MODELING OF ADVANCED DAYLIGHTING SYSTEMS TO IMPROVE ILLUMINANCE AND UNIFORMITY IN ARCHITECTURAL DESIGN STUDIOS

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ABSTRACT

MODELING OF ADVANCED DAYLIGHTING SYSTEMS TO IMPROVE ILLUMINANCE AND UNIFORMITY IN ARCHITECTURAL DESIGN STUDIOS

The daylighting performance is an important asset that deeply affects the occupants' visual comfort. In study and work environments, it is crucial to maintain adequate and uniformly distributed daylight. Deficiencies in daylighting conditions of these environments may cause health problems, work performance loss and excessive energy consumption. The varying nature of daylight in daily and yearly basis is a strong challenge on that matter. Advanced daylighting systems have been developed to overcome this challenge. Improving the daylighting performance of existing buildings is another difficulty in daylighting design, since the aspects like orientation, window area and surrounding elements affect indoor illuminance levels and uniformity. Thus, daylighting design needs should be carefully considered at the initial design stages of the buildings. Regarding to these, four architectural design studios facing southwest, southeast, northwest and northeast were selected in Izmir Institute of Technology Faculty of Architecture. In these studios, daylighting measurements including illuminance at specific points were conducted in May and June 2012. The aim of this thesis is to improve the illuminance and uniformity in the selected studios. Simulation models were built in Ecotect; and the field measurements were then used to validate the Ecotect model. To reach the best daylighting performance, simulations were carried out by Desktop Radiance with applying advanced daylighting systems, namely laser cut panels, prismatic panels and light shelves. The simulation findings were analyzed and discussed. It is considered that retrofitting efforts after the construction would be inadequate regarding daylighting, unless complying with the standards during the design process.

ÖZET

MİMARİ TASARIM STÜDYOLARINDA AYDINLIK DÜZEYİ VE DÜZGÜNLÜĞÜN İYİLEŞTİRİLMESİ AMACIYLA GELİŞMİŞ DOĞAL AYDINLATMA SİSTEMLERİNİN MODELLENMESİ

Doğal aydınlatma performansı, kullanıcıların görsel konforunu etkileyen önemli bir değerdir. Eğitim ve çalışma mekanlarında doğal aydınlatmanın yeterli ve düzgün dağılımlı olmasını sağlamak gereklidir. Doğal aydınlatma koşullarındaki eksiklikler sağlık problemlerine, iş performansı kaybına ve enerji tüketiminin fazla olmasına neden olabilir. Günışığının gerek gün içinde gerekse de yıl bazındaki değişken yapısı bu kapsamda önemli bir sorundur. Gelişmiş doğal aydınlatma sistemleri de bu sorunla başa çıkmak için oluşturulmaktadırlar. Yön, pencere alanı ve dış çevre elemanları gibi faktörler de iç hacimdeki aydınlık düzeyini ve düzgünlüğünü etkilediği için; mevcut binaların doğal aydınlatma performansının iyileştirilmesi de başka bir sorundur. Böylece, bina tasarımı ile bütünleştirilmiş olması gereken doğal aydınlatma ile ilgili kararlar, tasarım aşamasında öncelikli olarak belirlenmelidir. Bu bağlamında, İzmir Yüksek Teknoloji Enstitüsü'nde yer alan ve kuzeydoğu, kuzeybatı, güneydoğu, güneybatı yönlenime sahip dört farklı mimari tasarım stüdyosu belirlenmiştir. Belirli noktalarda mayıs ve haziran aylarında günışığı aydınlık düzeyi ölçümleri gerçekleştirilmiştir. Bu tezin amacı, gelişmiş doğal aydınlatma sistemlerini kullanarak bu dört adet mimari tasarım stüdyosundaki aydınlık düzeyi ve düzgünlük değerlerini iyileştirmektir. Ecotect ile benzetim modelleri oluşturulmuş ve saha ölçümleri bu modeli doğrulamak için kullanılmıştır. En iyi doğal aydınlatma performansına ulaşmak amacıyla, gelişmiş doğal aydınlatma sistemlerinden lazer kesim paneller, prizmatik paneller ve ışık rafları uygulanarak Desktop Radiance ile benzetim gerçekleştirilmiştir. Benzetim bulguları analiz edilerek değerlendirilmiştir. Tasarım sürecinde ilgili standartlara uygunluk sağlanmadan, yapım aşamasından sonraki iyileştirme çabalarının doğal aydınlatma açısından yetersiz kaldığı anlaşılmaktadır.

To my grandmother,

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CHAPTER 1

INTRODUCTION

In this chapter are presented first, the general topic of the study. Second, arguments and research problem are explained in relation to previous studies who worked on similar subjects. Then, objectives are mentioned as primary and secondary objectives. The procedure of the study is explained in the next part, and finally the contents of the study are briefly explained under disposition.

1.1. Argument

Daylighting systems are still the core elements to benefit from daylight to obtain a satisfactory visual environment and to save energy effectively by allowing optimum amount of light penetration into the interiors. They are composed of glazing, fenestration, shading devices and/or light guiding systems. By following recent technologies, it is almost possible to conclude that their efficiency will increase considerably. Combination of system elements, application of new materials with optical properties, and their sizing possibilities led to design advanced daylighting systems continuously (Cutler, Sheng, Martin, Glaser, & Andersen, 2008; International Energy Agency [IEA], 2000; Tsangrassoulis, 2008).

Daylighting performance, on the other hand, is the critical issue to design interiors with adequate and properly distributed daylight illuminance to avoid glare problems and occupant discomfort (Fontoynont, 1999). Significant energy savings may also be obtained. Unequally distributed illuminance or disturbing brightness levels may cause serious health problems and work-performance loss in study and work environments (Leslie, 2003; Miyazaki, Akisawa, & Kashiwagi, 2005).

Consequently, designers demand to use several design tools to foresee the outcomes of these issues about daylighting systems and to analyze their performance in the design stage. It is then possible to correct any deficiencies (glare, uneven illuminance) before construction. Generally, these tools are scale models, analytical calculations and simulations (Egan, 2002; Littlefair, 2002). Daylighting simulation tools have recently been more user friendly ones that are the most preferred by architects and researchers.

