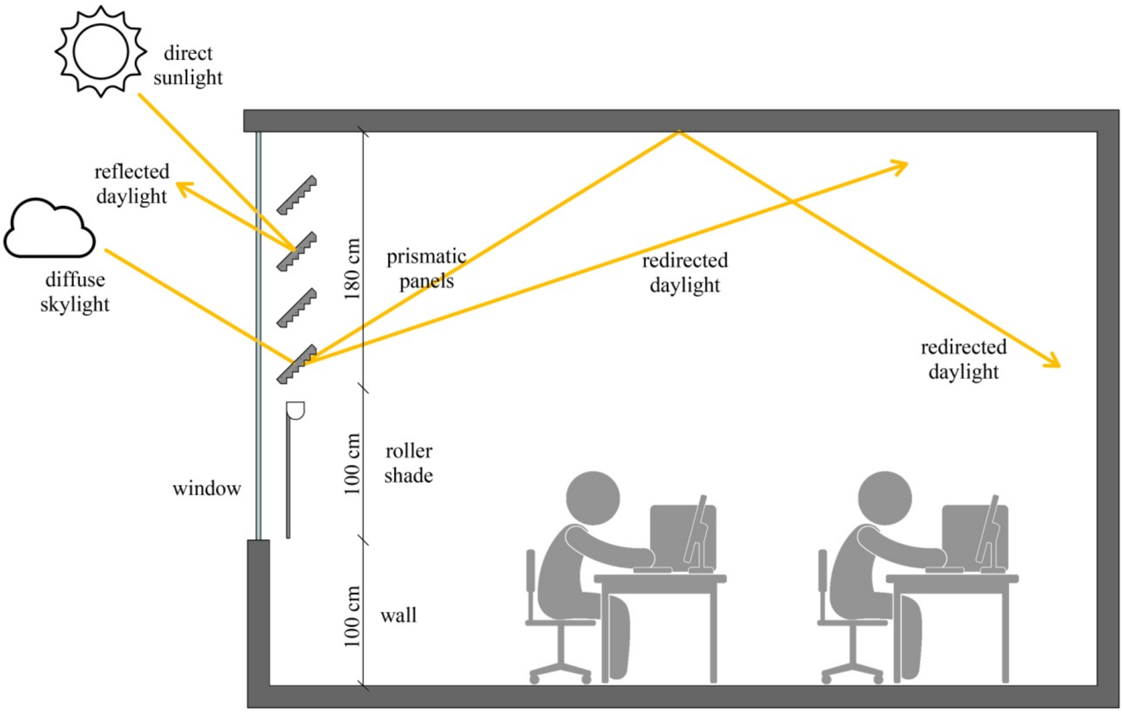


Figure 3.8. Schematic illustration of daylighting strategy applied on vertical window.

The simulation model of all design alternatives were generated in Relux Pro. The reflectance values of walls, ceiling and floor were assigned respectively as 0.50, 0.85, 0.20, according to IEA Task 27. The measurement points were set to be 0.75 m above the floor and 0.6 m away from the wall surfaces. The measurement points were set to be 75 cm above the floor, 60 cm away from the walls surfaces and 60 cm spacing between each point. Totally 171, 126 and 81 measurement points were determined for the 12 m, 9 m and 6 m deep room, respectively. Simulations were carried out on solstice and equinox days under CIE clear sky conditions at 10:00, 13:00 and 16:00 in March, June and September and at 9:30, 12:30 and 15:30 in December. In order to examine clearly the ability of the prismatic panels in daylight redirection, the simulations were run assuming that the room faced south. The 10% transparent sunshade was considered at the lower part of the window.

3.4. Multiple Regression Modeling

The validation process included statistical error analysis which is explained in Section 4.1 in detail. It covers the calculations of coefficient of determination (R^2), root mean square error, and coefficient of variation.

The data elaboration included ANOVA. Factors/ parameters were examined by one-way analysis of variance, as listed below;

i. The phases to define relationship between design alternatives (combination of room depth-WWR) and daylight illuminance are listed as below. Daylit zone for each design alternative was statistically defined in this way.
   a. Firstly, measurement rows, parallel to window wall, on reference plane were examined for each design alternative. There were three groups according to zoning status. These were attached/corner, attached/intermediate and detached.
   b. In the second phase, the nearest row from the window which satisfies min. 300 lx was set for each design alternative (i.e. for Aspect Ratio 1, meaning that, 6m room depth with 30% WWR, the measurement row at 3.6m distance from window satisfies the daylight requirement. That corresponds to almost 78% of floor area). So the area between window and that measurement row defines the daylit area.
   c. In the third phase, the groups of design alternatives based on daylight illuminance values at the nearest row were set.
   d. In the fourth phase, the five groups were tested by single factor ANOVA at a 5% level of significance. (α=0.05)

A multiple regression model (MRM) is constructed to determine the performance of a prismatic panel in room with varying room depth and WWR, estimating daylight illuminance on work plane, using data generated in Relux. The model aims to determine the relationship among variables calculating the performance of a dependent variable on independent variables, representing with an equation (3.4). MRM is a mathematical model to estimate values.

$$Y=\beta_0+\beta_1\times X_1+\beta_2\times X_2+\beta_3\times X_3+\cdots+\beta n\times Xn+\varepsilon \qquad (3.4)$$

where, Y is the dependent variable, β_0 is a constant, X_1, X_2, X_3 and X_n are independent variables, and β_1, β_2, β_3 and β_n are regression coefficients.

The regression coefficients were predicted using 1365 data sets obtained from Relux. Room depth, WWR, point-x and point-y are independent variables; daylight illuminance is the dependent variable.

CHAPTER 4

RESULTS

This chapter involves the evaluation of the study results under 3 sections. Section 4.1 presents a comparative evaluation of the simulation outputs with the illuminance values obtained in the on-site measurement. Section 4.2 provides a visual performance evaluation of alternative rooms with different room depth-WWR configurations where prismatic panels are installed. Section 4.3 presents the construction of a multiple regression model as an alternative method to computer simulation programs in estimating illuminance values on the work plane.

4.1. Validation of the Simulation Model

The simulation model generated based on real room characteristics and on-site measurements were run for identical days and hours. Illuminance values at 19 measurement points shown in Figure 3.2 were compared in order to determine how well the simulation outputs match up with the actual measurement results.

The coefficient of determination (R^2) was calculated in Excel to measure the accuracy of the simulation model. This is useful to find out the possibility of predicting the actual value of a point where illuminance value is obtained using the simulation tool. R^2 is the value between 0-1 and the closer this value is to 1, the more simulation outputs match with the actual measurement. The results obtained on 23rd November for clear sky conditions and 21st December for overcast sky conditions are shown in Figure 4.1 and Figure 4.2 respectively. The coefficient of determination (R^2) values ranged between 0,93 and 0,99 for all simulations run at three different hours in the above dates; indicates that Relux outputs show high accuracy with the actual measurements. In other words, finding an illuminance value of a certain point by simulation presents about 93-99 percent possibility of predicting its corresponding value in the actual measurement.

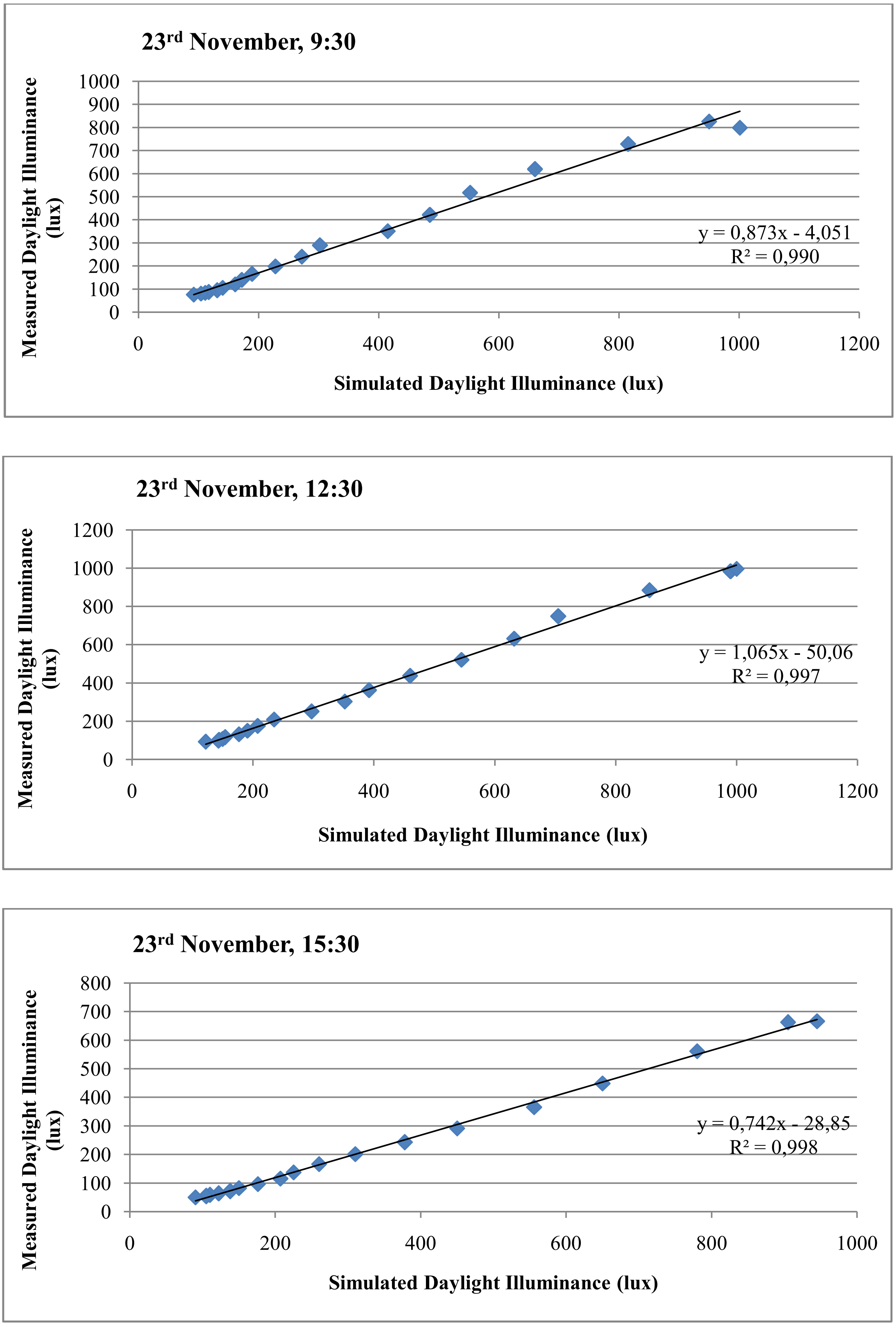


Figure 4.1. Correlations between measurement and simulation results for November (clear sky conditions)

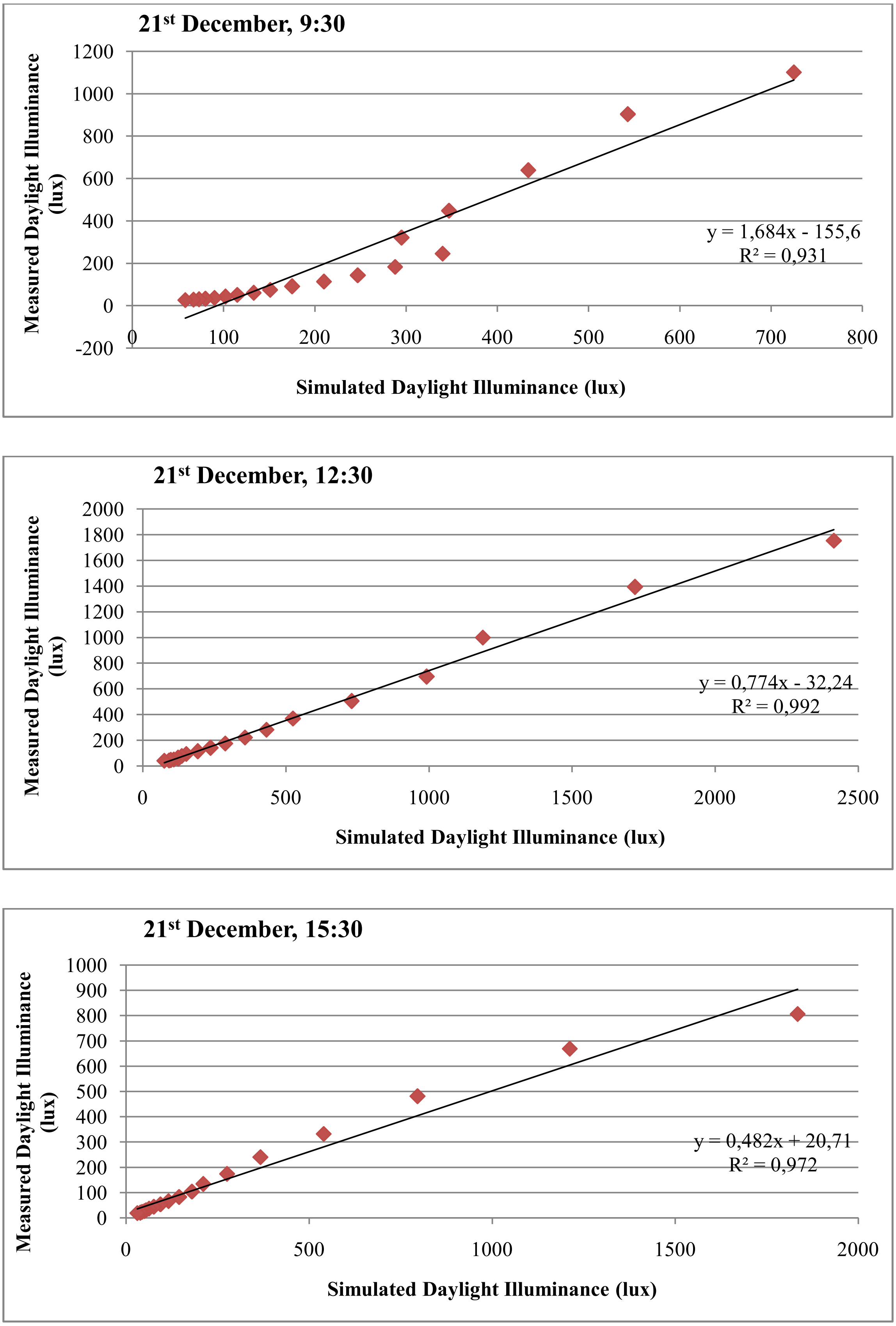


Figure 4.2. Correlations between measurement and simulation results for December (overcast sky conditions)

Root Mean Square Error (RMSE) is a quadratic metric that measures the magnitude of the error used to determine the difference between the predicted values and the actual values by following equation (4.1):

$$E = \sqrt{\frac{\sum_{t=1}^{N} \left(o_{1,t} - m_{1,t}\right)^2}{N}} \tag{4.1}$$

where, E is the RMS error, o is the illuminance output of Relux, m is the measured illuminance, N is the number of the measurement points. The RMSE values ranged between 34,04 and 284,95 for same days and hours. Coefficient of Variation (CV) which is another statistical indicator for validation of the simulation model was also calculated by given formula (4.2):

$$CV = \frac{RMSE}{\bar{m}} * 100 \tag{4.2}$$

where, $\bar{m}$ is the mean of the measured illuminance. RMSE and CV values indicating errors and deviations in the simulation model are given in the Table 4.1.

While the least error found on 23rd November at 12:30 pm with 34,02 of RMSE and 18% of CV, the highest error occurred on 21st December at 15:30 pm with 284,95 of RMSE and 0,87 of CV.

Table 4.1. Statistical error analysis of the simulation model.

Day	Time	RMSE (%)	CV
23rd November	09:30	66,87	0,18
	12:30	34,02	0,08
	15:30	139,25	0,39
21st December	09:30	145,07	0,61
	12:30	209,92	0,39
	15:30	284,95	0,87

It has been furthermore observed that the Relux simulation tool gave relatively more accurate results under clear sky conditions. Yet, it has better predicted the lower illuminance values at the back of the room better than the higher illuminance values measured near the window.

4.2. Visual Performance Evaluation of Alternative Rooms

The performance of movable prismatic panels was examined for rooms with different room depth-WWR configurations and schematic representation of the rooms is given in Figure 4.3.

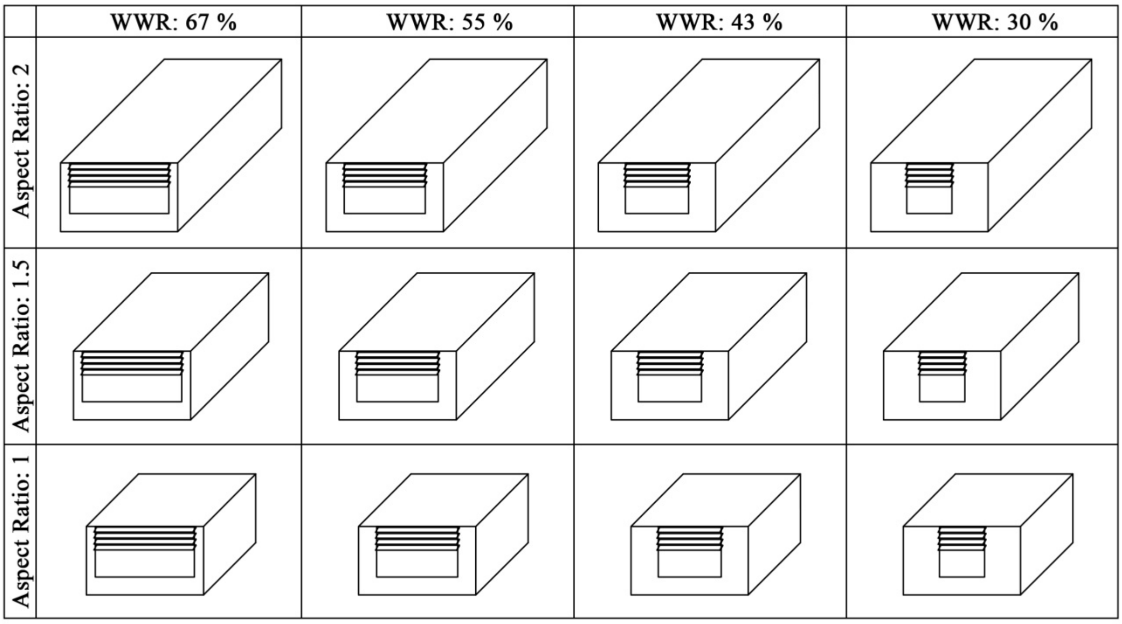


Figure 4.3. Design alternatives based on room depth and WWR.

The virtual model of the each room was generated separately in Relux and simulations were run for solstice and equinox days at three different hours. The details of the room characteristics and prismatic panels are stated in Section 3.3.2. The measurement points set to be 0.6 m distance between each other for each room depth are given in Appendix A.

Simulation results were evaluated by using climate-based metrics that allow the assessment of an entire daylit area, taking daily and annual climatic variation of the full year into account. Two metrics have been developed by Christoph Reinhart based on two different performance parameters which are adequacy of daylight illuminance and potential risk of excessive sunlight exposure (Heschong et al. 2012). The first metric sDA (Spatial Daylight Autonomy) presents the percentage of floor area that meets or exceeds minimum acceptable daylight illuminance level of 300 lx on horizontal surfaces for the occupied hours per year. The second metric ASE (Annual Sunlight Exposure) is described as the percentage of floor area that exposed more than 1000 lx of direct sunlight over 250 hours per year. It has been recommended that these two metrics should be taken into consideration together during the daylight performance evaluation process of an area (Heschong et al. 2012).

The illuminance values obtained through Relux simulations for all design alternatives were evaluated considering the illuminance threshold of sDA (300 lx) and ASE (1000 lx) and compared under 3 subsections based on room depth and window-to-wall ratio. It is expected that the measurement points with illuminance above 300 lx will be as much as possible, and the measurement points with illuminance above 1000 lx will be as few as possible. Minimum acceptable floor area of 55% for SDA and 7% for ASE according to IES were taken as a baseline during the evaluation process.