Simulation tools have become essential in the design and evaluation process of buildings. Specifically, they assist in daylighting performance studies and design with a growing interest (Kim & Chung, 2011; Reinhart & Fitz, 2006). Well-proposed daylighting strategies may decrease the buildings' total energy consumption and enhance user comfort. Thus, it is necessary to evaluate the quantity and quality of daylight in a space both in the early design stage and during occupation (IEA, 2010; Kim & Chung, 2011). This is recently a considerable component of sustainable design. Thus, it is expected that, simulation tools should provide accurate visual and quantitative outcomes in the preliminary steps of design.

To examine what kind of deficiencies about daylighting systems and components exist in occupied buildings, simulation tools may be used. Several daylighting tools are integrated in the comprehensive energy performance calculation methods and legislations. Thus, it is necessary to obtain daylighting numerical outputs and visual outcomes close to the real situations. The question related above is how their physical correctness, adaptability and usability are determined and which one is more suitable in design decision support and evaluation process than others.

This can be examined by comparing recently-used daylighting simulation software in daylighting design with the ones integrated in analysis process. The most reliable, adaptable and usable one would become the prevalent one to develop new daylighting technologies. The major deficiencies pointed out as a result of a comparison among software would be inputs to improve such software technologies in future. The best accuracy obtained from one tool would assist professionals to design high energy saving potential buildings, high user comfort in interiors, and low construction and operating costs. The consideration is to seek the proper tool to predict the daylighting performance and take early-precautions against deficiencies in the early design stages. It is necessary to determine the appropriate tool to propose daylighting technology decisions such as innovative shading and light guiding devices as building components. This determination will depend on pointing out their strength and weaknesses. Consequently, several criteria such as, compatibility with third party programs, working as a plug-in or as standalone in nature, user interface, ease of use, characteristics of output data, existence and source of climatic data, daylighting analysis and calculation methods, 3D modeling capability would be the key points to be examined by several studies.

In view of the recent and ongoing research, this thesis presents the modeling of advanced daylighting systems to evaluate illuminance and uniformity in architectural design studios in Izmir Institute of Technology Faculty of Architecture. First, a preliminary study was conducted to determine the appropriate tool to propose daylighting technology decisions such as innovative shading and light guiding devices as building components (Kazanasmaz & Fırat, 2012). So, literature about the application of daylighting simulations tools, their technical comparisons and their strengths/or weaknesses were reviewed. The analysis tool for this thesis was selected by the comparison of the recently and mostly used daylighting simulation software, namely, Desktop Radiance, Design Builder, Ecotect and Velux Visualizer, in daylighting design with the ones integrated in analysis process. Then, the simulation models were built in Ecotect and lighting analyses were conducted by Desktop Radiance. The performance of the model and the existing lighting conditions were quantitatively investigated and validated by measurements. The aim was to determine the optimum design solution by applying advanced daylighting systems with different size and material combinations.

Architectural design students need to study in a properly designed visual environment. The success of their works/or products are directly and initially related with their visual performance. Detailed drawings and models which are composed of tiny pieces of materials would easily be seen and perceived by only satisfying a uniform and high amount of illuminance. At this point, this study would guide all related professionals who should be aware of this problem. Designers should pay attention to apply requirements mentioned in the standards/or norms about daylighting in the design stage. Every retrofitting application to overcome the deficiencies of an improperly-designed daylighting system might not improve the visual performance of the interior space. Thus, early precautions should be taken in the design stage by utilizing appropriate design tools. This study would be a trial one to display this argument.

1.2. Objectives

Objectives of this study were suggested and employed by utilizing field measurements of daylight illuminance and modeling new daylighting systems under the purpose of evaluating the daylight illuminance and uniformity in architectural design studios.

The objectives of this study were defined as primary and secondary objectives.

The primary objectives of this study were:

a. to evaluate advanced daylighting systems in order to obtain optimum design solutions for the architectural design studios by developing Ecotect / Radiance model;
b. to draw attention to the daylighting simulation tools that might help the architects to make time and cost effective pre-tests before the construction stages;
c. to remind professionals / designers about the necessity of daylighting systems which should be considered at the design stage.

The secondary objectives of this study were:

a. to explore daylighting issues in educational buildings and advanced daylighting systems;
b. to discover the usability and adaptability of daylighting simulation tools;
c. to calculate uniformity ratios related to daylight illuminance;
d. to compare the illuminance and uniformity ratios for each daylighting system;
e. to explore the each daylighting system’s applicability in the existing architectural studios.

1.3. Procedure

This thesis aimed to find an optimum daylighting solution in architectural design studios by employing a simulation model under the light of field measurements. In the view of this purpose, this study was carried out in five phases:

In the first, a general survey about daylighting design criteria of educational buildings and an overview of advanced daylighting systems and daylighting simulation tools was conducted.

In the second, physical description of the educational building which belong to the Faculty of Architecture in İzmir Institute of Technology and climatic data of İzmir were introduced briefly. Field measurements of daylight illuminance were carried out in four architectural studios in the mentioned building in the Faculty of Architecture in IYTE. Daylight illuminance and uniformity ratios were noted down in separate data sheets for each measurement time.

In the third, by utilizing the collected data, a simulation model of the existing studios were prepared after the survey. A comparison between the measurements and simulation findings was used to validate and finalize the simulation model.

In the fourth, as the simulation model was set, trial models were arranged by applying proposed advanced daylighting systems in order to improve the illuminance and uniformity in the studios.

In the fifth, the findings of each model with a daylighting system were compared and evaluated according to standards, design norms and previous literature in order to find an optimum solution for an existing building.

CHAPTER 2

LITERATURE SURVEY

2.1. Daylighting Performance of Educational Buildings

Providing evenly-distributed and adequate daylight into the educational buildings is highly substantial, since the daylighting performance of these interiors deeply affects the students' learning capability, motivation, study performance, stamina and psychological conditions (Erlalelitepe, Aral, & Kazanasmaz, 2011; Güvenkaya & Küçükdoğu, 2009; Kesten & Yener, 2006; Winterbottom & Wilkins, 2009; Yener, Güvenkaya, & Şener, 2009). Also educational facilities are mostly day time occupied buildings and optimizing use of daylight in these interiors would prevent excessive use of electric energy (Erlalelitepe et. al., 2011; Güvenkaya & Küçükdoğu, 2009; Kesten & Yener, 2006; Yener et. al., 2009). Thus, maintaining adequate amount of daylight and an even distribution is crucial in daylighting design of these spaces (Erlalelitepe et. al., 2011; Kesten & Yener, 2006; Yener et. al., 2009).