4.2.1. Results Based on Room Depth

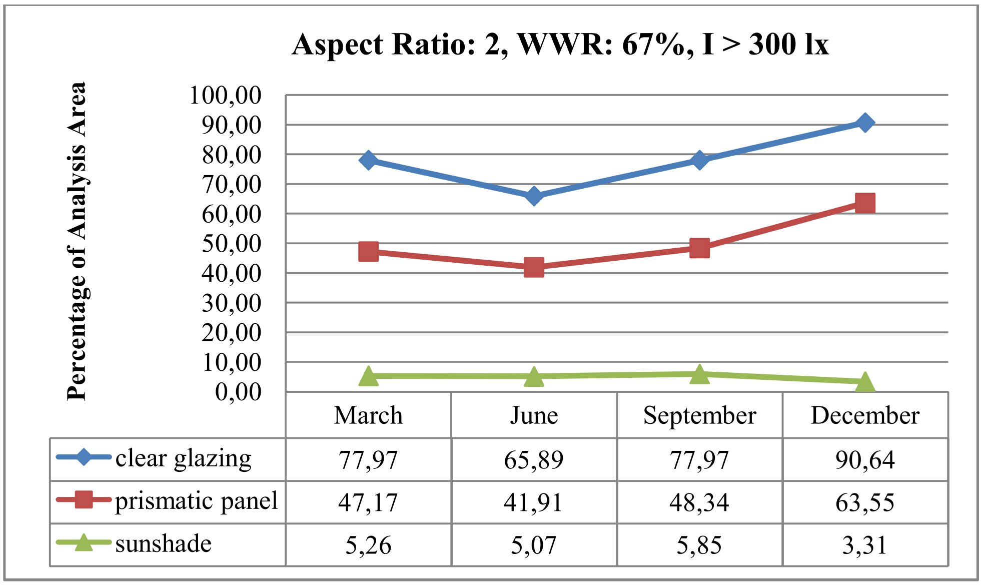
The purpose here is to identify areas that have sufficient daylight, do not receive enough daylight and are exposed to excessive sunlight for each room depth-WWR configurations and evaluate them in the context of recommendations. Regarding this, the illuminance values below 300 lx that are inadequate to perform a certain task and illuminance levels over 1000 lx that are associated with potential overheating and glare throughout the room were specified by marking with different colors on the tables obtained through Relux. An example of a colored table according to illuminance levels is given in Appendix B. The illuminance levels in each room with prismatic panels were compared with calculations run for the same room without any shading system applied (clear glazing) and the same room with conventional shading. In the case of conventional shading in the room, the windows are covered with 10% transparent roller shade.

Since Relux does not capable of performing sDA and ASE calculations, these values were estimated manually using the illuminance values in the tables. In order to simplify the calculation, it was found that the illuminance at each measurement point represents what percentage of the annual working hours. For instance, it was assumed that each measurement point simulated in Relux for 21st March at 10:00 represents 180 working hours from 8 am to 11 am in the spring months which at the same time corresponds 7.5% of total working hours in a year (considering 2400 working hours per year). Likewise, calculations at 13:00 and 16:00 represents 240 working hours from 11 am to 15 pm and 180 working hours from 15 pm to 18 pm which also corresponds 10% and 7.5% of total working hours in a year, respectively. The same method was applied for 21st June, 23rd September and 21st December, and the percentage of annual working hours when illuminance at each measurement point meets or exceeds 300 lx were determined. Finally, the measurement points that meets or exceeds 300 lx at least 50% of working hours per year were marked on working plane, and ratio of these points to the total measurement points were calculated in order to achieve sDA value. For the calculation of ASE, the measurement points that exposed to illuminance over 1000 lx for more than 250 working hours per year were determined and ratio of these points to the total measurement points were calculated.

Below, the percentage of the analysis area that meets or exceeds the illuminance of 300 lx and 1000 lx; also the sDA and ASE values calculated by taking annual working hours into account are given separately for each design alternatives based on room depth.

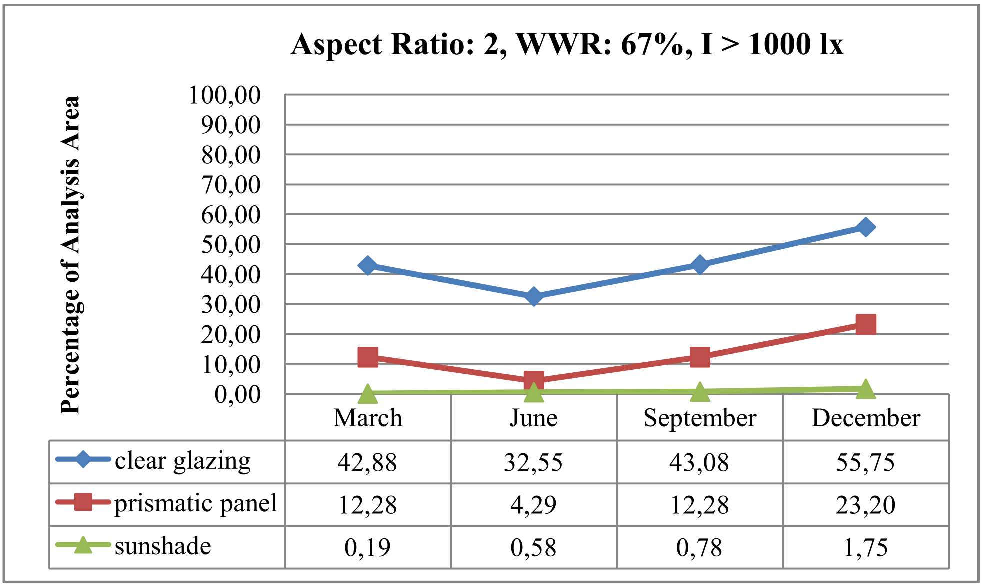
Aspect Ratio: 2 (Room Depth 12 m)

According to Relux outputs for room configuration with a 12 m depth and 67% WWR (Figure 4.4), the 50.24% of the analysis area received sufficient daylight (illuminance over 300 lx) and 13,01% of the analysis area exposed to direct sunlight (illuminance over 1000 lx). Compared to the room with clear glazing, the area that receives sufficient daylight decreased by %35,56, yet, area that receives more than 1000 lx also decreased by 69,65%. In the case of applying conventional roller shade to the entire window, the illuminance levels throughout the room decreased significantly and sufficient daylight cannot be received even near the window. Spatial Daylight Autonomy (sDA) for this room configuration was found as %48,54 which indicates the percentage of the area that meets or exceeds target illuminance of 300 lx for at least 50% of working hours in a year. The value obtained is almost equal to the value recommended by the IES. The percentage of the area that exceeds 1000 lx for more than 250 working hours in a year (ASE) was found as 35,09% which is much more than the recommended value. Still, room with prismatic panels offers more balanced daylight distribution between window zone and back of the room compared to room with clear glazing. Daylight levels across the room were decreased due to shading capability of prismatic panels but still remained at an acceptable level.



	March	June	September	December
clear glazing	77,97	65,89	77,97	90,64
prismatic panel	47,17	41,91	48,34	63,55
sunshade	5,26	5,07	5,85	3,31

(a)

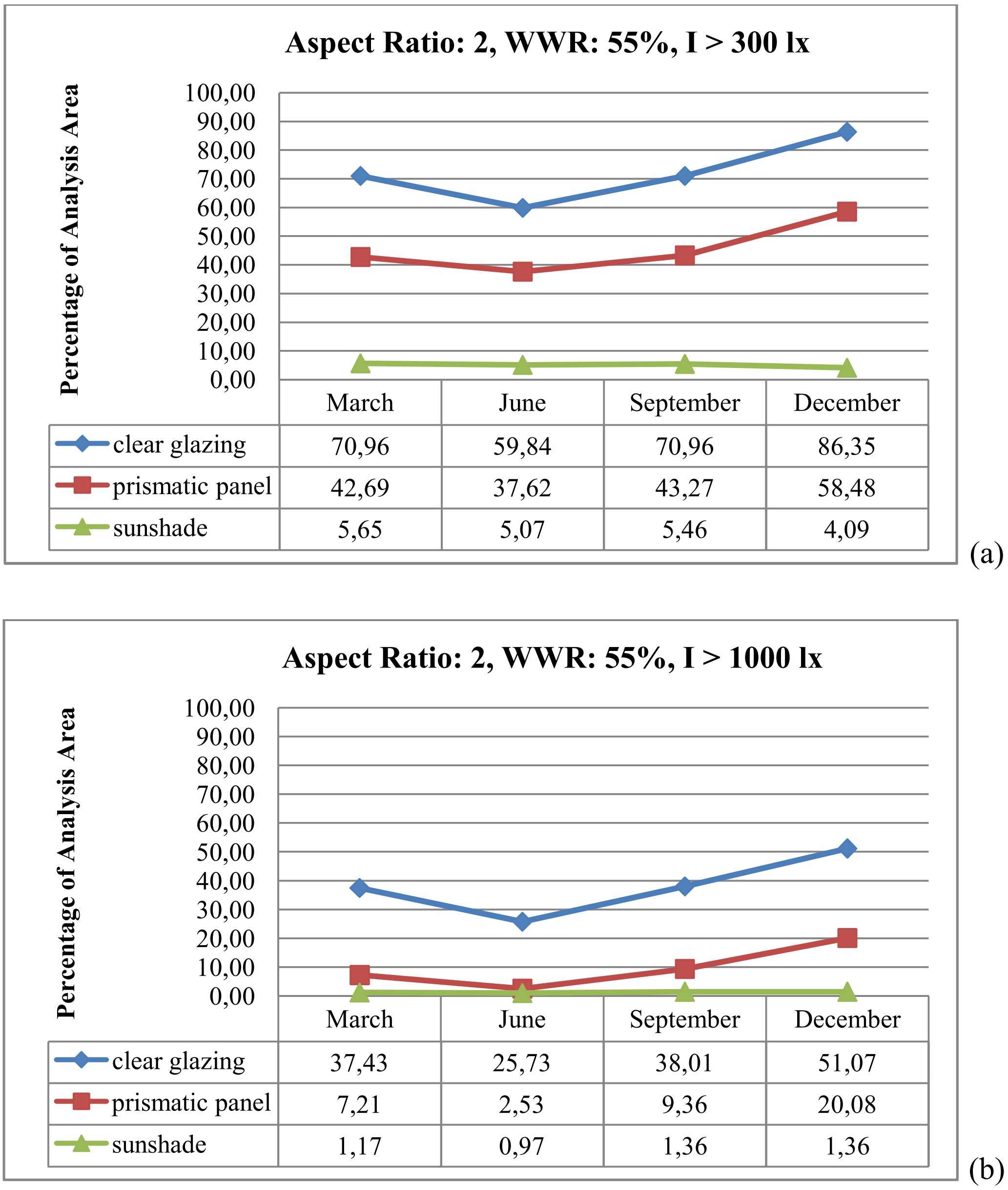


	March	June	September	December
clear glazing	42,88	32,55	43,08	55,75
prismatic panel	12,28	4,29	12,28	23,20
sunshade	0,19	0,58	0,78	1,75

(b)

Figure 4.4. Daylighting performance of the room with 12m depth and 67% WWR; illuminance over (a) 300 lx and (b) 1000 lx.

In the room with 55% WWR (Figure 4.5), 45.52% of the area received sufficient daylight and 9,80% of the area exposed to direct sunlight. Compared to the room with clear glazing, the area that has illuminance above 300 lx and 1000 lx decreased by 36,80% and 74,25%, respectively. In terms of annual working hours, there is a slight decrease in sDA compared to the room with 67% WWR, but the value fell short of the recommendations with 45,03%. Although there is a significant drop in illuminance more than 1000 lx with decreasing window area, ASE value was still above the recommended value with 28,65%.

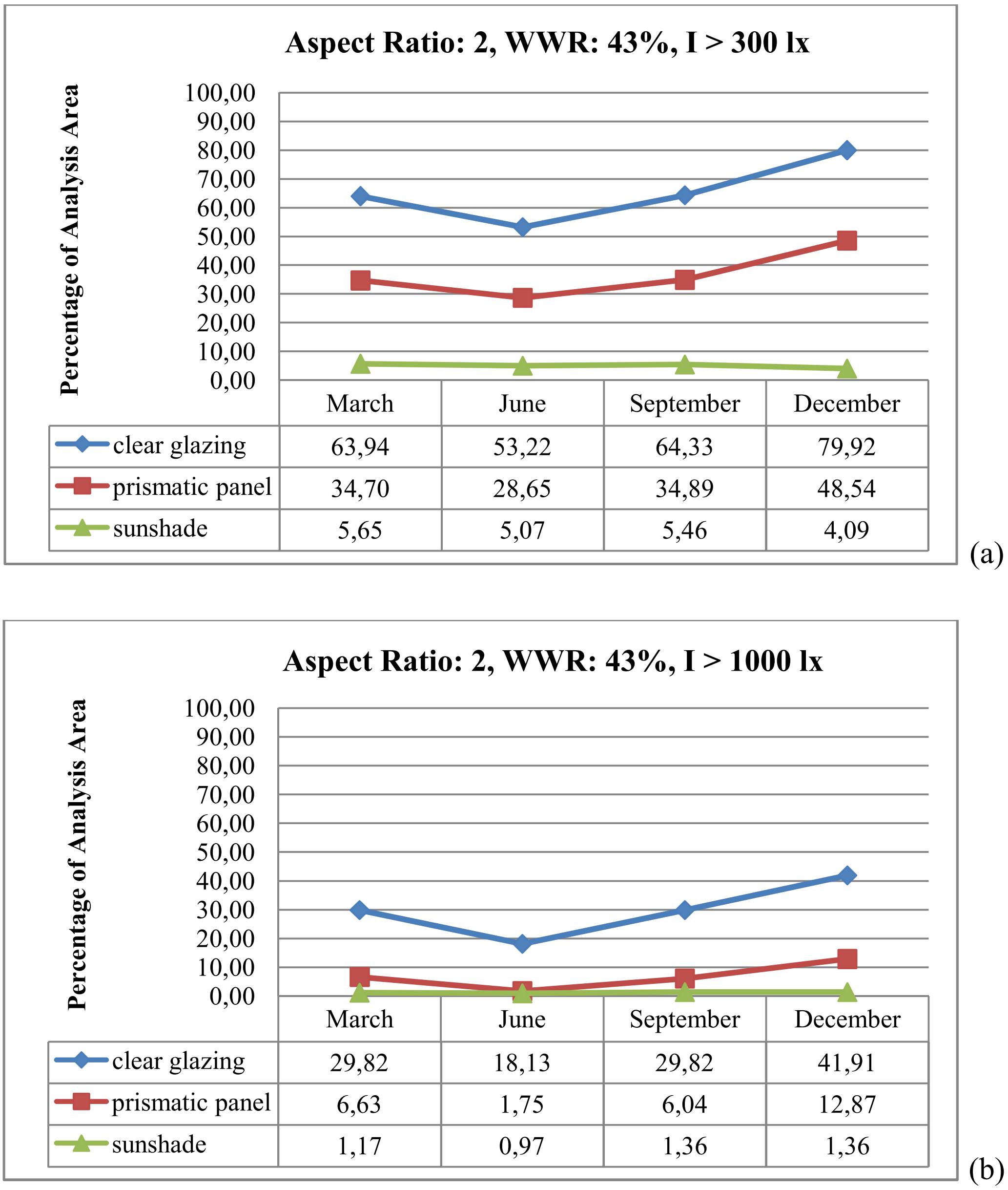


	March	June	September	December
clear glazing	70,96	59,84	70,96	86,35
prismatic panel	42,69	37,62	43,27	58,48
sunshade	5,65	5,07	5,46	4,09

	March	June	September	December
clear glazing	37,43	25,73	38,01	51,07
prismatic panel	7,21	2,53	9,36	20,08
sunshade	1,17	0,97	1,36	1,36

Figure 4.5. Daylighting performance of the room with 12m depth and 55% WWR; illuminance over (a) 300 lx and (b) 1000 lx.

In the room with 43% WWR (Figure 4.6), the area that receives illuminance of over 300 lx is 36,70% with a decrease of 43,84%, while illuminance over 1000 lx is 6,82% with a decrease of 77,20% compared to the room with clear glazing. The sDA and ASE for this room configuration was found as 38,60% and 19,88%, respectively. Even though the area exposed to excessive sunlight was significantly reduced, ASE was in an unacceptable range since area with more than 10% ASE is associated with unsatisfactory visual comfort by IES.

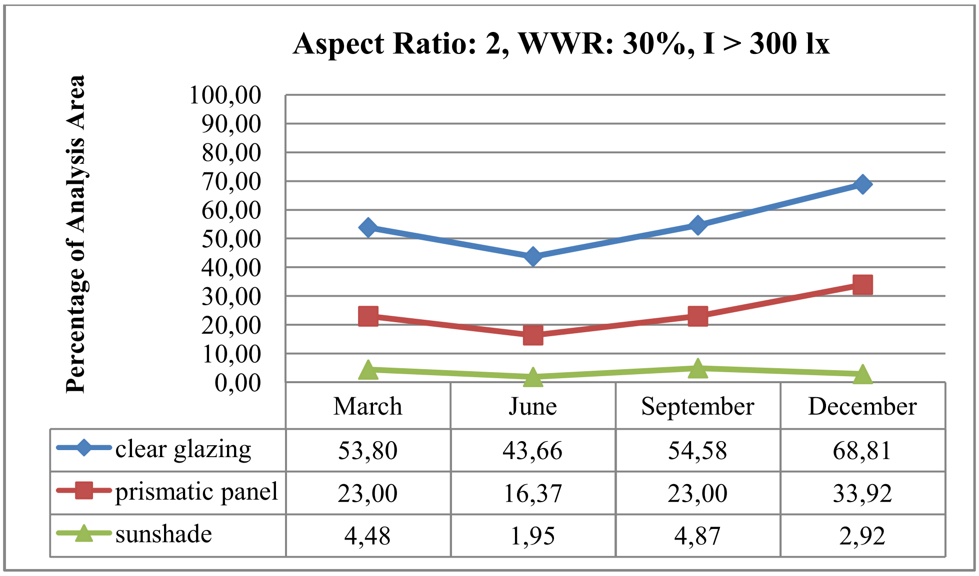


	March	June	September	December
clear glazing	63,94	53,22	64,33	79,92
prismatic panel	34,70	28,65	34,89	48,54
sunshade	5,65	5,07	5,46	4,09

	March	June	September	December
clear glazing	29,82	18,13	29,82	41,91
prismatic panel	6,63	1,75	6,04	12,87
sunshade	1,17	0,97	1,36	1,36

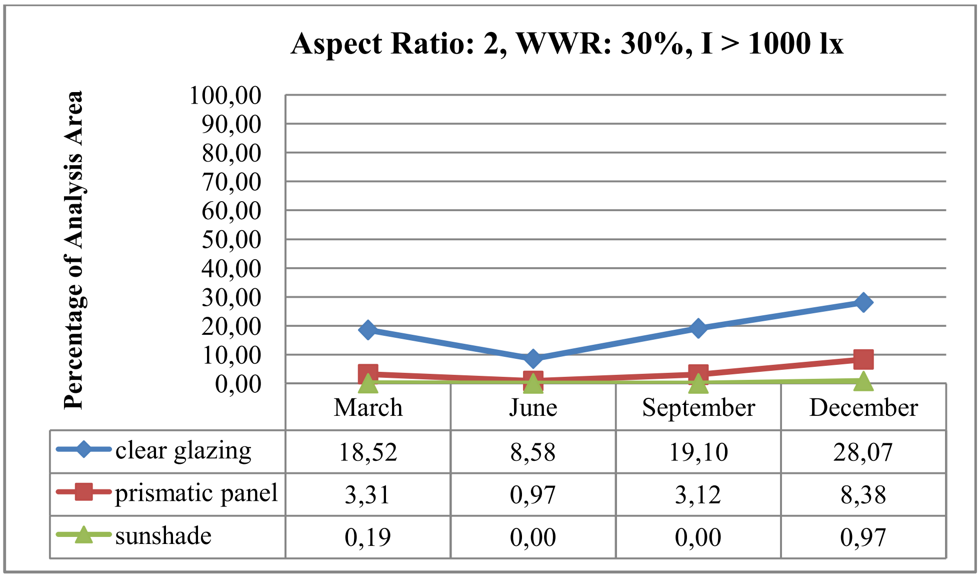
Figure 4.6. Daylighting performance of the room with 12m depth and 43% WWR; illuminance over (a) 300 lx and (b) 1000 lx.