2.1.1. Daylighting Design Criteria

In the educational buildings, the spaces that learning and teaching activities take place have special daylighting needs. In order to provide a healthy environment for conducting the educational tasks in these interiors, the horizontal daylight illuminance on the working plane levels (on the desk and table surfaces) as well as the vertical illuminance on the boards and walls should be adequate and uniformly distributed and glare problems that may occur in these surfaces should be eliminated (Erlalelitepe et. al., 2011; Yener et. al., 2009). In order to prevent overheating problems and glare, occupant controlled shading systems should be introduced in the conditions that direct sun light enters the classrooms. Artificial lighting systems also should be integrated with daylighting to minimize the electric energy usage (Kesten & Yener, 2006; Yener et. al., 2009).

In a research conducted by Erlalelitepe et. al. (2011), daylighting conditions of five spaces facing different directions and used for different purposes (lecture hall, classroom, laboratory, office and hall) at the building of Department of Mechanical Engineering at Izmir Institute of Technology was analyzed. According to the field measurements conducted in these spaces in December, daylighting levels in the southwest and southeast facing spaces, namely, lecture hall, office and classroom, was adequate in only one measurement day, during the measurements conducted in the morning and at noon. The illuminance levels measured in the office was lower than the classroom, although the two spaces had the same amount of glazing ratio and were facing the same direction. According to Erlalelitepe et. al. (2011), the difference in the illuminance might be because of the different sun control strategies of the two spaces; vertical and horizontal elements forming balconies in front of the offices prevented the sun more than the metal sun shading elements on the classroom windows. Erlalelitepe et. al. (2011) concluded that, existing façade design of the studied building should be reconsidered with different shading and glazing systems.

Güvenkaya and Küçükdoğu (2009) conducted a research aiming to determine “the most appropriate direction dependant façade orientation” in the elementary school buildings. A typical classroom designed by the Ministry of Public Works and Settlement was selected for the study and daylighting calculations were conducted using Radiance; first with the existing façade, latter with the proposed configurations. The shading devices used in the proposed façades were horizontal and tilted at different angles regarding the sun’s movement and direction of the applied façade. Two façade configurations were proposed; first one consisted of fixed shading devices and was assumed to be used during the whole educational season (proposal 1) and the other one was assumed to be used only when the shading is needed (proposal 2). The Radiance simulations indicated that, proposal 1 (fixed configuration throughout the educational season) was a better alternative than the existing façades when applied to the north and south facades. Proposal 1 caused 17% to 54% more electric energy consumption than the existing condition, when applied to east and west facades. The findings indicated that Proposal 2 was a better alternative than the existing condition; with a reduced energy consumption of 0.35% to 0.9 % when applied to the north façade, 41% to 74% to the south façade, 23% to 64% to the west façade and 37% to 78% to the east façade (Figure 2.1).

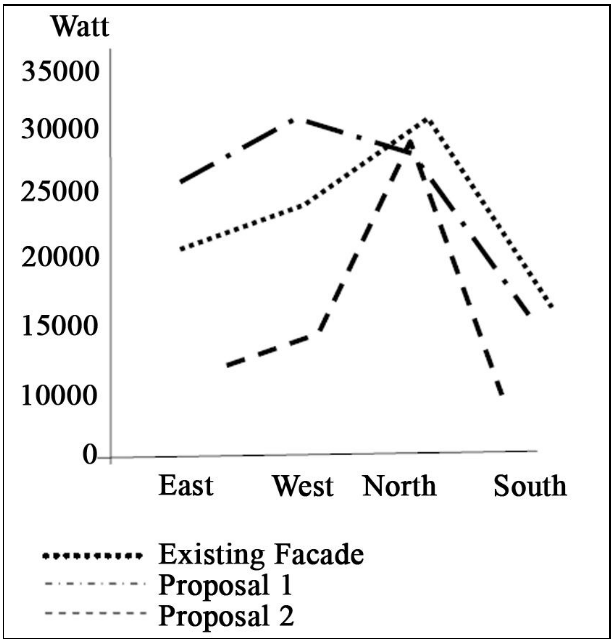


Figure 2.1. Energy performances of the alternative facade configurations
(Source: Güvenkaya & Küçükdoğu, 2009)

2.1.2 Daylighting Standards

Daylighting legislations could not have been thoroughly identified and developed due to the unforeseen and unstable nature of daylight. Legislations and regulations regarding daylight should not only consider illuminance levels but also take illumination time frame into consideration (Erlalelitepe et. al., 2011).

In some of the developed building codes and regulations, requirements for educational buildings are present. These standards differ from each other regarding on which principals they base on; daylight - factor, window – size, daylighting etc. (Boubekri, 2004; Erlalelitepe et. al., 2011).

A window-size based standard in UK, The British Code BR 8206 (Part 2), requires a window area of %25 of the total external wall area in institutional buildings, while DIN 5034 – 4 , a German standard, determines required daylight levels regarding the difficultness of the conducted visual tasks in the interiors (Boubekri, 2004; Erlalelitepe et. al., 2011) (Figure 2.2).

British Draft Development DD 73 Standard determines illumination levels regarding the purpose of use of the building interiors. According to the standard, in drawing offices in the educational, office or factory buildings; illumination of 500 to

750 lux should be maintained. The standard recommends maintaining illuminance of 300 to 500 lux in formal teaching and seminar rooms, 300 to 500 lux in deep plan teaching spaces, 300 lux in the music and music practice rooms (Boubekri, 2004; Erlalelitepe et. al., 2011).

Stage	Daylight Illuminance (Lux)	Visual Task
1	15	Temporary Task
2	30	
3	60	Easy Task
4	125	
5	250	Normal Task
6	500	
7	750	Difficult Task
8	1000	
9	1500	Very Difficult Task
10	2000	
11	3000	Very Special Task
12	5000 and more	

Figure 2.2. Recommended daylight illuminance (lux) in the DIN 5034 – 4 Standard
(Source: Boubekri, 2004)

2.2. Daylighting Systems

International Energy Agency [IEA] (2010) defines a daylighting system as a system which “combines simple glazing with some other element that enhances the delivery or control of light into a space” (p. 3). According to IEA, the functions of the daylighting systems can be summarized as follows:

- Introducing daylight into deeper spaces from the window wall than is possible with conventional designs.
- Increasing usable daylight at climates with dominant overcast skies or at climates where sun control is crucial.
- Increasing usable daylight in the case of exterior obstructions and transporting daylight into windowless spaces.