When the WWR is 30% (Figure 4.7), the area that receives illuminance of over 300 lx is 55.21% in the room with clear glazing and this value decreased to 24.07% with the application of prismatic panels. The area with the illuminance more than 1000 lx also fell from 18.57% to 3.95% compared to the room with clear glazing. The decrease in illuminances above 1000 lx is higher, thus, the ASE remained within an acceptable range with 9.94% when annual working hours taken into account. However, sDA of 38,60% fell short in terms of the daylight adequacy in the room.



	March	June	September	December
clear glazing	53,80	43,66	54,58	68,81
prismatic panel	23,00	16,37	23,00	33,92
sunshade	4,48	1,95	4,87	2,92

(a)



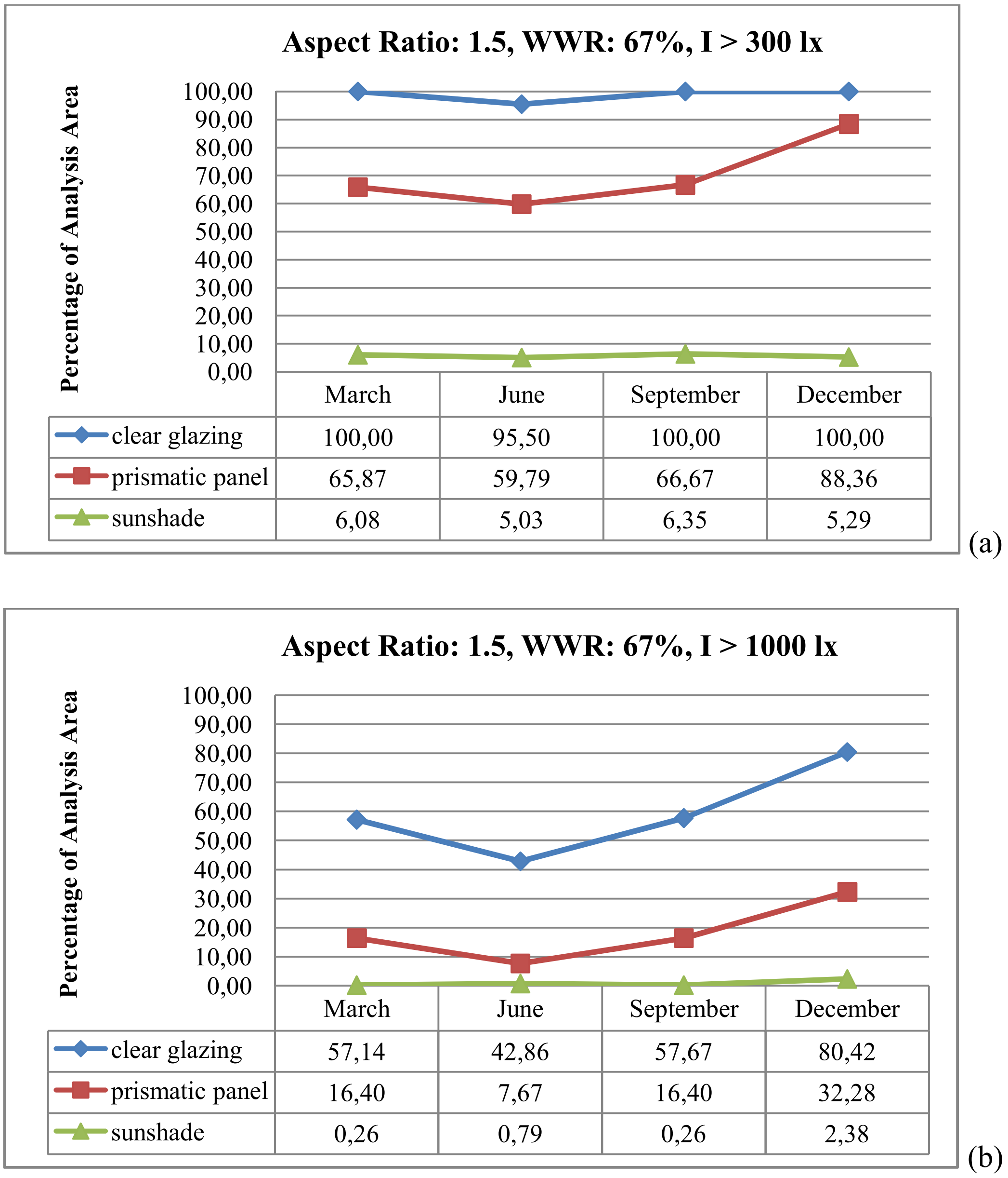
	March	June	September	December
clear glazing	18,52	8,58	19,10	28,07
prismatic panel	3,31	0,97	3,12	8,38
sunshade	0,19	0,00	0,00	0,97

(b)

Figure 4.7. Daylighting performance of the room with 12m depth and 30% WWR; illuminance over (a) 300 lx and (b) 1000 lx.

Aspect Ratio: 1.5 (Room Depth 9 m)

In case the window-to-wall ratio is 67% (Figure 4.8), almost the entire area in the room with clear glazing received sufficient daylight; however, more than half of this area exposed to direct sunlight above 1000 lx. With the application of prismatic panels to the window, the percentage of the area with illuminance above 300 lx decreased to 70.17%. Also, the percentage of the area with illuminance above 1000 lx decreased by one third and became 18.19%. The 68.25% sDA obtained for this room configuration is satisfactory in the context of the recommendations, while the 47.62% ASE exceeded the acceptable value.

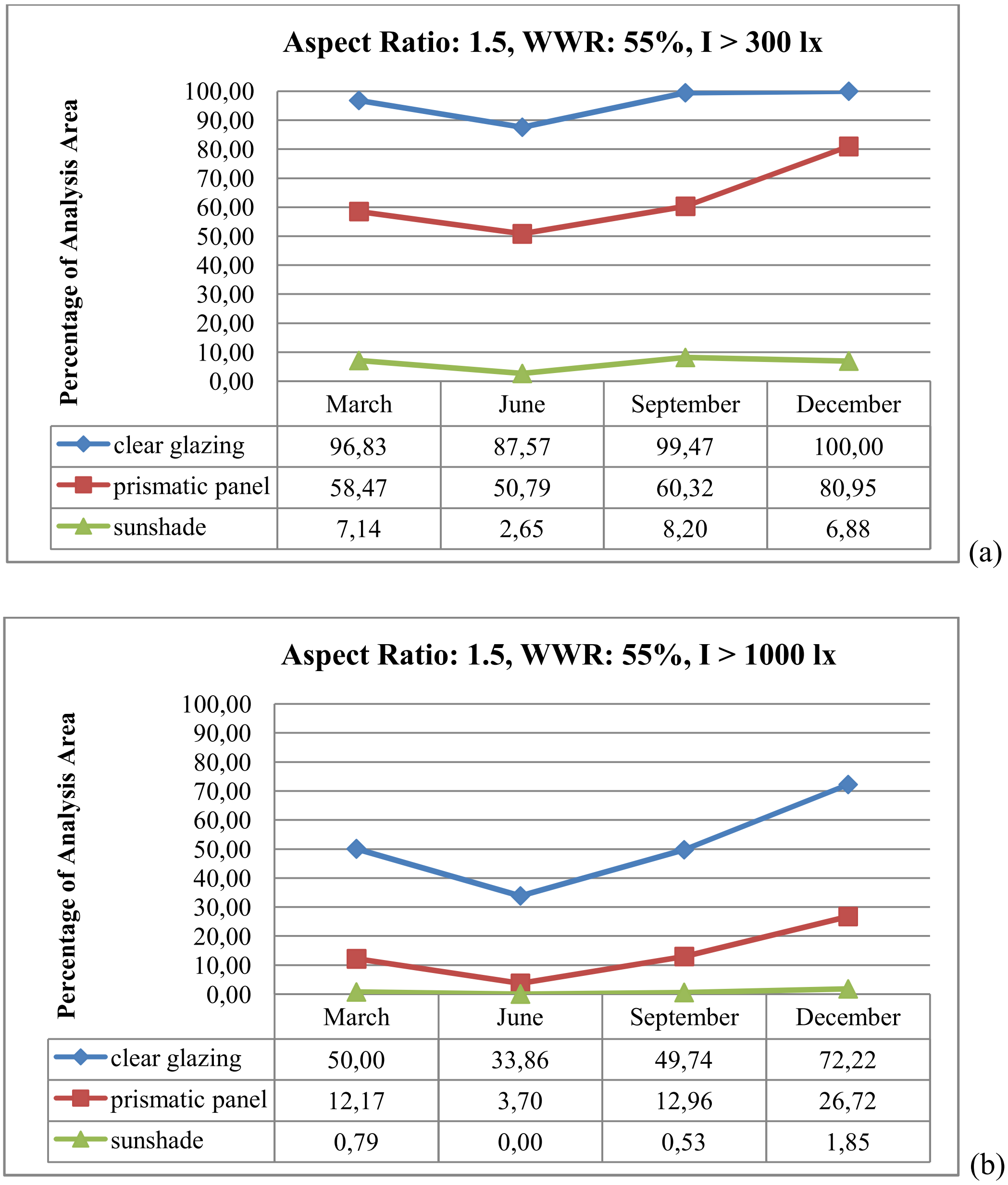


	March	June	September	December
clear glazing	100,00	95,50	100,00	100,00
prismatic panel	65,87	59,79	66,67	88,36
sunshade	6,08	5,03	6,35	5,29

	March	June	September	December
clear glazing	57,14	42,86	57,67	80,42
prismatic panel	16,40	7,67	16,40	32,28
sunshade	0,26	0,79	0,26	2,38

Figure 4.8. Daylighting performance of the room with 9m depth and 67% WWR; illuminance over (a) 300 lx and (b) 1000 lx.

In the room with 55% WWR (Figure 4.9), illuminance levels decreased slightly but still more than half of the area receives sufficient daylight. The percentage of the analysis area that receives illuminance over 300 lx and 1000 lx became 62,63% and 13,89%, respectively. The 61,90% sDA found for this room is within the acceptable range but 38,89% ASE is well above the recommended value.



	March	June	September	December
clear glazing	96,83	87,57	99,47	100,00
prismatic panel	58,47	50,79	60,32	80,95
sunshade	7,14	2,65	8,20	6,88

	March	June	September	December
clear glazing	50,00	33,86	49,74	72,22
prismatic panel	12,17	3,70	12,96	26,72
sunshade	0,79	0,00	0,53	1,85

Figure 4.9. Daylighting performance of the room with 9m depth and 55% WWR; illuminance over (a) 300 lx and (b) 1000 lx.

When the WWR is 43% (Figure 4.10), 88.82% of the area received sufficient daylight in the room with clear glazing and almost half of it consists of illuminance above 1000 lx. This indicates that, as the window size decreases, the decrease in the work plane illuminance above 1000 lx is more than illuminance above 300 lx. In the room with prismatic panels, the percentage of area with illuminance above 300 lx was almost halved compared to unshaded room and became 50,99%. The area with illuminance over 1000 lx also decreased significantly and became 9,46%. The recommended sDA is almost achieved with 51,59% value, unlike ASE value of 26,19%.

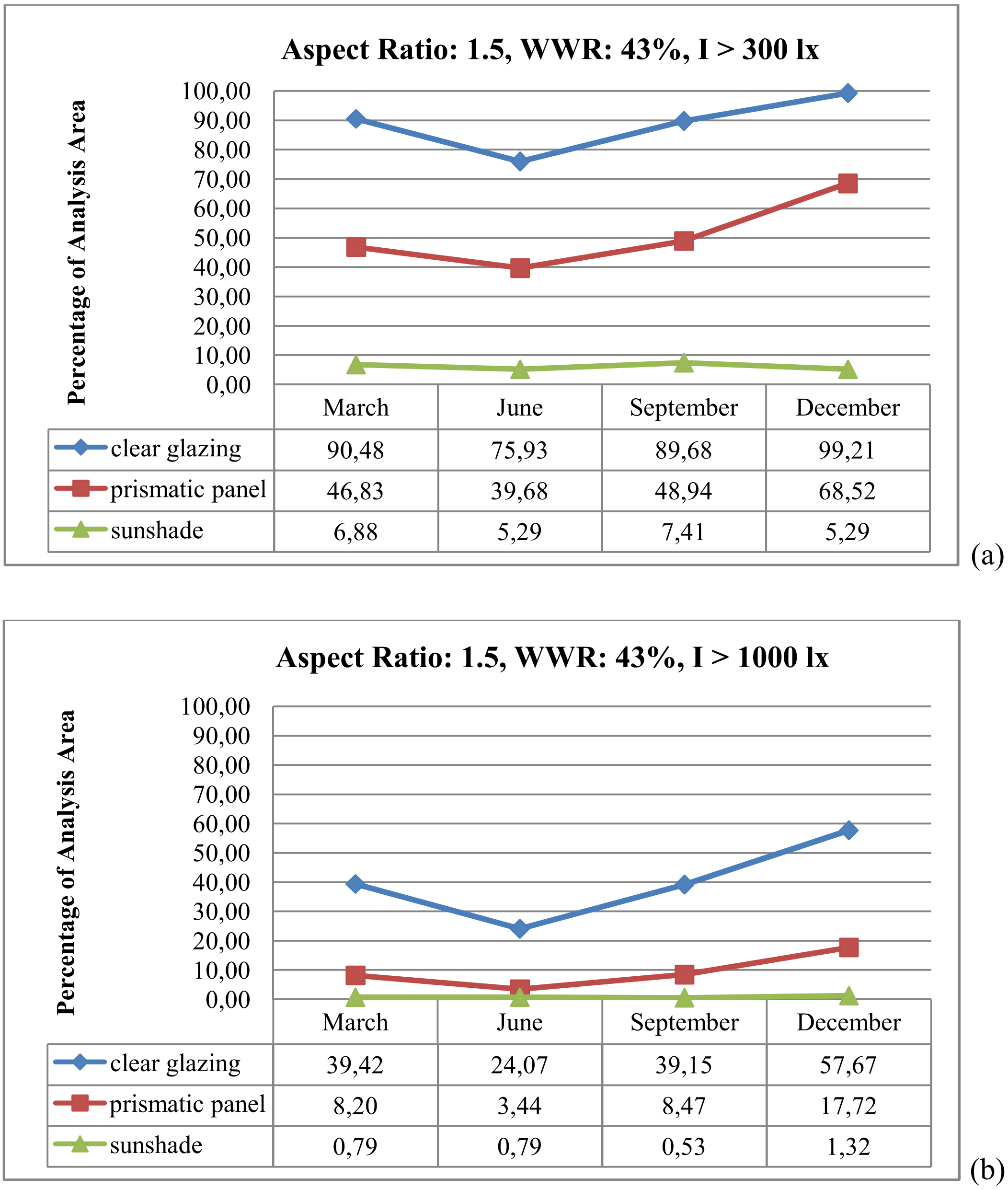


Figure 4.10. Daylighting performance of the room with 9m depth and 43% WWR; illuminance over (a) 300 lx and (b) 1000 lx.

In the room with 30% WWR (Figure 4.11), daylight levels decreased significantly compared to room with clear glazing. Only the 33,13% of the analysis area received adequate daylight and 5,82% of the space exposed to direct sunlight. The decline in illuminance above 1000 lux enabled the ASE to be almost within an acceptable range with 13,49%, but the 34,92% sDA remained below the recommended value.

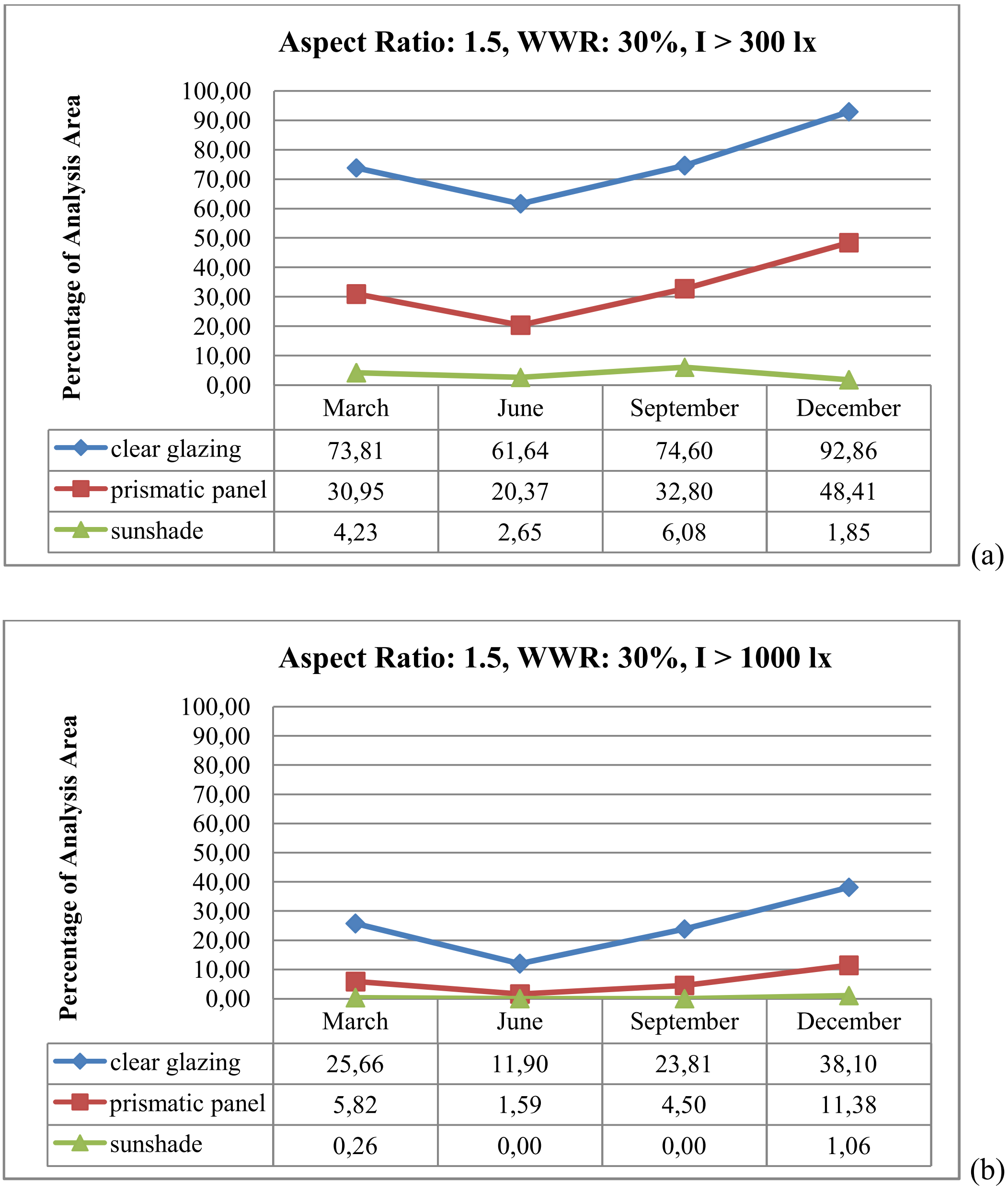
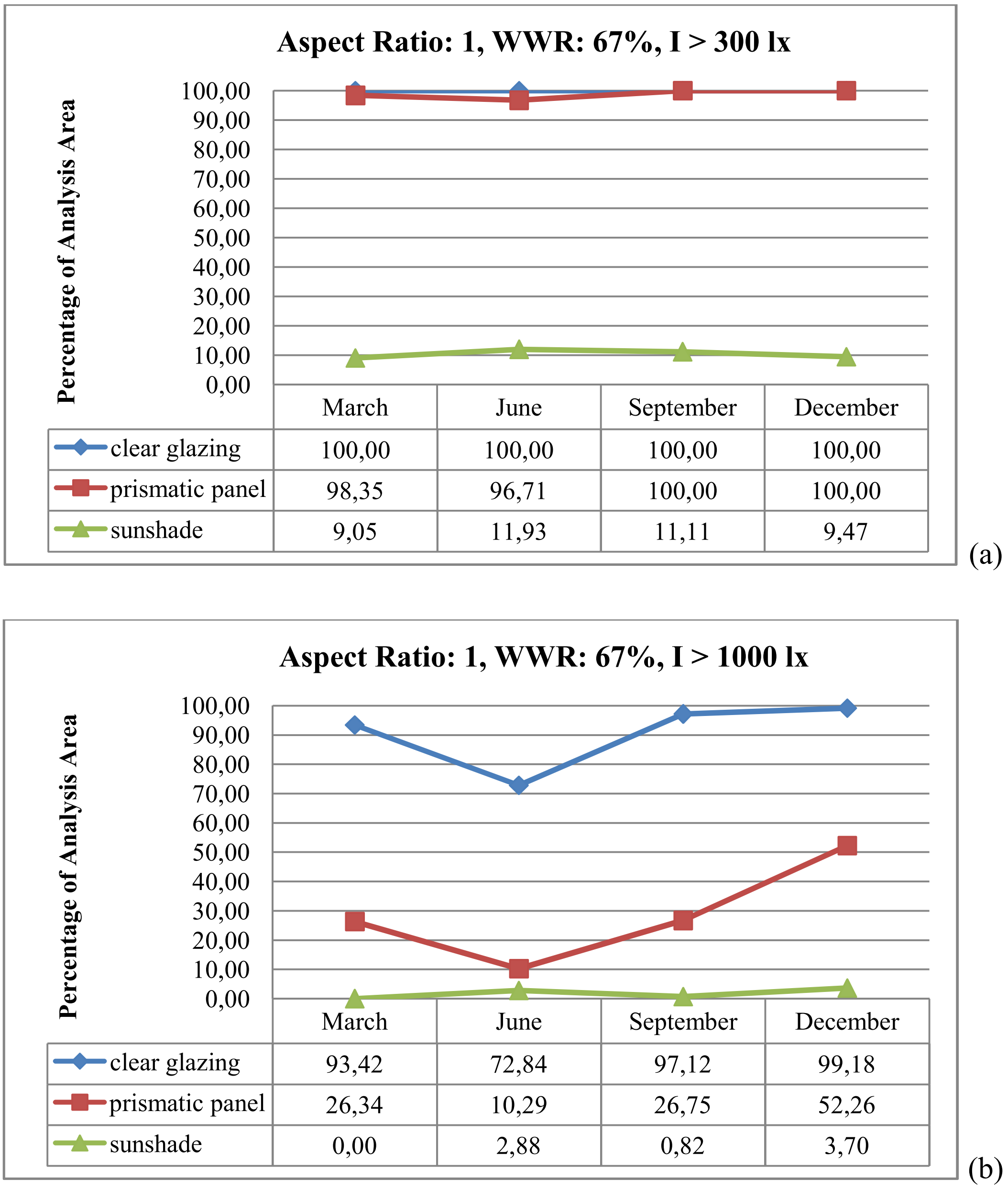


Figure 4.11. Daylighting performance of the room with 9m depth and 30% WWR; illuminance over (a) 300 lx and (b) 1000 lx.

Aspect Ratio: 1 (Room Depth 6 m)

In the case of clear glazing, the entire area received illuminance more than 300 lx for all window-to-wall ratio (WWR) alternatives. However, the illuminance over 1000 lx was reduced by decreasing the window size. On the other hand, daylight distribution across the area varied for all room depth-WWR configurations by the application of prismatic panels. In the room with WWR of 67% (Figure 4.12), the area that received illuminance over 300 lx is almost same with that in room with clear glazing. The sDA found as 100,00% which indicates that the entire area received illuminance over 300 lx for at least 50% of annual working hours. On the other hand, there is a significant decrease in illuminance over 1000 lx. The percentage of the area exposed to direct sunlight decreased from 90,64% to 28,91%. Nevertheless, ASE found as 77,78% which indicates that the greater part of the area exposed illuminance over 1000 lx more than 250 working hours in a year.

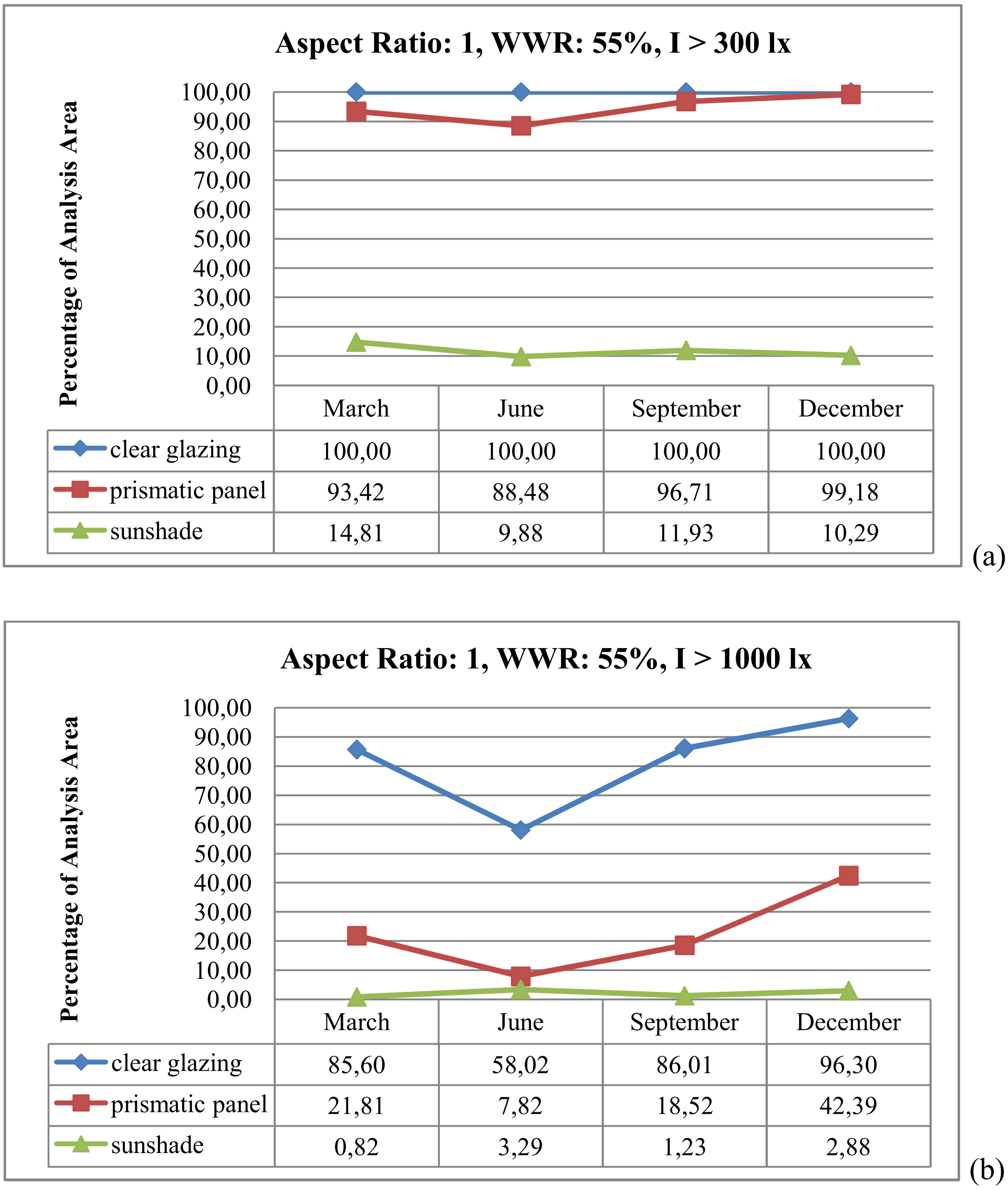


	March	June	September	December
clear glazing	100,00	100,00	100,00	100,00
prismatic panel	98,35	96,71	100,00	100,00
sunshade	9,05	11,93	11,11	9,47

	March	June	September	December
clear glazing	93,42	72,84	97,12	99,18
prismatic panel	26,34	10,29	26,75	52,26
sunshade	0,00	2,88	0,82	3,70

Figure 4.12. Daylighting performance of the room with 6m depth and 67% WWR; illuminance over (a) 300 lx and (b) 1000 lx.

By decreasing the window-wall ratio to 55% (Figure 4.13), the illuminance over 300 lx dropped slightly but sDA remained constant as 100,00%. The percentage of the area with illuminance over 1000 lx also decreased to 20,63% and ASE became 65,43% which is far above the recommended value.

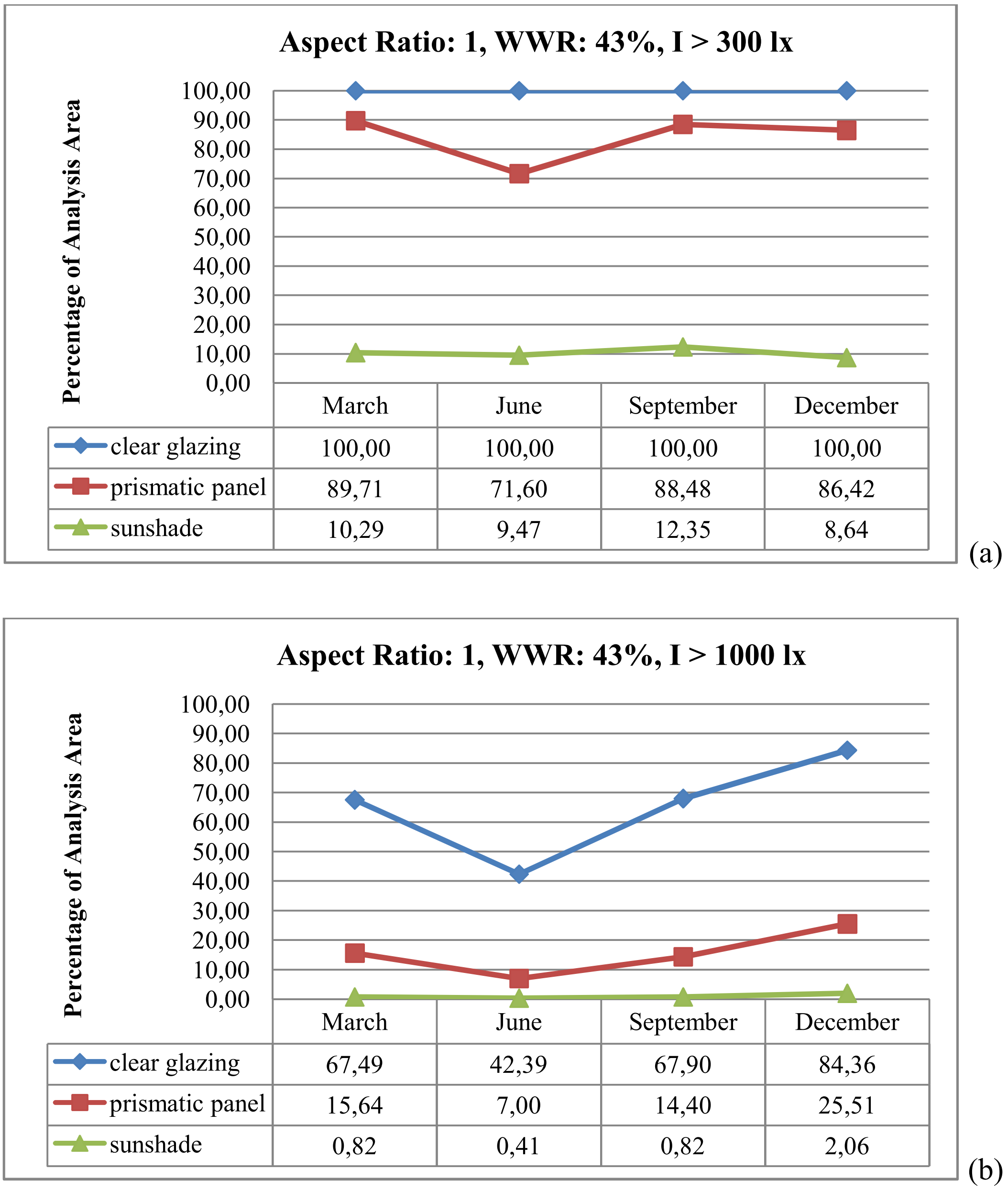


	March	June	September	December
clear glazing	100,00	100,00	100,00	100,00
prismatic panel	93,42	88,48	96,71	99,18
sunshade	14,81	9,88	11,93	10,29

	March	June	September	December
clear glazing	85,60	58,02	86,01	96,30
prismatic panel	21,81	7,82	18,52	42,39
sunshade	0,82	3,29	1,23	2,88

Figure 4.13. Daylighting performance of the room with 6m depth and 55% WWR; illuminance over (a) 300 lx and (b) 1000 lx.

In the room with 43% WWR (Figure 4.14), the percentage of area that has illuminance over 300 lx and 1000 lx decreased to 85,02% and 15,64%, respectively. The sDA and ASE were found as 92,59% and 40,74%, respectively. These values are satisfactory for daylight adequacy for given area but unfavourable in terms of visual and thermal comfort.

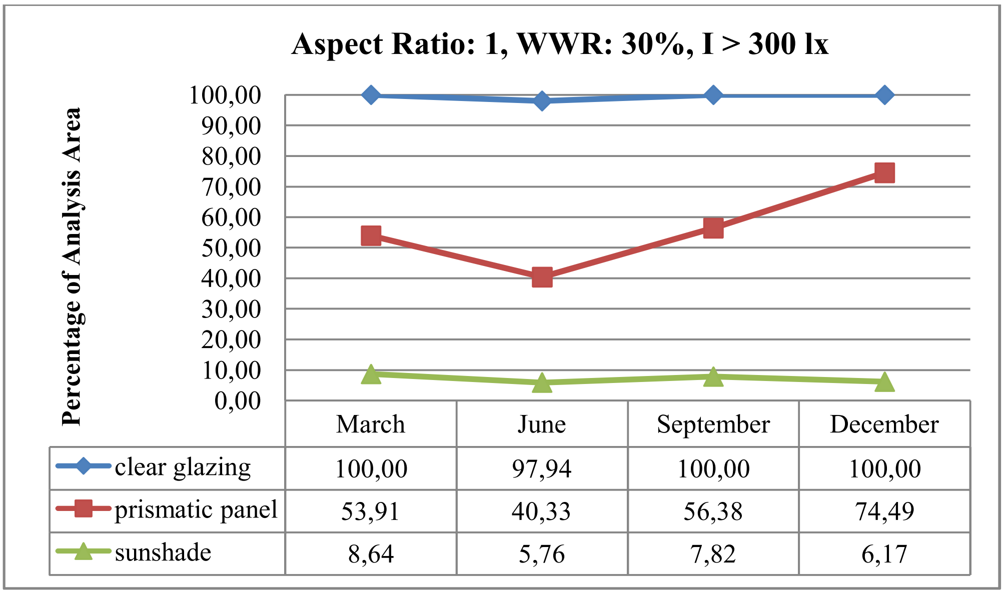


	March	June	September	December
clear glazing	100,00	100,00	100,00	100,00
prismatic panel	89,71	71,60	88,48	86,42
sunshade	10,29	9,47	12,35	8,64

	March	June	September	December
clear glazing	67,49	42,39	67,90	84,36
prismatic panel	15,64	7,00	14,40	25,51
sunshade	0,82	0,41	0,82	2,06

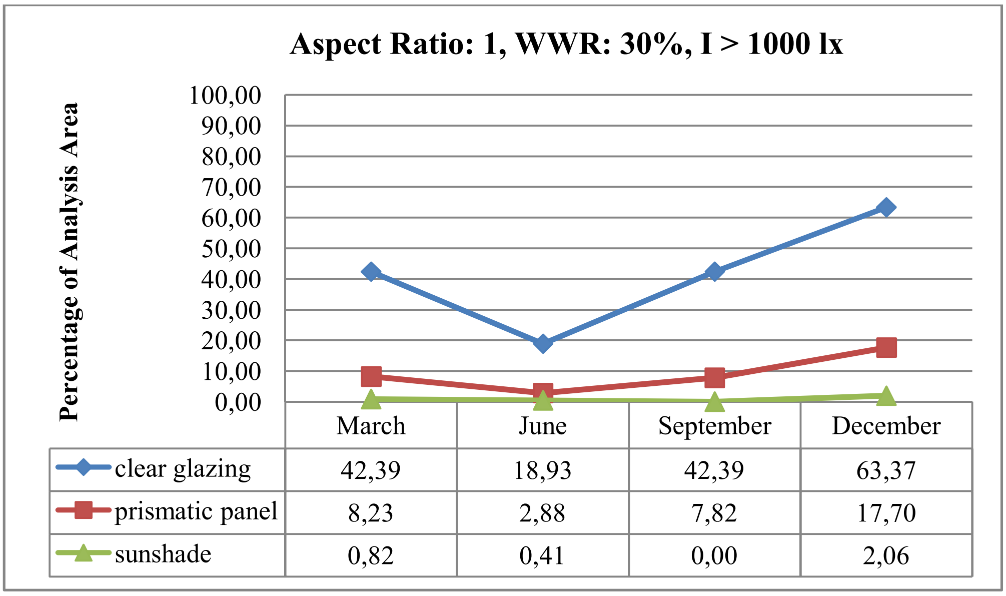
Figure 4.14. Daylighting performance of the room with 6m depth and 43% WWR; illuminance over (a) 300 lx and (b) 1000 lx.

In the final room configuration with 30% WWR (Figure 4.15), almost half of the room area received adequate daylight with percentage of 56,28% and only 9,16% of the area exposed to direct sunlight. The sDA found as 59,26% which is above the recommended value. Yet, even in the room with the least window-to-wall ratio, the recommended ASE value could not be achieved and remained as 20,99%.



	March	June	September	December
clear glazing	100,00	97,94	100,00	100,00
prismatic panel	53,91	40,33	56,38	74,49
sunshade	8,64	5,76	7,82	6,17

(a)



	March	June	September	December
clear glazing	42,39	18,93	42,39	63,37
prismatic panel	8,23	2,88	7,82	17,70
sunshade	0,82	0,41	0,00	2,06

(b)

Figure 4.15. Daylighting performance of the room with 6m depth and 30% WWR; illuminance over (a) 300 lx and (b) 1000 lx.

Overall Assessment

A number of common conclusions can be drawn by evaluating the results obtained for all WWR-Room depth configurations:

- The illuminance values across the room were decreased with the reducing window-to-wall ratio (WWR) as shown in Appendix C. Daylight illuminance throughout the room ranges between 37 lx – 1481 lx. Measurement points illuminated by the sun patch – illuminance over 20 000 lx) – are not shown in graphs.

- In the case of applying 10% transparent conventional shading instead of prismatic panels, illuminance values across the room decreased substantially and adequate daylight could not provided for any design alternatives.
- In the winter months, daylight penetrated deeper into rooms due to the lower position of the sun and illuminance values increased throughout the room. The prismatic panels were incapable of sun shading during these months and the inclined sun rays passed through between panels led to a considerable increase of illuminance values above 1000 lx. This excessive daylight exposure is also the reason for the high ASE values. Majority of the sun patches were observed in winter. Interior renderings of each design alternative on equinox and solstice days at noon are given in Appendix D.
- In the summer months, the amount of daylight entering the room dropped off due to the higher position of the sun. The sun shading affect of the panels was prominent, since sunlight striking from right angles was reflected by the prism structure. This resulted in a decrease in illuminance values above 1000 lx, which ensures ASE to be within the acceptable range in these months.
- In the spring and autumn, the amount of daylight entering the room and the daylight distribution is almost identical. The illuminance values throughout the room are higher than those in summer and lower than those in winter.
- When the prismatic panels were applied, the percentage of decrease in illuminance over 1000 lx for the each room depth-WWR configurations was approximately the same compared to the room with clear glazing. The percentage of decrease slightly rose up as the window-to-wall ratio (WWR) decreased. Likewise, the percentage of decrease in illuminance over 300 lx was almost the same in rooms of 12m and 9m depth. But in rooms of 6 m depth, the decrease in these values was far less compared to rooms with clear glazing except for the case with 30% WWR (See Appendix E).
- Considering the results obtained above, the percentage of the area with illuminance above 300 lx calculated regardless of a specific time fraction for a space, almost corresponds to the estimated sDA value for this space. Contrary to this, the estimated ASE value is considerably greater than the percentage of the area that meets or exceeds illuminance above 1000 lx (Figure 4.16).