The working principle of daylighting systems includes adding reflective or refractive elements into the glazing system, regarding the purpose of their use. The daylighting behaviours of the systems also depend on where they are installed in the buildings; to the building façade or to the skylight, for instance. In principal, the daylighting systems have two main characteristics: they have or do not have shading capability. The systems that provide shading block direct sunlight entirely and allow diffuse skylight into the interiors; or they use direct sunlight and redirect it into the spaces. On the other hand, the systems that do not provide shading redirect sunlight into deeper spaces away from the daylighting apertures (IEA, 2010; Köster, 2004; Kischkoweit - Lopin, 2002; Lim & Kim, 2010).

The types of daylighting systems can be summarized as follows; louver and blind systems (prismatic louvers, light deflecting glass mirror louvers, mirroring louvers, daylight louvered blinds, turnable lamellas), light shelves, prismatic light-deflection systems (prismatic panels, laser cut panels), anidolic systems (ceilings, zenithal openings, solar blinds), shading systems with holographic optical elements, scattering systems and light transporting systems (light pipes, solar tubes, heliostats, fibres) (Bostancı, 2006; Hansen, 2006; IEA, 2000; IEA, 2010; Köster, 2004; Kischkoweit - Lopin, 2002). In this thesis, three of these systems, namely, laser cut panels, prismatic panels, and light shelves, which are in close relation with the conducted study are explained in detail.

2.2.1. Laser Cut Panels

Laser cut panels are daylight-redirecting elements that have been developed by the Australian physicist Ian Edmonds (Köster, 2004). Laser Cut Panels are effective light deflection systems and improve the distribution of daylight and reject excessive solar heat gains in the interiors. The panels have been applied in a wide range of regions throughout the world; from equatorial and subtropical to the high latitudes, where redirection of daylight is crucial to avoid glare and excessive solar gains, and also where the panels can redirect low-elevation daylight into low illuminated interiors (Greenup, Edmonds, & Compagnon, 2000; Reppel & Edmonds, 1998).

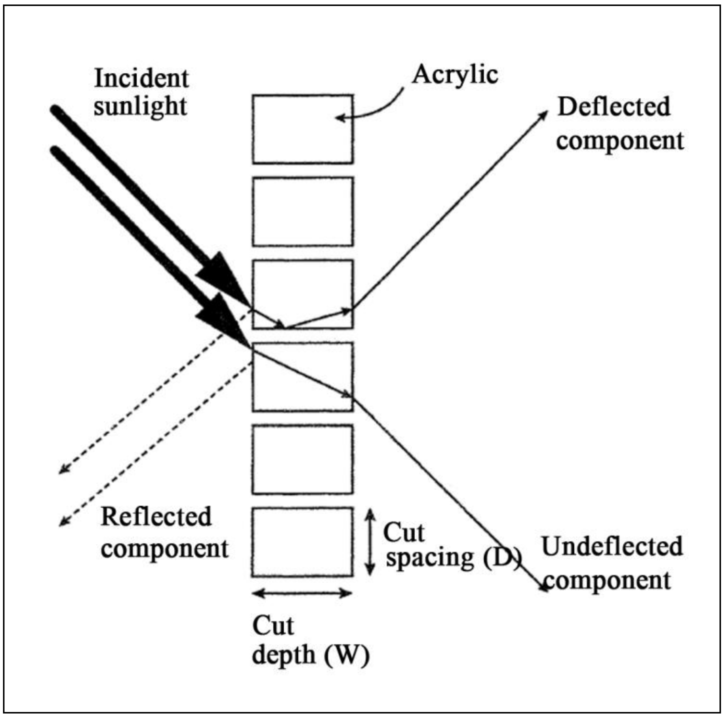


Figure 2.3. Operation of LCP material
(Source: Greenup, Edmonds, & Compagnon, 2000)

Laser cut panels are made of clear acrylic and are produced by laser cutting into the acrylic sheets that create arrays of rectangular elements. Each cut surface within the panel acts as a mirror. The panels work on the principle of redirecting daylight coming to the panel by refraction, internal reflection and then refraction (Figure 2.3). Since all the deflections are in the same direction, they are highly effective; much more effective than the prismatic glass (Edmonds & Greenup, 2002; Greenup et. al., 2000; Hocheng, Huang, Chou, & Yang, 2010; IEA, 2000).

A peripheral frame and vertical columns should be left uncut in the acrylic sheets in order to maintain structural strength (Figure 2.4). The peripheral frame should be 20 - 30 mm, while vertical columns are left 10 – 20 mm in a 1000mm x 600mm panel, for instance (IEA, 2000). The laser cuts can be processed throughout the panel or partway to the panel; although the latter is not preferred due to the manufacturing difficulties. Making the cuts at an angle to the normal to direct the deflected light to a more controlled direction is also possible (Edmonds & Greenup, 2002; Greenup et. al., 2000; IEA 2000; Reppel & Edmonds 1998).

The panels are transparent and they do not prevent exterior view, but some distortion is inevitable (Figure 2.4). Also, the redirected daylight coming from the panels may cause glare problems in the interiors when the occupants are near the windows. Thus, placing the panels to the daylighting openings instead of view windows or above eye level is suggested (IEA, 2000).

Laser cut panels can be applied to the windows as fixed sun shading systems, fixed or movable daylight redirecting systems or sun shading – daylight redirecting systems in louver or venetian forms. The panels can also be applied to the skylights in fixed configuration (IEA, 2000).

Figure 2.4. Peripheral frame and support columns
(Source: International Energy Agency, 2000)

When fixed vertically into a window, the laser cut panels transmit most of the light incident from below 20^o and deflect most of the light incident from above 45^o; which means a high portion of high elevation light is deflected onto the ceiling. This deflected light on the ceiling than becomes a secondary light source of diffuse illumination and illuminate farther back into the rooms; like in the case of using light shelves (Edmonds & Greenup, 2002; Greenup et. al., 2000; IEA, 2000).

Energy savings that can be obtained by using laser cut panels depend on the application; but, by using fixed panels in the upper one third of an open window to deflect light farther back into the room, increase the average level of natural light in the deeper areas by 10 to 30%, depending on sky conditions (Edmonds & Greenup, 2002; IEA, 2000).

There are many application examples of laser cut panels, mostly in daytime occupied buildings like offices or educational facilities.

In a research conducted at an office building in Sandvika, Norway at latitude 59^oN, two identical rooms, a control room and a test room, were used to comprehend the daylighting effects of the laser cut panels. Laser cut panels were positioned above a view window in the test room. The illuminance measurements were carried out in the rooms and the results showed that; during overcast sky conditions, the laser cut panels had almost no effects on the illuminance or the distribution of daylight in the test room. But in the clear sky conditions, especially in the intermediate zone of the room, the panels increased the illuminance at most parts of the day, during the year (IEA, 2000).

An array of narrow laser cut panels was mounted horizontally in a window in an office building in Brisbane, Australia; latitude 27^o south. Daily variation of irradiance through north, east and west facing windows were evaluated as shown in Figure 2.5. Broken lines show irradiance through an open window; full lines show irradiance through the angle selective glazing in this irradiance – time graph.

The results showed that, the panel configuration (angle selective glazing) was most effective at east and west windows for the applications in Brisbane (latitude 27^o south). In the Southern Hemisphere, north facing windows did not receive much radiant input during summer, while east and west windows predominantly caused the undesirable summer heat (Figure 2.5). The angle selective glazing rejected more than 75% of the incident solar energy between 7 am and noon on east and noon and 5 pm on west facing windows at mid-summer. On the other hand, the glazing reduced the average radiant gain about 20% at mid-winter and 30% at equinox on the southern façade. In east and west facades, the glazing was more effective with the average radiant gains over the day are 30% at summer, 35% at equinox and 43% in winter (Edmonds & Greenup, 2002).

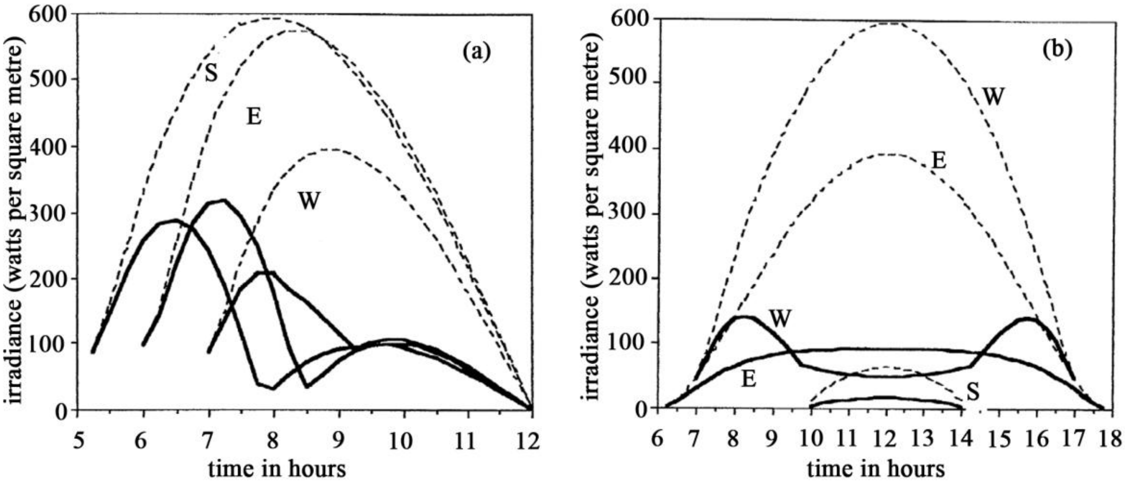


Figure 2.5. Irradiance – time graph from east (a) and north (b) facing windows for mid-summer (S), equinox (E) and mid-winter (W) (Source: Edmonds & Greenup, 2002)

Reppel and Edmonds (1998) compared the results of the previous angle selective glazing application in Brisbane (sub-tropical, latitude 27^{o} south) with an application in Paris (temperate, latitude 49^{o} north). The results showed that at south façade, (corresponding to the north façade in Brisbane) the performance was similar to Brisbane from summer to equinox, with about 25% transmittance of incident radiance. From equinox to mid-winter, the average daily transmittance increased up to 70% at mid-winter. For the facades facing east and west, the average daily transmittances were 33% at mid-summer, 43% at equinox and 67% at mid-winter. Broken lines show irradiance through an open window; full lines show irradiance through the angle selective glazing in this irradiance – time graph (Figure 2.6). In the light of these, the angle selective glazing displayed a favoring performance in temperate latitudes by decreasing the radiant gains remarkably in summer, while slightly decreasing the gains in winter.

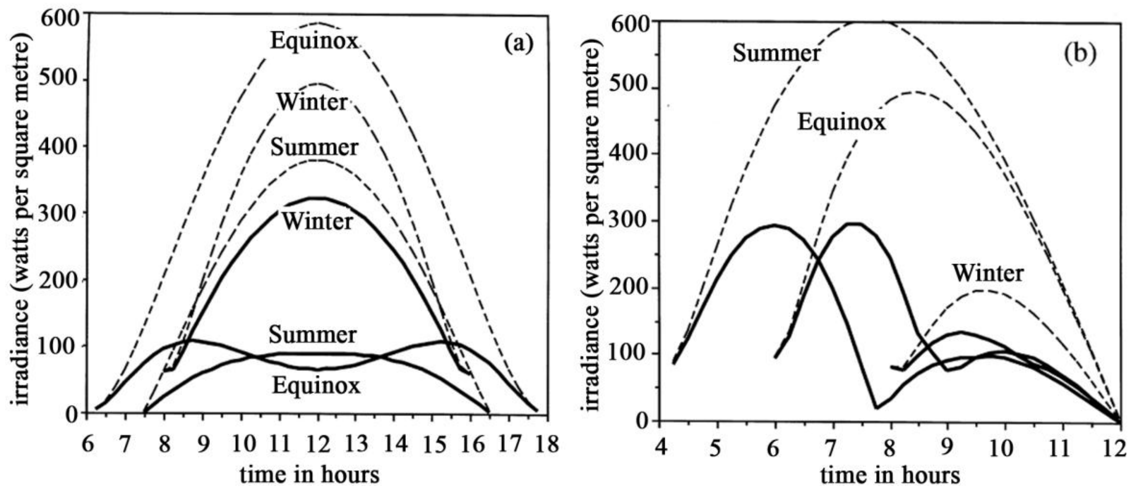


Figure 2.6. Irradiance – time graph through East (a) and South (b) facing windows for mid-summer (S), equinox (E) , mid-winter (W) (Source: Reppel & Edmonds, 1998)

Thanachareonkit, Scartezzini and Robinson (2006) conducted a research on the simulation techniques of complex fenestration systems (in this case, prismatic films and laser-cut panels) by using Radiance simulation software. A scale model under a sky simulator was compared with an identical Radiance model under CIE sky while they were both equipped with conventional glazing, laser-cut panel and prismatic film on the side aperture respectively. The results indicated that, the simulation techniques of Radiance were adequate for analyzing complex fenestration systems.