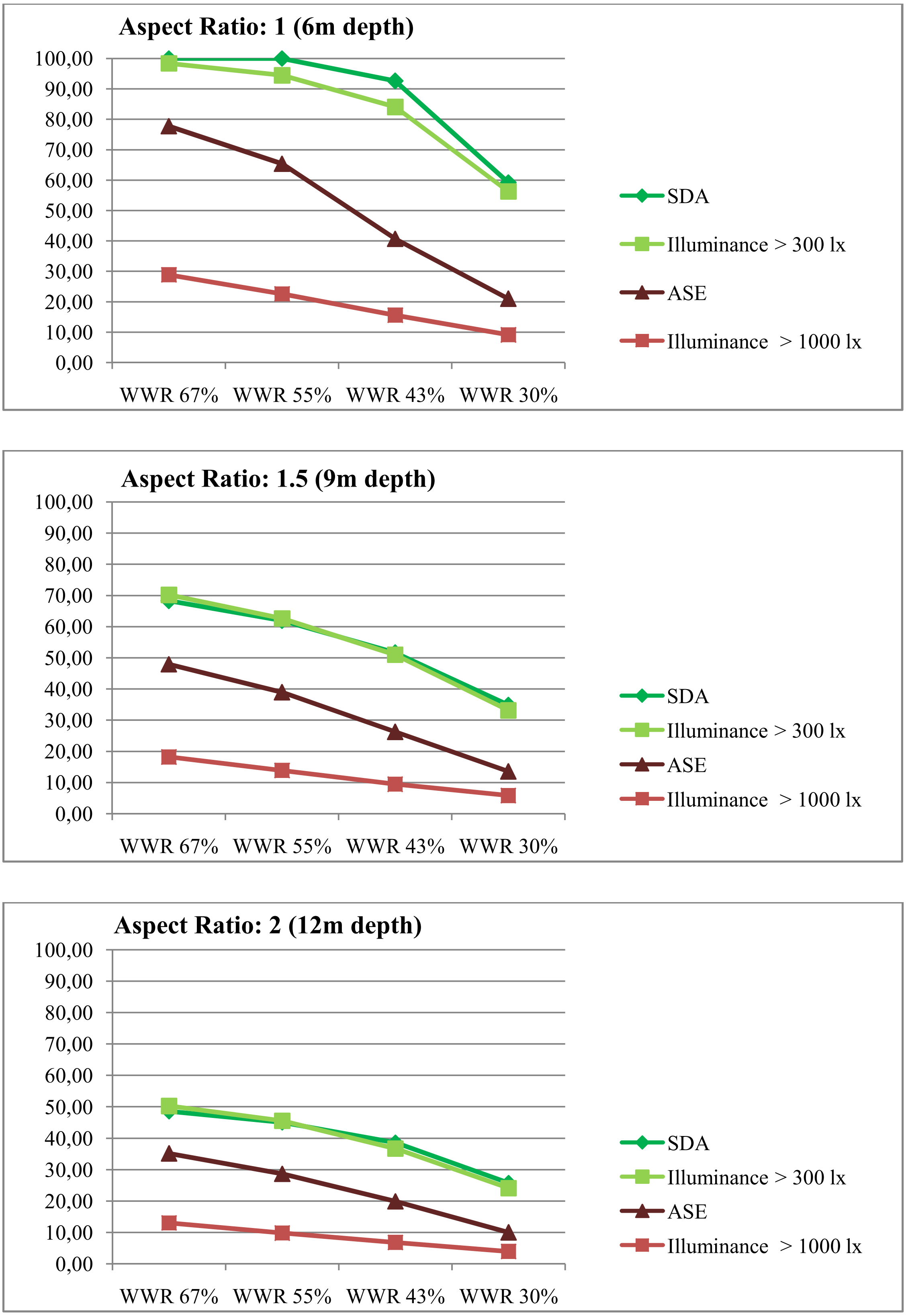
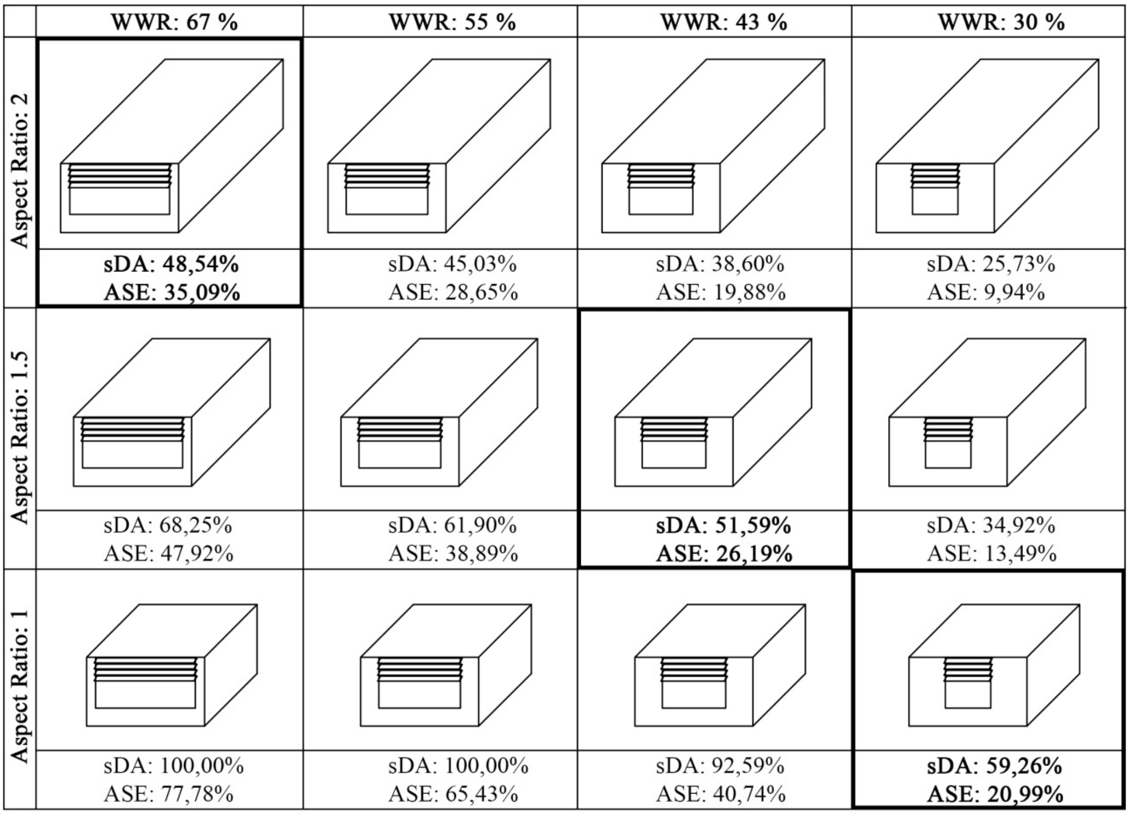


Figure 4.16. Comparison of sDA and ASE values with the percentage of analysis area that meets or exceeds illuminance of 300 lx and 1000 lx regardless of a specific time fraction.

- Based on hourly measurements, the illuminance values obtained at 10 am show an increasing distribution towards the west side of the room. A similar illuminance distribution takes place towards the east side of the room for measurement carried out at 16 pm. In the measurement at 13 pm, the illuminance values show a more even distribution and spread deeper into the room (See Appendix A).
- In accordance with minimum IES requirements, the most satisfying sDA value found to be 48,54% in a room of 12m depth with 67% WWR. An sDA of 51,59% and 59,26% is achieved in a room of 9m depth with 43% WWR and 6m depth with 30% WWR, respectively (Figure 4.17).
- The ASE value obtained for each design alternative exceeds the minimum acceptable ASE of 7% recommended by IES. The closest ASE values were obtained with the least WWR alternative of 30% in all room depths. This value is 9,94%, 13,49% and 20,99% in room of 12m, 9m and 6m depth, respectively.

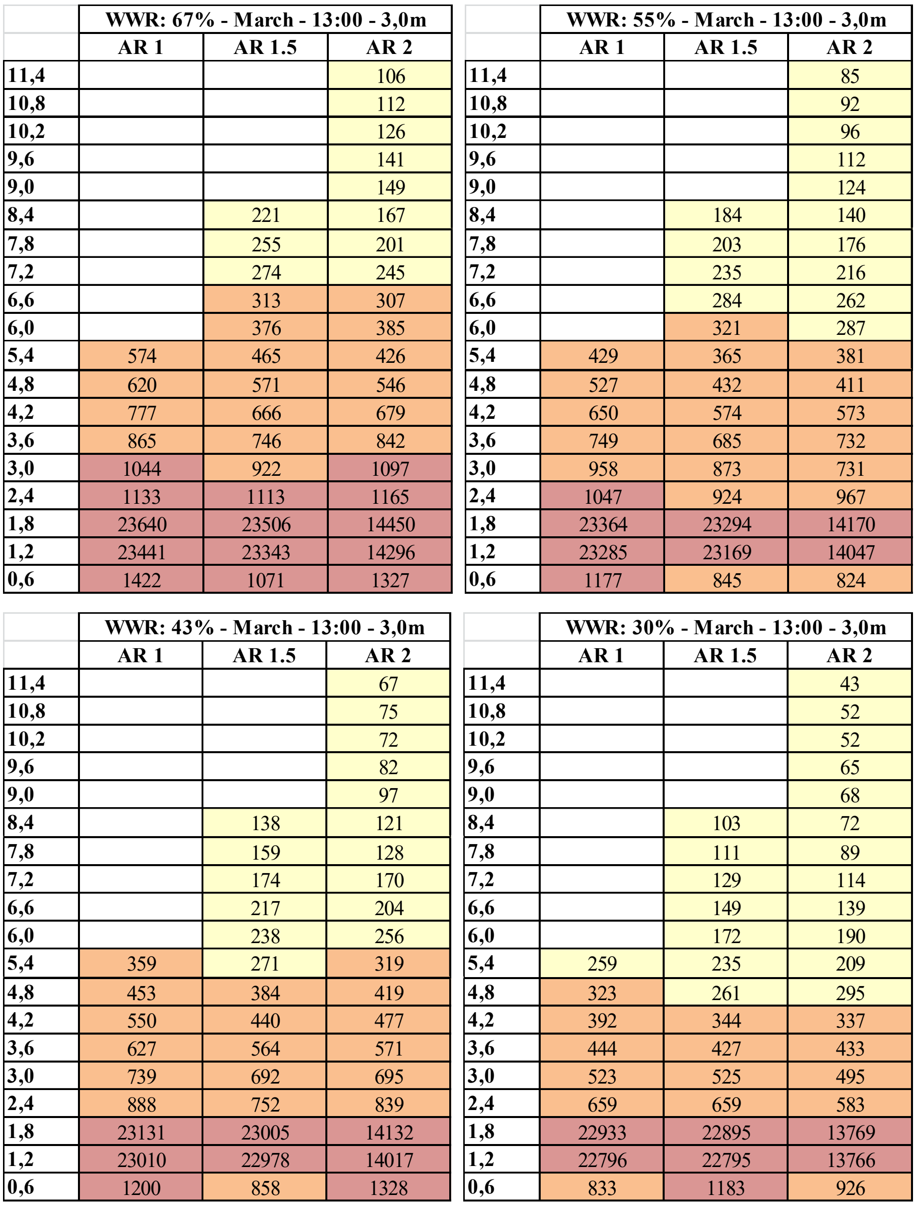


	WWR: 67 %	WWR: 55 %	WWR: 43 %	WWR: 30 %
Aspect Ratio: 2	**sDA: 48,54%** **ASE: 35,09%**	sDA: 45,03% ASE: 28,65%	sDA: 38,60% ASE: 19,88%	sDA: 25,73% ASE: 9,94%
Aspect Ratio: 1.5	sDA: 68,25% ASE: 47,92%	sDA: 61,90% ASE: 38,89%	**sDA: 51,59%** **ASE: 26,19%**	sDA: 34,92% ASE: 13,49%
Aspect Ratio: 1	sDA: 100,00% ASE: 77,78%	sDA: 100,00% ASE: 65,43%	sDA: 92,59% ASE: 40,74%	**sDA: 59,26%** **ASE: 20,99%**

Figure 4.17. The recommended WWR values for various room depths in terms of minimum IES requirements.

4.2.2. Results Based on WWR

This section explains the changes in effective daylit area depending on the room depth when the window-to-wall ratio is fixed. In the rooms with the same window-wall ratio (WWR), daylight distribution was evaluated considering the illuminance values in the middle row of the measurement plane which extend along the room depth. An example of the illuminance distribution according to simulations performed at 13 pm in March is shown in Figure 4.18.



	WWR: 67% - March - 13:00 - 3,0m		
	AR 1	**AR 1.5**	**AR 2**
11,4			106
10,8			112
10,2			126
9,6			141
9,0			149
8,4		221	167
7,8		255	201
7,2		274	245
6,6		313	307
6,0		376	385
5,4	574	465	426
4,8	620	571	546
4,2	777	666	679
3,6	865	746	842
3,0	1044	922	1097
2,4	1133	1113	1165
1,8	23640	23506	14450
1,2	23441	23343	14296
0,6	1422	1071	1327

	WWR: 55% - March - 13:00 - 3,0m		
	AR 1	**AR 1.5**	**AR 2**
11,4			85
10,8			92
10,2			96
9,6			112
9,0			124
8,4		184	140
7,8		203	176
7,2		235	216
6,6		284	262
6,0		321	287
5,4	429	365	381
4,8	527	432	411
4,2	650	574	573
3,6	749	685	732
3,0	958	873	731
2,4	1047	924	967
1,8	23364	23294	14170
1,2	23285	23169	14047
0,6	1177	845	824

	WWR: 43% - March - 13:00 - 3,0m		
	AR 1	**AR 1.5**	**AR 2**
11,4			67
10,8			75
10,2			72
9,6			82
9,0			97
8,4		138	121
7,8		159	128
7,2		174	170
6,6		217	204
6,0		238	256
5,4	359	271	319
4,8	453	384	419
4,2	550	440	477
3,6	627	564	571
3,0	739	692	695
2,4	888	752	839
1,8	23131	23005	14132
1,2	23010	22978	14017
0,6	1200	858	1328

	WWR: 30% - March - 13:00 - 3,0m		
	AR 1	**AR 1.5**	**AR 2**
11,4			43
10,8			52
10,2			52
9,6			65
9,0			68
8,4		103	72
7,8		111	89
7,2		129	114
6,6		149	139
6,0		172	190
5,4	259	235	209
4,8	323	261	295
4,2	392	344	337
3,6	444	427	433
3,0	523	525	495
2,4	659	659	583
1,8	22933	22895	13769
1,2	22796	22795	13766
0,6	833	1183	926

Figure 4.18. Variation of daylight distribution according to room depth in rooms with different WWR; illuminance below 300 lx (yellow), between 300 lx and 1000 lx (orange) and over 1000 lx (red).

According to Figure 4.17, when the WWR is 67%, the daylit area extends 6,6m away from window in the room of 12m and 9m depth. This distance is 5.4m in the room of 6m depth, which means that the entire room is daylit. The area exposed to illuminance over 1000 lx extends up to 3,0m; this corresponds to more than half of the floor area in the room of 6m depth.

In case the WWR is 55%, the daylit area receded to distance of 5.4 m and 6,0m from window in the room of 12m and 9m respectively. The area that receives illuminance over 1000 lx also receded to 1,8m away from window in these room depth alternatives. The area exposed to illuminance over 1000 lx receded by one measurement row in room of 6m depth. When WWR is 43%, the daylit area in the room of 9m fell behind the 6.0m row to 4.8m away from window. The area with illuminance more than 1000 lx receded to 1,8m from window in the room of 6m.

In the final case with 30% WWR, the area up to 4,2 m away from the window received enough daylight in the room of 9m and 12m. This area extended to 4,8m in the room of 6 m depth. The area exposed to direct sunlight remained the same.

The tables comparing the illuminance distributions for September, June and December are given in Appendix F. The daylit area reaches maximum and minimum depths in December and June, respectively. In December, the area up to 5.4 m away from the window is exposed to illuminance above 1000 lx. In summer, only the nearest measurement row to window receives excessive sunlight.

As mentioned in the previous sections, the depth of a daylit zone is considered to be 1.5 to 2 times the window head height in a standard sidelit space. In this case, the daylight area supposed to lie between 5,7m to 7,6m away from the window. Even though illuminance values decreased by the application of prismatic panels on window; this range is provided for all design alternatives except rooms with 30% window-wall ratio (WWR).

4.2.3. Results Based on Combinations of Room Depth-WWR

Results above indicate the relation between room depth and illuminance; and WWR and illuminance seperately. Here, the relation between design alternatives based on the combinations of room depth versus WWR, and daylight illuminance was analyzed by examining the nearest measurement rows on reference plane which satisfy the required illuminance, that is 300 lx (See Appendix B). For this, the results of the simulation performed at 13:00 in March were used. The floor area between window and the nearest measurement row defines the daylit area. So, statistical analysis, one way analysis of variance, was applied to find what the maximum floor area benefits from daylight when there is prismatic panel on window. The prismatic panel is effective within that area. The aim is to reach a conclusion with no relations between design alternatives according to daylight illuminance at those specific measurement rows. The null hypothesis is stated as below.

$H_0:\tau_i=0$; there is no relation among design alternatives according to illuminance (Table 4.2).

Table 4.2. Relation between design alternatives and illuminance.

Groups	*Count*	*Sum*	*Average*	*Variance*
Design alternative 1 (A.R:1, WWR: 30%)	9	3010	334.44	3042.03
Design alternative 2 (A.R: 1.5, WWR: 43%)	9	2922	324.67	2274.00
Design alternative 3 (A.R: 1.5, WWR: 55%)	9	2661	295.67	730.25
Design alternative 4 (A.R: 2, WWR: 67%)	9	3112	345.78	1083.94
Design alternative 5 (A.R: 2, WWR: 55%)	9	3087	343.00	814.50

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	14729.47	4	3682.37	2.32	0.074	2.60
Within Groups	63557.78	40	1588.94			
Total	78287.24	44				

According to by one-way analysis of variance, F value, 2.32, is less than F critic ($\alpha=0.05$, 4, 2.60 for 40). Accordingly, H_0 was accepted at 5% level of significance. It was concluded that daylight illuminance did not vary significantly according to design alternatives. So, the daylit area presents similarly satisfying daylight performance at each type of design alternative. Design alternative 1 (room with aspect ratio of 1—6m-room depth and 30% WWR) satisfies daylight criteria in almost 78% of floor area. Design alternative 2 (room with aspect ratio of 1.5 – 9m-room depth and 43% WWR) provides the daylit area with 57% floor area. Design alternative 3 (room with aspect ratio of 1.5 – 9m-room depth and 55% WWR) on the other hand satisfies daylight similarly with 71 % floor area. Almost 51 % floor area receives adequate daylight in

Design alternative 4 (room with aspect ratio of 2 – 12m-room depth and 67% WWR). A very slightly smaller floor area of 47% benefits from daylight in Design alternative 5 with a smaller window (room with aspect ratio of 2 – 12m-room depth and 55% WWR). Consequently, these WWR values have become the suggested/recommended ones for these corresponding room depths in this study.

4.3. Results of Multiple Regression Analysis

Performance evaluation of the prismatic system shows us minimum window areas specific to each aspect ratio in relation to room depth. When Aspect Ratio is 1, almost 78% of floor area satisfies the required minimum illuminance of 300 lx with 30% WWR. When Aspect Ratio is 1.5, almost 57% of floor area gets adequate daylight with 43% WWR. When Aspect Ratio is 2, almost 52% of floor area is under full of daylight with 67.5% WWR.

The initial step for evaluating the outputs of multiple regression analysis is to specify the coefficient of inferential statistical R^2, to applicate F-test to the regression equation. R^2 is an accurate criterion for the prediction outputs in supplementary studies of the model in future. R^2 is a value between 0–1. Values closer to 1 indicate that predicted data fits the actual data very well. Most of the changes in the dependent variable can be explained by independent variables (Chatterjee and Hadi 2015). Here, R^2 is found as 0.78 meaning that 78 percent of the change in illuminance can be explained by variables, room depth, WWR, point-x and point-y.

Table 4.3. Summary outputs of multiple lineer regression analysis.

Regression Statistics	
Multiple R	0,884929603
R Square	0,783100403
Adjusted R Square	0,782462463
Standard Error	142,3744012
Observations	1365

Regarding ANOVA results, a very low value of significance F(0.00) indicating the relation between variables and the illuminance is statistically significant at the level of *p*-value <.05. There was a significant impact of room depth, WWR, point–x and point-y on illuminance value at the *p* <.05 level, *(F (4,1360)=1227.55; p <.05).*

Table 4.4. Coefficients of the estimated model.

	Coefficients	*Standard Error*	*t Stat*	*p-value*
Intercept	406,5507784	22,20710807	18,30723645	4,26442E-67
room depth	-4,261033844	1,824677113	-2,335226224	0,019676415
wwr	8,376481959	0,28009153	29,90623081	1,9188E-151
point-x	-84,56381345	1,46971113	-57,53771045	0
point-y	15,20244599	2,441405343	6,22692419	6,32627E-10

As every *P*-value relating to each variable is below the significance level in Table 2, their significant effect on predicting illuminance is apparent. Minus indicator i.e. in room depth coefficient presents a negative relation that higher the room depth, lower the illuminance. Yet, higher the WWR, higher the illuminance. The most dominating variable becomes point-x, the least effecting one is room depth. Overall model is suitable for illuminance predictions. Using coefficients in the table, expected value of illuminance can be formulated (4.3) as below:

$$Illuminance = 406,55 - 4.26\ Room\ Depth + 8.38\ WWR - 84.56\ Point\text{-}x + 15.20\ Point\text{-}y \quad (4.3)$$

CHAPTER 5

DISCUSSIONS AND CONCLUSIONS

The subject matter of this study was the performance of prismatic panels attached in a south-facing, side-lit room with varying room depths and window-to-wall-ratios (WWR) in a simulation model and in a regression model. A deep-plan classroom (more than 2 times of window head height) in an educational building located at IZTECH Campus was chosen as the reference case on purpose to examine the prismatic panels' ability to deliver daylight beyond the typical effective daylight zone and provide sun shading for occupants seated near the window. In the climate of Izmir with predominantly sunny skies, it is not possible to achieve good daylighting performance with clear glazing alone since daylight levels varies dramatically. Therefore, it is assumed that prismatic panels would provide a more balanced distribution of daylight by avoiding excessive sunlight that cause negative impacts on occupants without reducing the required daylight level in interiors in such a geographic location.

There are several studies investigating the characteristics and performance of prismatic systems, especially in deep-plan office buildings. Different from those, the main objective of this study was proposing revisions to the daylighting standards by finding out the least possible WWR value in relation to room depth with consideration of prismatic systems in side windows. The second objective was presenting an alternative approach to computer simulation programs to predict illuminance in different room and window configurations when prismatic panels are installed.

The methodology was based on simulating a base model in Relux and testing it with alternative models composed of incrementally defined WWR and room depth configurations. The determination of new design alternatives was based on daylighting standards regarding minimum acceptable window sizes and room depths in side lighted rooms and related previous studies in literature. In the evaluation process two current daylight metrics were used, namely sDA and ASE. The sDA presents the annual sufficiency of daylight levels with illuminance threshold of 300 lx, while ASE presents the potential risk of excessive sunlight penetration with illuminance threshold of 1000 lx across the work plane. Further, Relux outputs were used as inputs in constructing a multiple regression model to analyse the relation between room depth, window-to-wall-ratio(WWR) and daylight illuminance.

Following the application of prismatic panels on windows in each room depth-WWR configurations, the minimum WWR is found to be 67% in room of 12m depth, 43% in room of 9m depth and 30% in room of 6m depth. The system is more effective in deeper rooms; it decreases illuminance above 1000 lx which is associated with visual and thermal discomfort, and satisfying required daylight illuminance at least half of the area. Owing to their optical properties and daylight redirection ability, prismatic panels allow optimum amount of daylight entering in the room and offer better daylighting performance compared to a room equipped with conventional shading devices.

The measurements were performed under clear sky conditions for equinox and solstice days in order to examine distinctly the effect of prismatic panels in protection against direct sun and redirection of daylight. At high sun angles in summer, the significant drop in the number of measurement points with illuminance above 1000 lx indicates that prismatic panels are successful to enhance the room's daylighting while shading direct sunlight. On clear winter days, direct sunlight penetrated deeper inside the room at low sun angles and increased the illuminance values throughout the area, but bright patches occurred on surfaces due to the failure of the panels to provide sun shading.

Regarding sDA and ASE calculations, the most satisfying sDA value according to IES recommendations was found to be 48,54% in room of 12m depth with 67% WWR. In room of 9m depth, an sDA of 61,90% and 51,59% was achieved with WWR 55% and WWR 43% respectively. Finally, an sDA of 59,26% was achieved with the smallest WWR alternative of 30% in room of 6m depth. The ASE values calculated annually for each room depth-WWR alternatives were found greater than 7%, which is usually rated as unacceptable by IES for typical office cases. However, when these values were calculated on a monthly basis, it was observed that the reason of high ASE was the excessive sunlight exposure during winter months. The most satisfying values were found in summer; an MSE of 9,94% was found in room of 12m depth with 67% WWR. An MSE of 5,56% and 4,76% was achieved in room of 9m depth with 55% WWR and 43% WWR respectively. In room of 6m depth and 30% WWR, the MSE was found to be 20,99%. Keeping the climatic data of Izmir in mind, it can be said that ASE values may actually be lower as the majority of cloudy days are in winter months.

Depending on the daylighting objectives at the initial design phase, these values can give guidance to building professionals in choosing the optimal WWR for different room depths according to the latest daylight metrics.

The results also indicates that, the sDA value can be estimated approximately by finding out the percentage of the analysis area that exceeding illuminance of 300 lx regardless of a specific time fraction. In contrast, the ASE cannot be estimated in the same way since the difference between the percentage of the area with illuminance of over 1000 lx and the ASE obtained was quite high due to the specific time limit of 250 hours. Still, this can be the practical way of predicting daylight adequacy in space during the design phase.

Findings regarding statistical analysis show that the multiple regression model estimates daylight illuminance in a room with prismatic panels with a 78% prediction rate. This means 78 percent of the change in illuminance can be explained by formula based on variables, room depth, WWR, point-x and point-y. According to formula, the most dominating variable became point-x while the least effecting one is room depth. The computer simulation programs are not always useful due to their complexity and difficulty in accessibility. The new approach would be less time-consuming and beneficial in predicting the illuminance value of a point in given space.

Initially, this thesis would make a contribution to the literature establishing availability of the 'useful' daylight, i.e. daylight without over-exposure, in side lighted rooms in terms of improving visual performance, and thus motivation, productivity and well-being of occupants. The current daylighting standards and related previous studies in the literature include required window sizes for different room geometries, but these are restricted to conventional fenestration systems. However, this study emphasizes that a clear glazing without any daylighting system is inadequate to meet the visual performance requirements of the spaces used mostly during the daytime such as educational and office buildings. It has been shown that it is possible to control and use daylight efficiently with the application of advanced daylighting systems such as prismatic panels on vertical windows. The consideration of such systems simultaneously with the facade openings in the early design stages is more favourable in terms of avoiding problems related to the amount and distribution of daylight. Therefore, this study suggests new optimal window-to-wall ratios (WWR) in relation with varying room depths when prismatic panels attached in side windows and recommends rethinking of daylighting requirements mentioned in current daylighting standards. Additively, the proposed mathematical model can be an alternative to computer simulation programs for estimating illuminance values in different room depth and WWR alternatives with prismatic panels on fenestration.

It is expected that this study will provide knowledge about the improvement of visual conditions using advanced lighting systems in rooms with different room depth and window-to-wall ratios (WWR) for designers, researchers and others who interested in lighting design. Furthermore, some of the issues that cannot be addressed in this study due to limitations may be a subject of future works based on these noteworthy findings, as stated below:

- The prismatic panel model used in the study is manufactured by the company Siteco. The prism angle (45°) and slat angle (30°) of the panels modeled in Relux is based on real scale samples obtained directly from the manufacturers. However, in order to optimize visual conditions, the performance of different prism angles can be examined depending on the location and orientation of the room and the panels can be tilted (different slat angles) according to the position of the sun throughout the year.
- The simulations were carried out only on equinox and solstice days at three different times (e.g. 10:00 am, 13:00 and 16:00 pm) using sky model of Izmir and daylighting performance evaluations were made according to these results. In a further study, dynamic daylight simulations that take into account the annual working hours and climatic conditions of Izmir can be performed to achieve more accurate results (e.g. sDA and ASE values).
- This study was restricted to the use of natural light to examine the effect of prismatic panels on visual performance of rooms with different room depth and window sizes. Further, artificial lighting can be used in conjunction with daylight and potential energy savings/consumption can be calculated especially for the rear part of the room where sufficient daylight cannot be received.
- In this study, visual performance evaluations were carried out based only on quantitative criteria i.e. task illuminance as in lighting standards. Additionally, luminous conditions can be addressed since qualitative aspects such as glare and other factors that occupants might experience are more relevant and useful (Boubekri 2014).

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APPENDIX A

POSITION OF THE MEASUREMENT POINTS IN SIMULATION MODELS

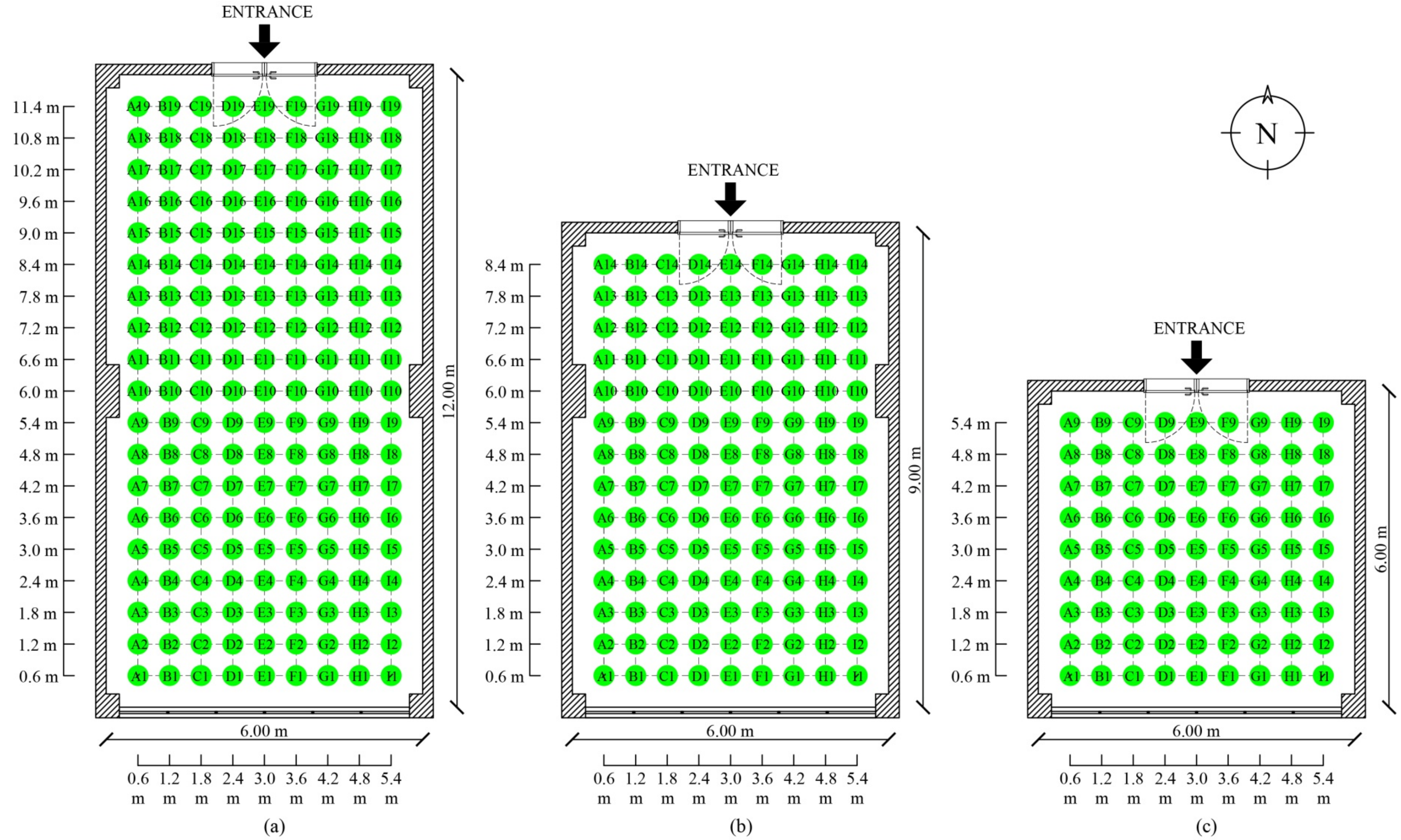
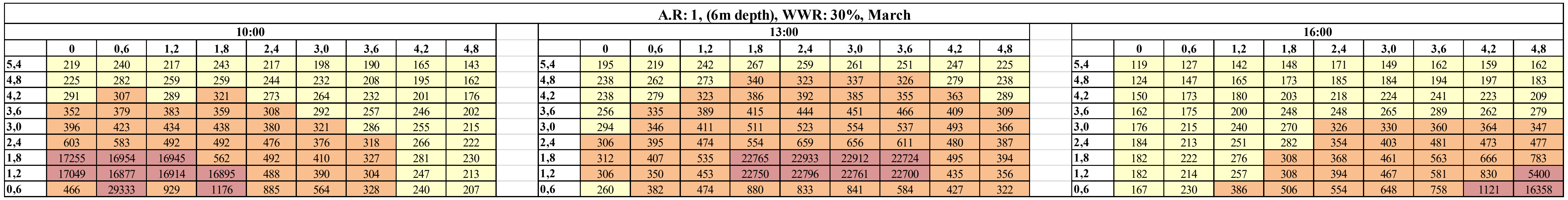


Figure A.1. Position of the measurement points in the room of (a) 12m depth, (b) 9m depth and (c) 6m depth.

APPENDIX B

COLORED TABLES BASED ON DIFFERENT DAYLIGHT LEVELS



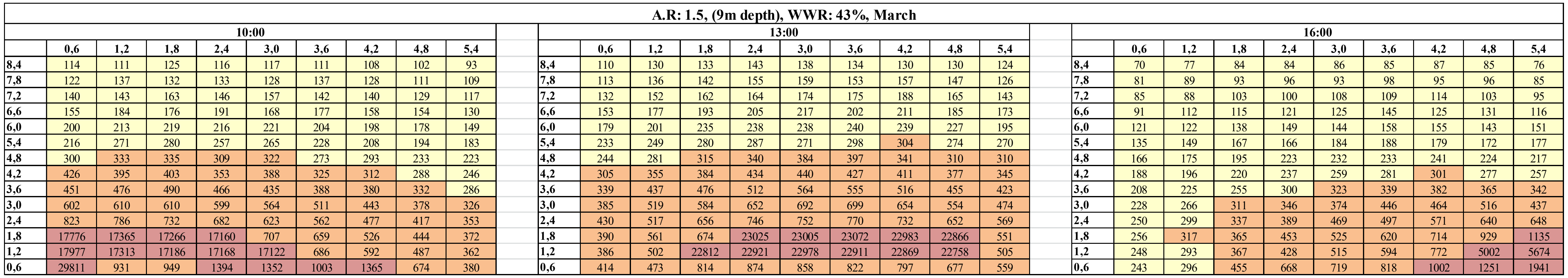
A.R: 1, (6m depth), WWR: 30%, March

	10:00								
	0	0,6	1,2	1,8	2,4	3,0	3,6	4,2	4,8
5,4	219	240	217	243	217	198	190	165	143
4,8	225	282	259	259	244	232	208	195	162
4,2	291	307	289	321	273	264	232	201	176
3,6	352	379	383	359	308	292	257	246	202
3,0	396	423	434	438	380	321	286	255	215
2,4	603	583	492	492	476	376	318	266	222
1,8	17255	16954	16945	562	492	410	327	281	230
1,2	17049	16877	16914	16895	488	390	304	247	213
0,6	466	29333	929	1176	885	564	328	240	207

	13:00								
	0	0,6	1,2	1,8	2,4	3,0	3,6	4,2	4,8
5,4	195	219	242	267	259	261	251	247	225
4,8	238	262	273	340	323	337	326	279	238
4,2	238	279	323	386	392	385	355	363	289
3,6	256	335	389	415	444	451	466	409	309
3,0	294	346	411	511	523	554	537	493	366
2,4	306	395	474	554	659	656	611	480	387
1,8	312	407	535	22765	22933	22912	22724	495	394
1,2	306	350	453	22750	22796	22761	22700	435	356
0,6	260	382	474	880	833	841	584	427	322

	16:00								
	0	0,6	1,2	1,8	2,4	3,0	3,6	4,2	4,8
5,4	119	127	142	148	171	149	162	159	162
4,8	124	147	165	173	185	184	194	197	183
4,2	150	173	180	203	218	224	241	223	209
3,6	162	175	200	248	248	265	289	262	279
3,0	176	215	240	270	326	330	360	364	347
2,4	184	213	251	282	354	403	481	473	477
1,8	182	222	276	308	368	461	563	666	783
1,2	182	214	257	308	394	467	581	830	5400
0,6	167	230	386	506	554	648	758	1121	16358

Figure B.1.Illuminance distribution in a room of 6m depth with 30% WWR; illuminance below 300 lx (yellow), between 300 lx and 1000 lx (orange) and above 1000 lx (red).



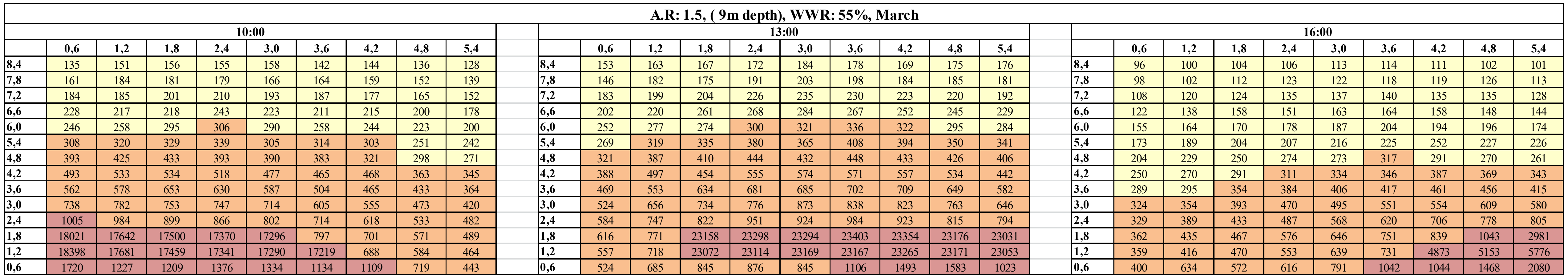
A.R: 1.5, (9m depth), WWR: 43%, March

	10:00								
	0,6	1,2	1,8	2,4	3,0	3,6	4,2	4,8	5,4
8,4	114	111	125	116	117	111	108	102	93
7,8	122	137	132	133	128	137	128	111	109
7,2	140	143	163	146	157	142	140	129	117
6,6	155	184	176	191	168	177	158	154	130
6,0	200	213	219	216	221	204	198	178	149
5,4	216	271	280	257	265	228	208	194	183
4,8	300	333	335	309	322	273	293	233	223
4,2	426	395	403	353	388	325	312	288	246
3,6	451	476	490	466	435	388	380	332	286
3,0	602	610	610	599	564	511	443	378	326
2,4	823	786	732	682	623	562	477	417	353
1,8	17776	17365	17266	17160	707	659	526	444	372
1,2	17977	17313	17186	17168	17122	686	592	487	362
0,6	29811	931	949	1394	1352	1003	1365	674	380

	13:00								
	0,6	1,2	1,8	2,4	3,0	3,6	4,2	4,8	5,4
8,4	110	130	133	143	138	134	130	130	124
7,8	113	136	142	155	159	153	157	147	126
7,2	132	152	162	164	174	175	188	165	143
6,6	153	177	193	205	217	202	211	185	173
6,0	179	201	235	238	238	240	239	227	195
5,4	233	249	280	287	271	298	304	274	270
4,8	244	281	315	340	384	397	341	310	310
4,2	305	355	384	434	440	427	411	377	345
3,6	339	437	476	512	564	555	516	455	423
3,0	385	519	584	652	692	699	654	554	474
2,4	430	517	656	746	752	770	732	652	569
1,8	390	561	674	23025	23005	23072	22983	22866	551
1,2	386	502	22812	22921	22978	22911	22869	22758	505
0,6	414	473	814	874	858	822	797	677	559

	16:00								
	0,6	1,2	1,8	2,4	3,0	3,6	4,2	4,8	5,4
8,4	70	77	84	84	86	85	87	85	76
7,8	81	89	93	96	93	98	95	96	85
7,2	85	88	103	100	108	109	114	103	95
6,6	91	112	115	121	125	145	125	131	116
6,0	121	122	138	149	144	158	155	143	151
5,4	135	149	167	166	184	188	179	172	177
4,8	166	175	195	223	232	233	241	224	217
4,2	188	196	220	237	259	281	301	277	257
3,6	208	225	255	300	323	339	382	365	342
3,0	228	266	311	346	374	446	464	516	437
2,4	250	299	337	389	469	497	571	640	648
1,8	256	317	365	453	525	620	714	929	1135
1,2	248	293	367	428	515	594	772	5002	5674
0,6	243	296	455	668	719	818	1002	1251	1941

Figure B.2. Illuminance distribution in a room of 9m depth with 43% WWR; illuminance below 300 lx (yellow), between 300 lx and 1000 lx (orange) and above 1000 lx (red).