An algorithm used to model the laser cut panel material in RADIANCE has been defined by Greenup et. al. (2000). Simulations were conducted by using this algorithm in a standard test model, a room with one window that is facing north. CIE clear sky with sun was used as in the simulations, and the model was located in Brisbane, Australia at 15:00 on 24 July. In the simulation results, deflected and undeflected components of the incident sunlight were observed. Sun patches were created in the ceiling by the deflected sunlight incident from the panels, causing the ceiling to appear more luminous and acting as a secondary light source (Figure 2.7). On the second part of the research, Greenup et al. conducted the same simulations for the overcast sky conditions, with CIE overcast sky in another test model equipped with two double glazed windows. Laser cut panels were integrated inside the double glazing this time;

thus became a daylighting system and the redirection of the transmitted daylight was stronger, generating a sun patch on the ceiling above the window (Figure 2.8).

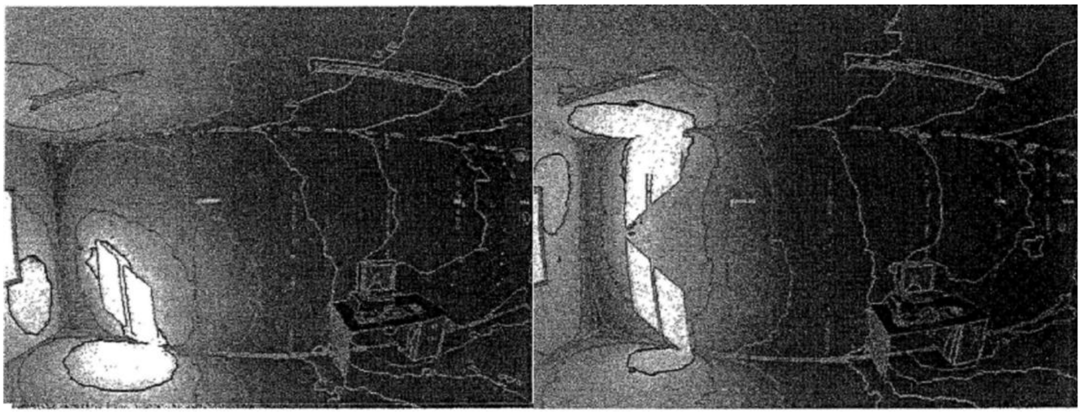


Figure 2.7. Simulation results of the test room (left) and the room with LCP (right)
(Source: Greenup, Edmonds, & Compagnon, 2000)

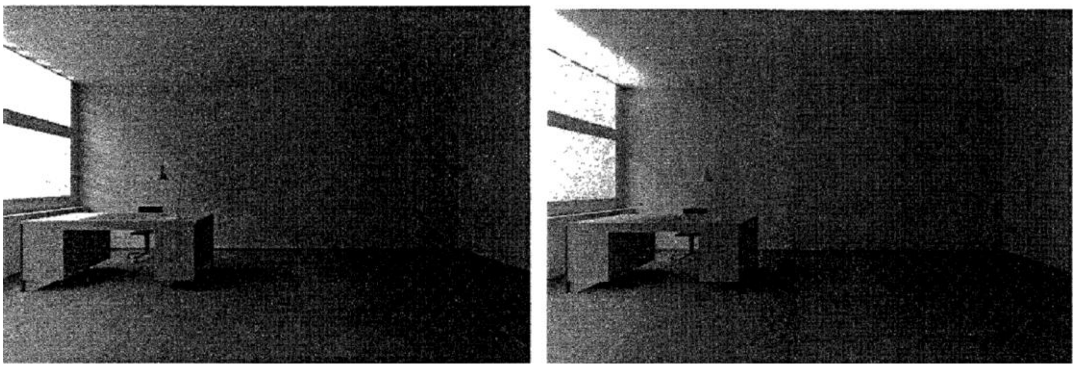


Figure 2.8. Simulation results of the test room (left) and the room with LCP (right)
(Source: Greenup, Edmonds, & Compagnon, 2000)

2.2.2. Prismatic Panels

Prismatic light-guiding systems (prismatic panels) have been developed by Christian Bartenbach (Köster, 2004). They are used for redirecting or refracting daylight. The main function of the panels is to deliver daylight into deeper areas away from the daylighting apertures (Hocheng et. al., 2010; IEA, 2000; IEA, 2010; Laouadi, Saber, Galasiu, & Arsenault, 2013; Littlefair & Motin, 2001; Sweitzer, 1991).

The prismatic panels are made of clear acrylic and are planar and sawtooth elements. The sawtooth surfaces have two refracting angles and as a system, the panels can be designed as reflective to certain angles of incident light while transmitting light coming from the remaining angles. The panels can be manufactured with two techniques; injection moulding and specialized etching. Injection moulding provides four commercially available refracting angles for the prismatic panels; which are 5°, 28°, 36° and 45° relative to the normal (Figure 2.9). One surface of each prism of the panels which are manufactured with injection moulding technique can be covered with aluminium film for higher reflectivity. The specialized etching technique generates prisms less than 1mm apart from each other on acrylic film. The film is than inserted into double glazed systems (IEA, 2000; IEA, 2010).

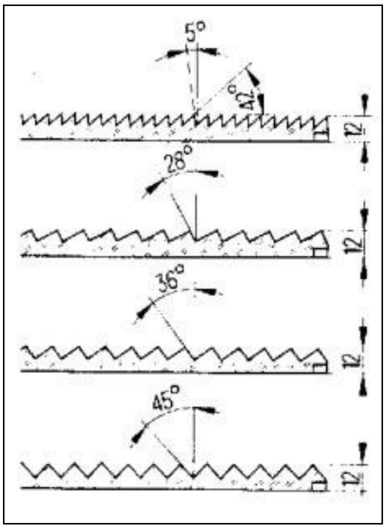


Figure 2.9. Prismatic panel configurations
(Source: International Energy Agency, 2000)

Prismatic panels can be used for solar shading or daylight redirection purposes. When the panels are used for shading, they can be in fixed or movable configurations and they block the direct sunlight and permit diffuse skylight into the interiors. Fixed sun-shading prismatic panel systems are usually applied to the glazed roofs and are designed regarding the sun movement. Movable sun-shading prismatic panel systems are used in louver forms in vertical or horizontal applications. When used as light redirecting devices, the panels are mounted to the facades and direct sun light or diffuse daylight into the rooms (IEA, 2000; IEA, 2010).

Several prismatic panel applications are present in 3M Centre Building in Minnesota, USA as prismatic film (light guides and emitters); 3M Office Building in Austin, Texas, USA as prismatic film (light reflecting, at roof of the atrium); Sparkasse, Bamberg, Germany as prismatic panels integrated into a double glazing (fixed sun-shading and light redirecting) and German Parliament Building, Bonn, Germany as prismatic panels (movable sun-shading) (IEA, 2000). The prismatic panel application in German Parliament Building is shown in Figure 2.10.

The daylight designers have been conducting studies regarding the daylighting performance and energy saving effects of the prismatic panels and trying to optimize them as daylighting systems.

Figure 2.10. Prismatic panels - German Parliament Building, Bonn
(Source: International Energy Agency, 2000)

In a research conducted at an office building in Sandvika, Norway at latitude 59°N, the daylighting measurements are conducted in two identical rooms, the test room and the reference room. In the test room, prismatic panels (45°) were used vertically and positioned above a view window; occupying 31% of the total glazing area. The window in the reference room had clear glazing. The results showed that under overcast skies, prismatic panels decreased the illuminance about % 25 - % 35 in the test room and the distribution was less uniform. But under summer clear sky conditions, the distribution was more uniform than the reference room. Also, the average illuminance was increased by 14% and this increase was up to 30% near the rear wall (IEA, 2000).

In a study conducted by the Building Research Establishment (BRE); a prismatic film system (62° and 78°) and a prismatic panel with light directing characteristics by Siemens (45° and 90°) was tested in the BRE office facility in Garston, UK. In summer and equinox, in direct sun, the illuminance was 10 to 20% higher at the intermediate and rear zones with prismatic film than the condition with clear glazing. Also, the film redirected sunlight to the ceiling, and illuminated the middle area. In winter, the performance of the prismatic film decreased under cloudy conditions (10 to 30% reduction), although the films prevented the glare. In summer, under clear sky conditions, prismatic light-directing panels mostly blocked sunlight and reduced illuminance in the room. In equinox, under clear sky conditions, illuminance increased at the rear zone over 100%. During overcast sky conditions, the panels reduced the illuminance in the room by 35 to 45 %. In winter, under clear sky conditions, the illuminance at the deepest areas in the room was decreased by half, because the panels prevented the light that would have illuminate the rear zone by redirecting it onto the front areas of the ceiling. The panels prevented glare in all daylighting conditions (IEA, 2000).

Sweitzer (1991) conducted a study aiming to determine the effects of the prismatic panel side lighting systems on visual comfort and electric usage in perimeter office workspace. Therefore, three bank office buildings were selected in Cologne, Bamberg and Hannover in Germany; all of which equipped with prismatic panel side lighting systems developed by Siemens AG. The systems consisted of exterior sun shielding and interior light-guiding prismatic panels (Figure 2.11). In Cologne, the exterior and interior panels were fixed in parallel, within rotating panels. In Bamberg and Hannover, the ext. panels were rotating relative to the fixed light- guiding panels.

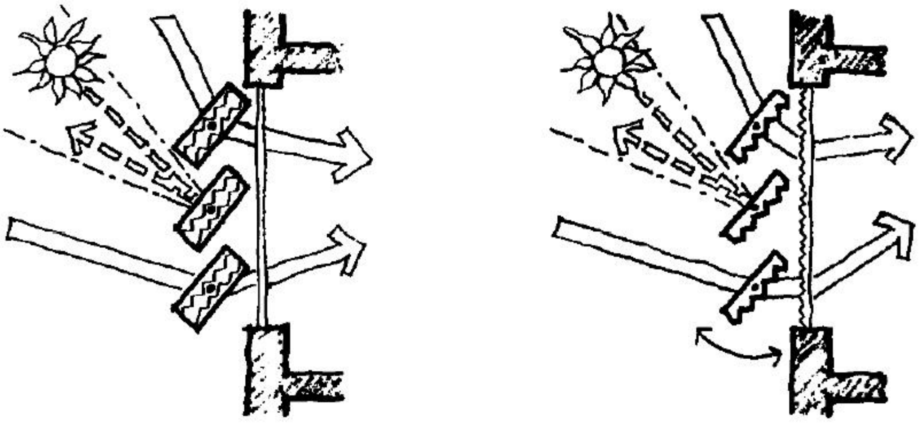


Figure 2.11. Prismatic panel systems used in Cologne (on the left) and Bamberg and Hannover (on the right) (Source: Sweitzer, 1991)

The results showed that; prismatic panel side lighting systems were affecting the distribution of daylight in perimeter zones, but these distributions were largely affected by window exposure. Also the articulated ceiling surfaces could cause overlapping reflections on wall surfaces, thus confuse light orientation (Sweitzer, 1991).

Littlefair and Motin (2000) conducted a study aiming to comprehend the effects of innovative daylighting systems on ceiling mounted photoelectric control systems; if and how they interfere with the perception of the sensors. Two identical rooms, one equipped with conventional glazing, the other one equipped with innovative systems (conventional venetian blinds, prismatic films and horizontal internal light shelf, respectively) were used for the experiments. The results of the prismatic film integrated room were very similar with the reference room equipped with conventional glazing; since the prismatic film did not redirect sunlight to the ceiling deep enough to reach the sensors. If the sensors were positioned closer to the window or the films redirected light far deeper onto the ceiling, the results could be different.

Laouadi, Saber, Galasiu and Arsenault (2012) aimed to develop a simplified model to compute the optical properties and determine the directions of the transmitted and reflected beams of the prismatic panels. The model was based on ray-tracing and was validated by computer simulations and integrated sphere and goniophotometer measurements.