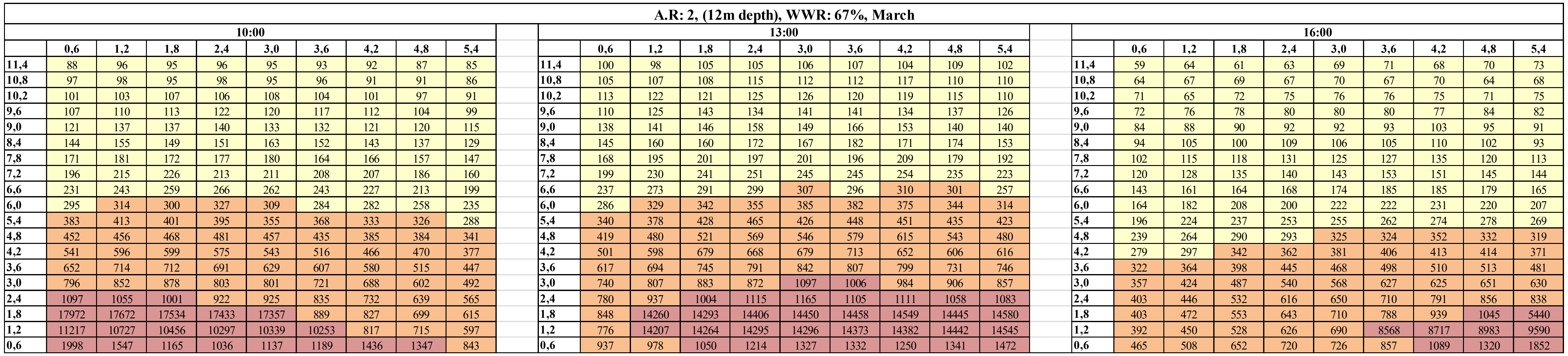
A.R: 1.5, (9m depth), WWR: 55%, March

	10:00								
	0,6	1,2	1,8	2,4	3,0	3,6	4,2	4,8	5,4
8,4	135	151	156	155	158	142	144	136	128
7,8	161	184	181	179	166	164	159	152	139
7,2	184	185	201	210	193	187	177	165	152
6,6	228	217	218	243	223	211	215	200	178
6,0	246	258	295	306	290	258	244	223	200
5,4	308	320	329	339	305	314	303	251	242
4,8	393	425	433	393	390	383	321	298	271
4,2	493	533	534	518	477	465	468	363	345
3,6	562	578	653	630	587	504	465	433	364
3,0	738	782	753	747	714	605	555	473	420
2,4	1005	984	899	866	802	714	618	533	482
1,8	18021	17642	17500	17370	17296	797	701	571	489
1,2	18398	17681	17459	17341	17290	17219	688	584	464
0,6	1720	1227	1209	1376	1334	1134	1109	719	443

	13:00								
	0,6	1,2	1,8	2,4	3,0	3,6	4,2	4,8	5,4
8,4	153	163	167	172	184	178	169	175	176
7,8	146	182	175	191	203	198	184	185	181
7,2	183	199	204	226	235	230	223	220	192
6,6	202	220	261	268	284	267	252	245	229
6,0	252	277	274	300	321	336	322	295	284
5,4	269	319	335	380	365	408	394	350	341
4,8	321	387	410	444	432	448	433	426	406
4,2	388	497	454	555	574	571	557	534	442
3,6	469	553	634	681	685	702	709	649	582
3,0	524	656	734	776	873	838	823	763	646
2,4	584	747	822	951	924	984	923	815	794
1,8	616	771	23158	23298	23294	23403	23354	23176	23031
1,2	557	718	23072	23114	23169	23167	23265	23171	23053
0,6	524	685	845	876	845	1106	1493	1583	1023

	16:00								
	0,6	1,2	1,8	2,4	3,0	3,6	4,2	4,8	5,4
8,4	96	100	104	106	113	114	111	102	101
7,8	98	102	112	123	122	118	119	126	113
7,2	108	120	124	135	137	140	135	135	128
6,6	122	138	158	151	163	164	158	148	144
6,0	155	164	170	178	187	204	194	196	174
5,4	173	189	204	207	216	225	252	227	226
4,8	204	229	250	274	273	317	291	270	261
4,2	250	270	291	311	334	346	387	369	343
3,6	289	295	354	384	406	417	461	456	415
3,0	324	354	393	470	495	551	554	609	580
2,4	329	389	433	487	568	620	706	778	805
1,8	362	435	467	576	646	751	839	1043	2981
1,2	359	416	470	553	639	731	4873	5153	5776
0,6	400	634	572	616	791	1042	1044	1468	2080

Figure B.3. Illuminance distribution in a room of 9m depth with 55% WWR; illuminance below 300 lx (yellow), between 300 lx and 1000 lx (orange) and above 1000 lx (red).



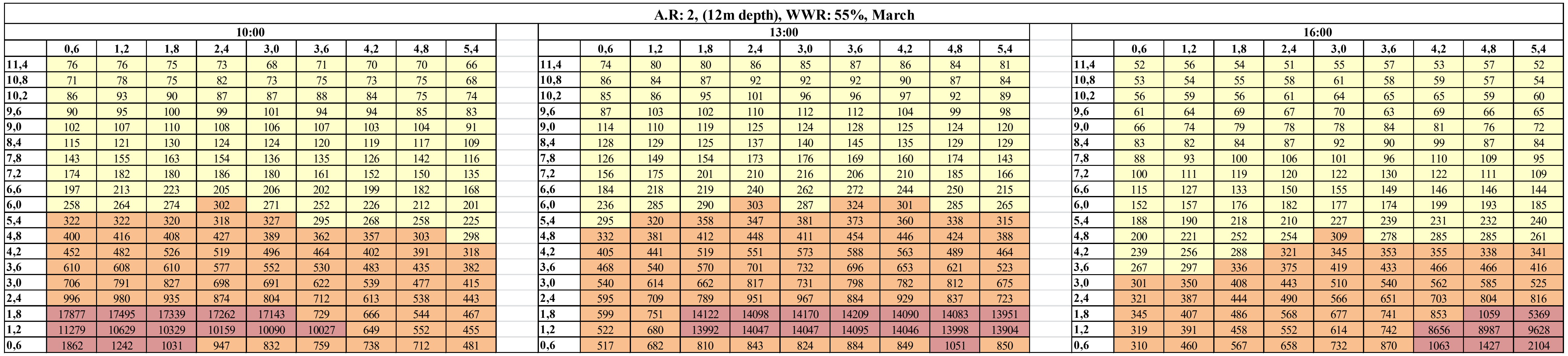
A.R: 2, (12m depth), WWR: 67%, March

	10:00								
	0,6	1,2	1,8	2,4	3,0	3,6	4,2	4,8	5,4
11,4	88	96	95	96	95	93	92	87	85
10,8	97	98	95	98	95	96	91	91	86
10,2	101	103	107	106	108	104	101	97	91
9,6	107	110	113	122	120	117	112	104	99
9,0	121	137	137	140	133	132	121	120	115
8,4	144	155	149	151	163	152	143	137	129
7,8	171	181	172	177	180	164	166	157	147
7,2	196	215	226	213	211	208	207	186	160
6,6	231	243	259	266	262	243	227	213	199
6,0	295	314	300	327	309	284	282	258	235
5,4	383	413	401	395	355	368	333	326	288
4,8	452	456	468	481	457	435	385	384	341
4,2	541	596	599	575	543	516	466	470	377
3,6	652	714	712	691	629	607	580	515	447
3,0	796	852	878	803	801	721	688	602	492
2,4	1097	1055	1001	922	925	835	732	639	565
1,8	17972	17672	17534	17433	17357	889	827	699	615
1,2	11217	10727	10456	10297	10339	10253	817	715	597
0,6	1998	1547	1165	1036	1137	1189	1436	1347	843

	13:00								
	0,6	1,2	1,8	2,4	3,0	3,6	4,2	4,8	5,4
11,4	100	98	105	105	106	107	104	109	102
10,8	105	107	108	115	112	112	117	110	110
10,2	113	122	121	125	126	120	119	115	110
9,6	110	125	143	134	141	141	134	137	126
9,0	138	141	146	158	149	166	153	140	140
8,4	145	160	160	172	167	182	171	174	153
7,8	168	195	201	197	201	196	209	179	192
7,2	199	230	241	251	245	245	254	235	223
6,6	237	273	291	299	307	296	310	301	257
6,0	286	329	342	355	385	382	375	344	314
5,4	340	378	428	465	426	448	451	435	423
4,8	419	480	521	569	546	579	615	543	480
4,2	501	598	679	668	679	713	652	606	616
3,6	617	694	745	791	842	807	799	731	746
3,0	740	807	883	872	1097	1006	984	906	857
2,4	780	937	1004	1115	1165	1105	1111	1058	1083
1,8	848	14260	14293	14406	14450	14458	14549	14445	14580
1,2	776	14207	14264	14295	14296	14373	14382	14442	14545
0,6	937	978	1050	1214	1327	1332	1250	1341	1472

	16:00								
	0,6	1,2	1,8	2,4	3,0	3,6	4,2	4,8	5,4
11,4	59	64	61	63	69	71	68	70	73
10,8	64	67	69	67	70	67	70	64	68
10,2	71	65	72	75	76	76	75	71	75
9,6	72	76	78	80	80	80	77	84	82
9,0	84	88	90	92	92	93	103	95	91
8,4	94	105	100	109	106	105	110	102	93
7,8	102	115	118	131	125	127	135	120	113
7,2	120	128	135	140	143	153	151	145	144
6,6	143	161	164	168	174	185	185	179	165
6,0	164	182	208	200	222	222	231	220	207
5,4	196	224	237	253	255	262	274	278	269
4,8	239	264	290	293	325	324	352	332	319
4,2	279	297	342	362	381	406	413	414	371
3,6	322	364	398	445	468	498	510	513	481
3,0	357	424	487	540	568	627	625	651	630
2,4	403	446	532	616	650	710	791	856	838
1,8	403	472	553	643	710	788	939	1045	5440
1,2	392	450	528	626	690	8568	8717	8983	9590
0,6	465	508	652	720	726	857	1089	1320	1852

Figure B.4. Illuminance distribution in a room of 12m depth with 67% WWR; illuminance below 300 lx (yellow), between 300 lx and 1000 lx (orange) and above 1000 lx (red).



A.R: 2, (12m depth), WWR: 55%, March

	10:00								
	0,6	1,2	1,8	2,4	3,0	3,6	4,2	4,8	5,4
11,4	76	76	75	73	68	71	70	70	66
10,8	71	78	75	82	73	75	73	75	68
10,2	86	93	90	87	87	88	84	75	74
9,6	90	95	100	99	101	94	94	85	83
9,0	102	107	110	108	106	107	103	104	91
8,4	115	121	130	124	124	120	119	117	109
7,8	143	155	163	154	136	135	126	142	116
7,2	174	182	180	186	180	161	152	150	135
6,6	197	213	223	205	206	202	199	182	168
6,0	258	264	274	302	271	252	226	212	201
5,4	322	322	320	318	327	295	268	258	225
4,8	400	416	408	427	389	362	357	303	298
4,2	452	482	526	519	496	464	402	391	318
3,6	610	608	610	577	552	530	483	435	382
3,0	706	791	827	698	691	622	539	477	415
2,4	996	980	935	874	804	712	613	538	443
1,8	17877	17495	17339	17262	17143	729	666	544	467
1,2	11279	10629	10329	10159	10090	10027	649	552	455
0,6	1862	1242	1031	947	832	759	738	712	481

	13:00								
	0,6	1,2	1,8	2,4	3,0	3,6	4,2	4,8	5,4
11,4	74	80	80	86	85	87	86	84	81
10,8	86	84	87	92	92	92	90	87	84
10,2	85	86	95	101	96	96	97	92	89
9,6	87	103	102	110	112	112	104	99	98
9,0	114	110	119	125	124	128	125	124	120
8,4	128	129	125	137	140	145	135	129	129
7,8	126	149	154	173	176	169	160	174	143
7,2	156	175	201	210	216	206	210	185	166
6,6	184	218	219	240	262	272	244	250	215
6,0	236	285	290	303	287	324	301	285	265
5,4	295	320	358	347	381	373	360	338	315
4,8	332	381	412	448	411	454	446	424	388
4,2	405	441	519	551	573	588	563	489	464
3,6	468	540	570	701	732	696	653	621	523
3,0	540	614	662	817	731	798	782	812	675
2,4	595	709	789	951	967	884	929	837	723
1,8	599	751	14122	14098	14170	14209	14090	14083	13951
1,2	522	680	13992	14047	14047	14095	14046	13998	13904
0,6	517	682	810	843	824	884	849	1051	850

	16:00								
	0,6	1,2	1,8	2,4	3,0	3,6	4,2	4,8	5,4
11,4	52	56	54	51	55	57	53	57	52
10,8	53	54	55	58	61	58	59	57	54
10,2	56	59	56	61	64	65	65	59	60
9,6	61	64	69	67	70	63	69	66	65
9,0	66	74	79	78	78	84	81	76	72
8,4	83	82	84	87	92	90	99	87	84
7,8	88	93	100	106	101	96	110	109	95
7,2	100	111	119	120	122	130	122	111	109
6,6	115	127	133	150	155	149	146	146	144
6,0	152	157	176	182	177	174	199	193	185
5,4	188	190	218	210	227	239	231	232	240
4,8	200	221	252	254	309	278	285	285	261
4,2	239	256	288	321	345	353	355	338	341
3,6	267	297	336	375	419	433	466	466	416
3,0	301	350	408	443	510	540	562	585	525
2,4	321	387	444	490	566	651	703	804	816
1,8	345	407	486	568	677	741	853	1059	5369
1,2	319	391	458	552	614	742	8656	8987	9628
0,6	310	460	567	658	732	870	1063	1427	2104

Figure B.5. Illuminance distribution in a room of 12m depth with 55% WWR; illuminance below 300 lx (yellow), between 300 lx and 1000 lx (orange) and above 1000 lx (red).

APPENDIX C

VARIATIONS OF ILLUMINANCE VALUES FOR EACH WINDOW-TO-WALL (WWR) BASED ON ROOM DEPTH

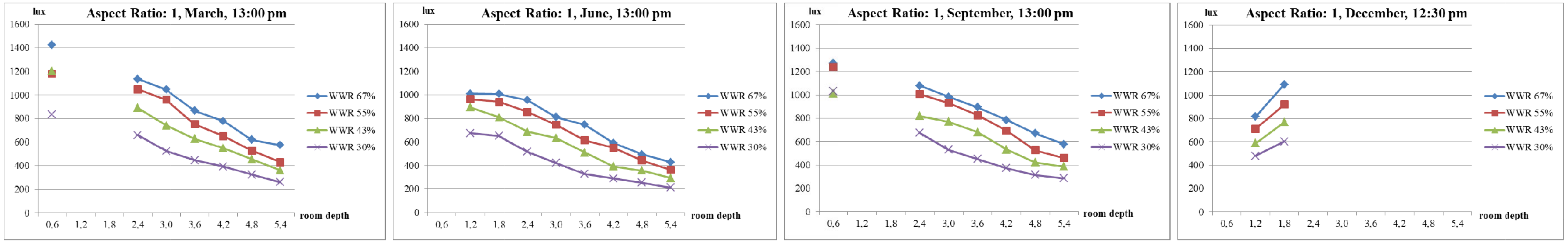


Figure C.1. Variations of illuminance values according to window-to-wall ratio (WWR) in room of 6m depth; in March, June, September and December.

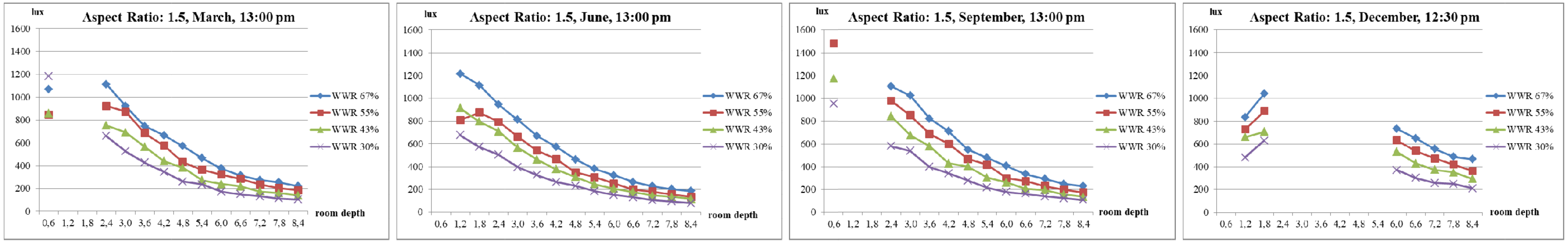


Figure C.2. Variations of illuminance values according to window-to-wall ratio (WWR) in room of 9m depth; in March, June, September and December.

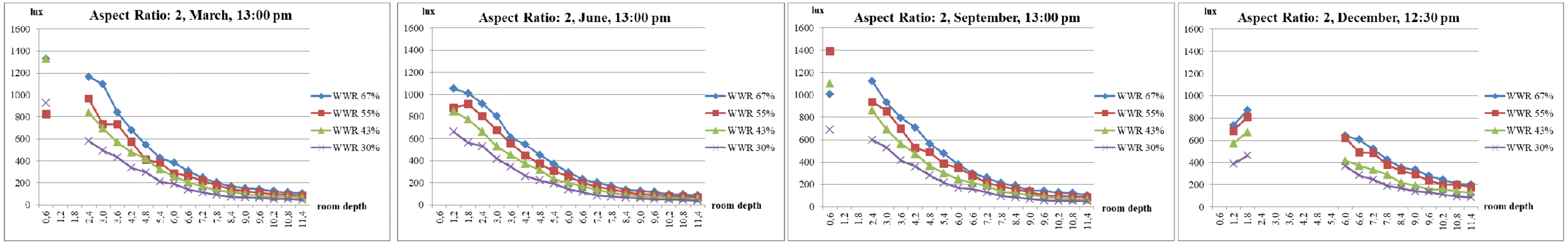
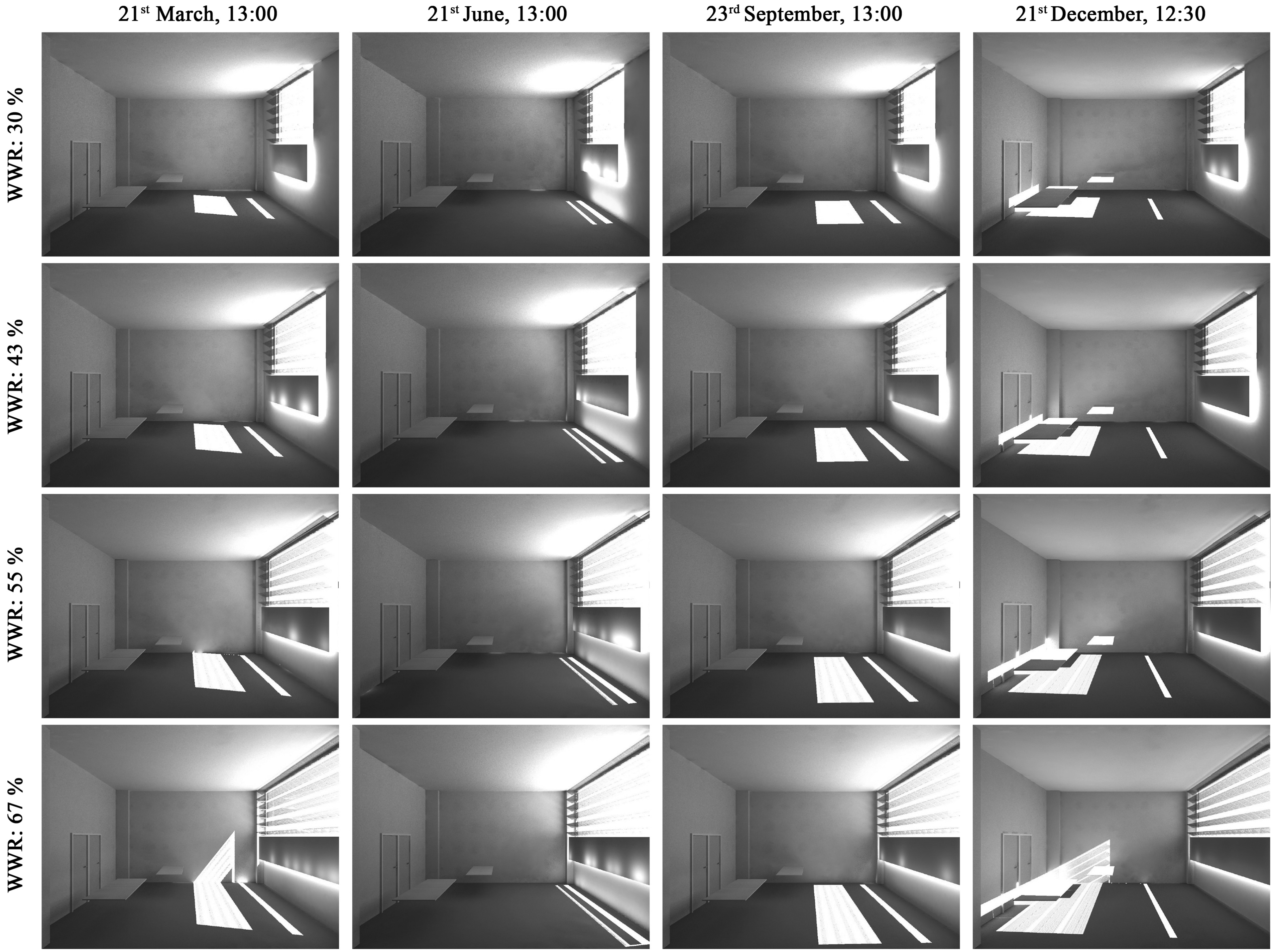


Figure C.3. Variations of illuminance values according to window-to-wall ratio (WWR) in room of 12m depth; in March, June, September and December.

APPENDIX D

INTERIOR RENDERINGS OF EACH ROOM DEPTH-WWR CONFIGURATION ON EQUINOX AND SOLSTICE DAYS AT NOON



21st March, 13:00

21st June, 13:00

23rd September, 13:00

21st December, 12:30

WWR: 30 %

WWR: 43 %

WWR: 55 %

WWR: 67 %

Figure D.1. Interior renderings of the room with Aspect Ratio: 1 (6m depth), on solstice and equinox days at noon.

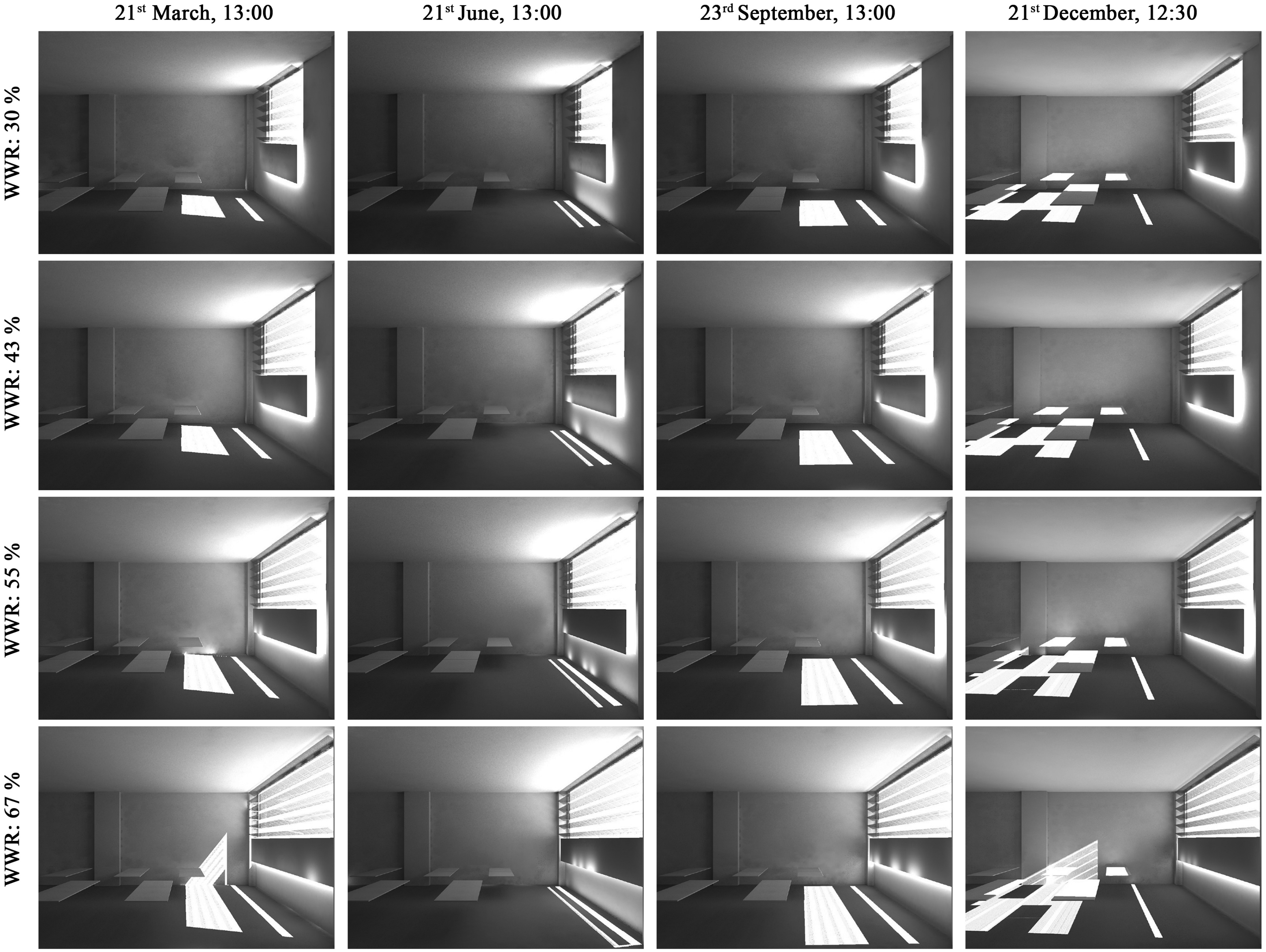


Figure D.2. Interior renderings of the room with Aspect Ratio: 1.5 (9m depth), on solstice and equinox days at noon.

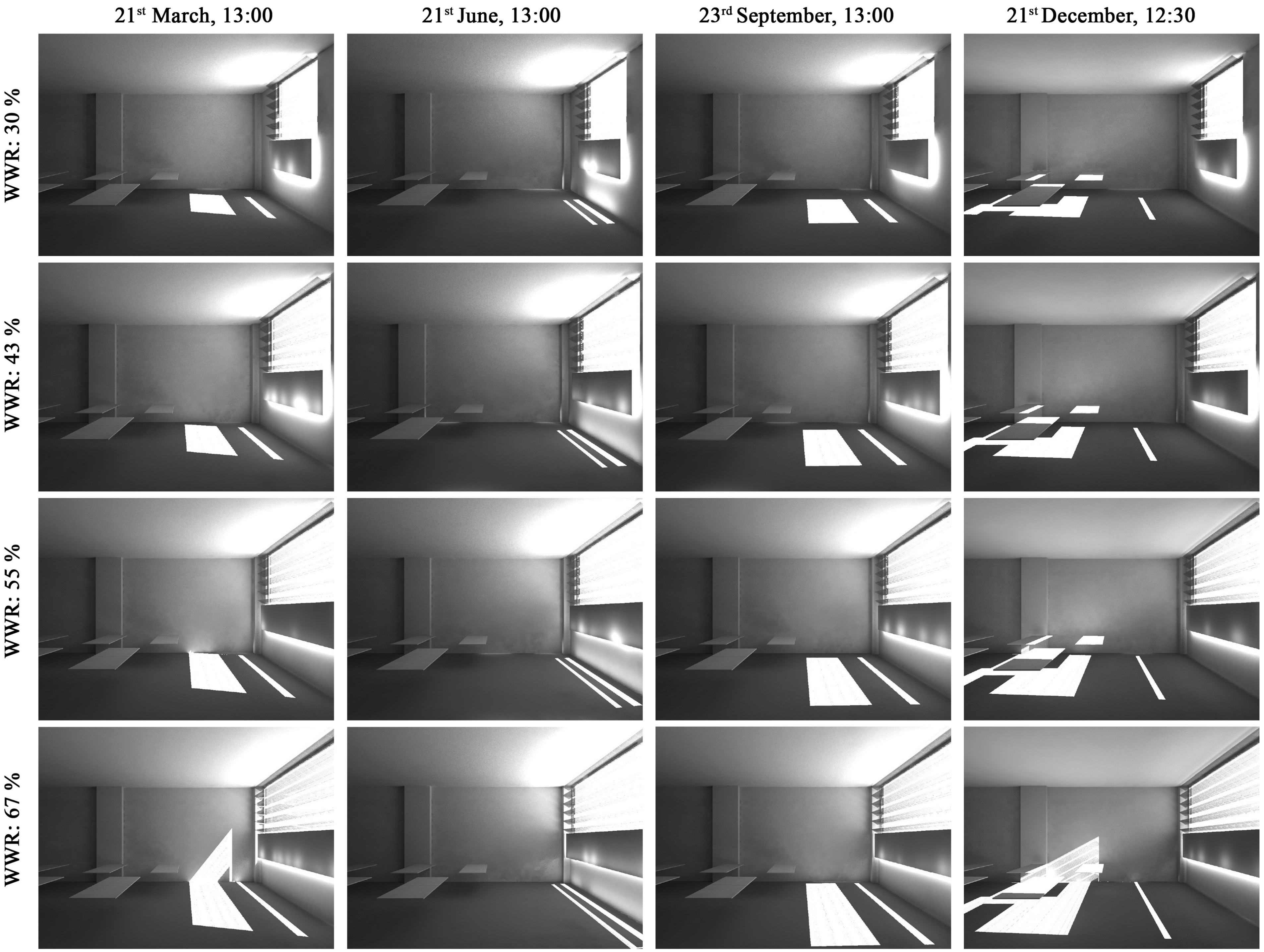


Figure D.3. Interior renderings of the room with Aspect Ratio: 2 (12m depth), on solstice and equinox days at noon.

APPENDIX E

PERCENTAGE OF DECREASES IN ILLUMINANCE COMPARED TO ROOM WITH CLEAR GLAZING WHEN PRISMATIC PANELS ATTACHED ON WINDOWS

Table E.1. Percentage of decreases in illuminance compared to room with clear glazing for each room depth-WWR alternatives.

		12 M DEPTH	**9 M DEPTH**	**6 M DEPTH**
WWR 67%	I > 300 lx	35,56 %	29,05 %	1,23 %
	I > 1000 lx	69,65 %	69,43 %	68,10 %
WWR 55%	I > 300 lx	36,80 %	34,74 %	5,56 %
	I > 1000 lx	74,25 %	73,00 %	72,22 %
WWR 43%	I > 300 lx	43,84 %	42,59 %	14,98 %
	I > 1000 lx	77,20 %	76,39 %	76,13 %
WWR 30%	I > 300 lx	56,30 %	56,25 %	43,43 %
	I > 1000 lx	78,70 %	76,59 %	78,07 %

APPENDIX F

CHANGES IN EFFECTIVE DAYLIT ZONE

	WWR: 67% - June - 13:00 - 3,0m		
	AR 1	**AR 1.5**	**AR 2**
11,4			87
10,8			93
10,2			96
9,6			117
9,0			126
8,4		187	136
7,8		203	171
7,2		229	200
6,6		264	231
6,0		324	293
5,4	428	380	369
4,8	494	464	452
4,2	592	572	545
3,6	745	671	610
3,0	812	812	801
2,4	955	944	913
1,8	1009	1115	1009
1,2	1009	1218	1050
0,6	7472	8066	4917

	WWR: 55% - June - 13:00 - 3,0m		
	AR 1	**AR 1.5**	**AR 2**
11,4			71
10,8			75
10,2			79
9,6			91
9,0			99
8,4		133	113
7,8		156	141
7,2		182	164
6,6		200	198
6,0		252	256
5,4	362	306	304
4,8	442	349	370
4,2	550	467	448
3,6	615	542	556
3,0	746	663	675
2,4	854	793	802
1,8	941	876	910
1,2	963	810	878
0,6	4531	6723	4521

	WWR: 43% - June - 13:00 - 3,0m		
	AR 1	**AR 1.5**	**AR 2**
11,4			57
10,8			60
10,2			66
9,6			72
9,0			76
8,4		117	93
7,8		133	109
7,2		145	136
6,6		177	166
6,0		206	200
5,4	293	246	231
4,8	357	308	317
4,2	393	377	370
3,6	511	463	450
3,0	634	565	528
2,4	687	709	660
1,8	810	796	773
1,2	893	913	845
0,6	7056	7434	4649

	WWR: 30% - June - 13:00 - 3,0m		
	AR 1	**AR 1.5**	**AR 2**
11,4			37
10,8			43
10,2			48
9,6			50
9,0			59
8,4		79	65
7,8		92	75
7,2		104	83
6,6		129	115
6,0		150	141
5,4	214	184	190
4,8	253	230	222
4,2	288	265	259
3,6	328	326	345
3,0	422	395	417
2,4	516	503	530
1,8	651	572	564
1,2	673	678	661
0,6	4776	7288	4730

Figure F.1. Variations of illuminance distribution on 21st June; illuminance below 300 lx (yellow), between 300 lx and 1000 lx (orange) and above 1000 lx (red).

	WWR: 67% - September - 13:00 - 3,0m		
	AR 1	**AR 1.5**	**AR 2**
11,4			105
10,8			123
10,2			128
9,6			144
9,0			146
8,4		229	188
7,8		247	211
7,2		293	258
6,6		335	300
6,0		407	377
5,4	579	478	476
4,8	671	548	565
4,2	785	712	707
3,6	893	823	794
3,0	983	1024	931
2,4	1078	1106	1122
1,8	24069	24174	14780
1,2	23995	24188	14628
0,6	1272	2052	1007

	WWR: 55% - September - 13:00 - 3,0m		
	AR 1	**AR 1.5**	**AR 2**
11,4			88
10,8			91
10,2			98
9,6			107
9,0			132
8,4		173	157
7,8		199	182
7,2		229	215
6,6		273	277
6,0		298	347
5,4	460	418	384
4,8	526	469	489
4,2	694	600	528
3,6	825	688	698
3,0	932	850	856
2,4	1006	981	938
1,8	23920	23996	14607
1,2	23818	23868	14561
0,6	1239	1481	1391

	WWR: 43% -September - 13:00 - 3,0m		
	AR 1	**AR 1.5**	**AR 2**
11,4			66
10,8			68
10,2			77
9,6			91
9,0			103
8,4		134	125
7,8		155	137
7,2		194	189
6,6		208	215
6,0		260	245
5,4	385	304	299
4,8	424	402	367
4,2	533	429	473
3,6	681	578	563
3,0	771	676	692
2,4	820	845	863
1,8	23714	23673	14371
1,2	23585	23578	14431
0,6	1011	1173	1103

	WWR: 30% - September - 13:00 - 3,0m		
	AR 1	**AR 1.5**	**AR 2**
11,4			49
10,8			52
10,2			52
9,6			57
9,0			69
8,4		106	85
7,8		121	96
7,2		138	130
6,6		162	157
6,0		177	169
5,4	287	216	215
4,8	316	277	279
4,2	372	341	361
3,6	451	399	415
3,0	529	537	531
2,4	675	580	600
1,8	23427	23485	14248
1,2	23403	23371	14118
0,6	1034	954	690

Figure F.2. Variations of illuminance distribution on 23rd September; illuminance below 300 lx (yellow), between 300 lx and 1000 lx (orange) and above 1000 lx (red).

	WWR: 67% - December - 12:30 - 3,0m		
	AR 1	**AR 1.5**	**AR 2**
11,4			202
10,8			207
10,2			243
9,6			278
9,0			335
8,4		467	355
7,8		487	424
7,2		555	522
6,6		650	606
6,0		733	641
5,4	13450	13803	13684
4,8	8512	8395	13801
4,2	8515	8548	13864
3,6	8570	8517	8480
3,0	8676	8639	12016
2,4	7512	7704	8493
1,8	1092	1042	870
1,2	816	835	734
0,6	22895	22923	22646

	WWR: 55% - December - 12:30 - 3,0m		
	AR 1	**AR 1.5**	**AR 2**
11,4			181
10,8			199
10,2			202
9,6			236
9,0			291
8,4		364	327
7,8		419	379
7,2		472	485
6,6		539	491
6,0		632	621
5,4	13295	13560	13602
4,8	8297	8287	8194
4,2	8290	8248	13789
3,6	8369	8408	8329
3,0	8464	8435	11934
2,4	7300	7388	8349
1,8	920	889	808
1,2	710	729	682
0,6	22645	22481	22591

	WWR: 43% - December - 12:30 - 3,0m		
	AR 1	**AR 1.5**	**AR 2**
11,4			130
10,8			142
10,2			160
9,6			158
9,0			194
8,4		294	219
7,8		349	290
7,2		373	333
6,6		431	372
6,0		529	417
5,4	13119	13466	13409
4,8	8093	8037	13435
4,2	8167	8124	13496
3,6	8207	8120	8251
3,0	8147	8342	11628
2,4	7038	7281	8185
1,8	766	708	672
1,2	589	661	572
0,6	22514	22892	22705

	WWR: 30% - December - 12:30 - 3,0m		
	AR 1	**AR 1.5**	**AR 2**
11,4			86
10,8			94
10,2			113
9,6			135
9,0			141
8,4		211	170
7,8		248	189
7,2		257	246
6,6		301	284
6,0		372	368
5,4	12886	13209	13179
4,8	7885	7836	7839
4,2	7958	7904	13309
3,6	7991	8019	7985
3,0	8056	8019	11440
2,4	6922	7055	7932
1,8	602	628	462
1,2	479	481	388
0,6	22489	22664	22427

Figure F.3. Variations of illuminance distribution on 21st December; illuminance below 300 lx (yellow), between 300 lx and 1000 lx (orange) and above 1000 lx (red).