2.2.3. Light Shelves

A light shelf is a daylighting system that provides shading, redirects down coming light into the spaces in an upward direction; working on the principal of improving daylight penetration, decreasing solar heat gains and preventing glare on work plan levels (Claros & Soler, 2002; Edmonds & Greenup, 2002; IEA, 2000).

The light shelves are used as internal or external devices in horizontal or nearly horizontal baffle positions (Claros & Soler, 2002; IEA, 2000; Soler & Oteiza, 1996). Their locations in the facades are determined regarding the room configuration, ceiling height, window height and eye level (IEA, 2000; Rao, & Tzempelikos, 2012). Their sizes and other characteristics like materials, shape, and slope should also be defined specifically regarding window orientation, room configuration and latitude (IEA, 2000).

The daylighting performance of the light shelves is much better in high direct sunlight climates, because of both their shading and light directing characteristics. They can also be applied to the south facades of deep interiors in the northern hemisphere (north façade in the southern hemisphere) with high efficiency. But, the light shelves do not provide that much satisfying performance in east and west orientations and in climates with dominant overcast skies (IEA, 2000).

A balance should be determined between the shading and daylighting needs of spaces when adjusting the position in the façade, orientation and depth of the shelves. The light shelves can be applied as fixed, solid systems (conventional light shelves), designed with curved geometry, segmented for passive reflection of sunlight, and may be coated with highly-reflective, semi - specular optical films (optically treated light shelves), or may be fixed light shelves that inhabit tracking rollers that have plastic reflective film surfaces above (sun – tracking light shelf) (IEA, 2000).

Some light shelf applications are present in Sacramento Municipal Utility District (SMUD) Headquarters, Sacramento, California (internal sloped light shelf, shown in Figure 2.12) and Palm Springs Chamber of Commerce, Palm Springs, California (optically treated light shelf integrated to a skylight, shown in Figure 2.13) (IEA, 2000).

Figure 2.12. Light shelf, SMUD Headquarters
(Source: International Energy Agency, 2000)

Figure 2.13. Optically treated light shelf within a skylight
(Source: International Energy Agency, 2000)

Aghemo, Pellegrino and Lo Verso (2008), conducted a study to compare the different types of shading systems, namely, overhangs, external, internal and internal + external light shelves, horizontal fins. The mentioned shading systems were applied to the 1/10 scale model of a sample high school classroom on south façade, and experiments were conducted under a sun and a sky scanning simulators. The measurements were repeated for clear and overcast sky conditions and both for winter and summer, for the dates December 21st and June 21st. Dimensioning and positioning of the shading systems were adjusted regarding the determined shading factor (SF) values for both measurement days (December 21st and June 21st), in order to acquire a comparable shading effect. The illuminance and daylight factor values were measured at the working plane level for 16 measurement points.

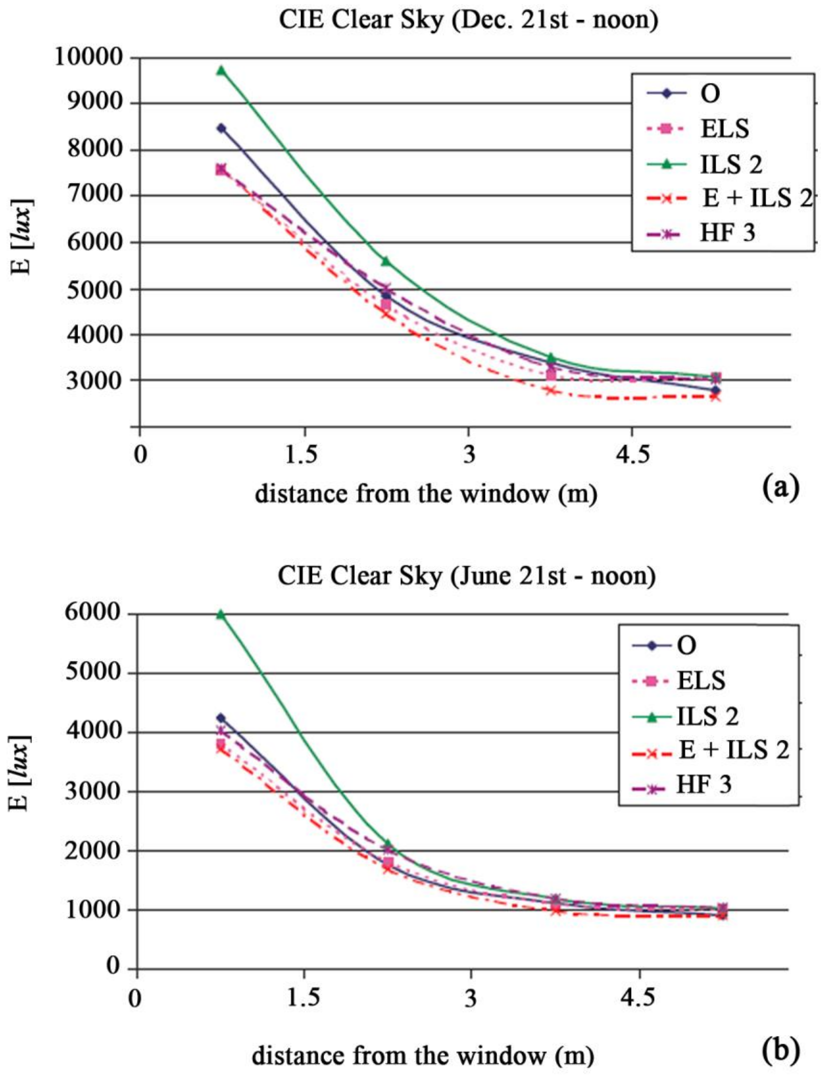


Figure 2.14. Illuminance distribution under CIE clear sky conditions for (a) December 21st and (b) June 21st (Source: Aghemo, Pellegrino, & Lo Verso, 2008)

The results showed that, in clear sky conditions, the internal light shelves provided the highest illuminance, while lowest values among the shading systems were acquired with external and internal + external light shelves. The illuminance distribution was better when external and external + internal light shelves were used, while the uniformity was reduced with the use of internal light shelves. The daylight penetration was higher when the external light shelves were used and lower with external + internal and internal light shelves, respectively (Figure 2.14).

It was observed that the shading systems apart from the internal light shelves were successful preventing direct sun light in June 21st. Also, the photographs taken inside the scale model showing the sunlight penetration inside the classroom produced with different types of light shelves for December 21st were shown in Figure 2.15.

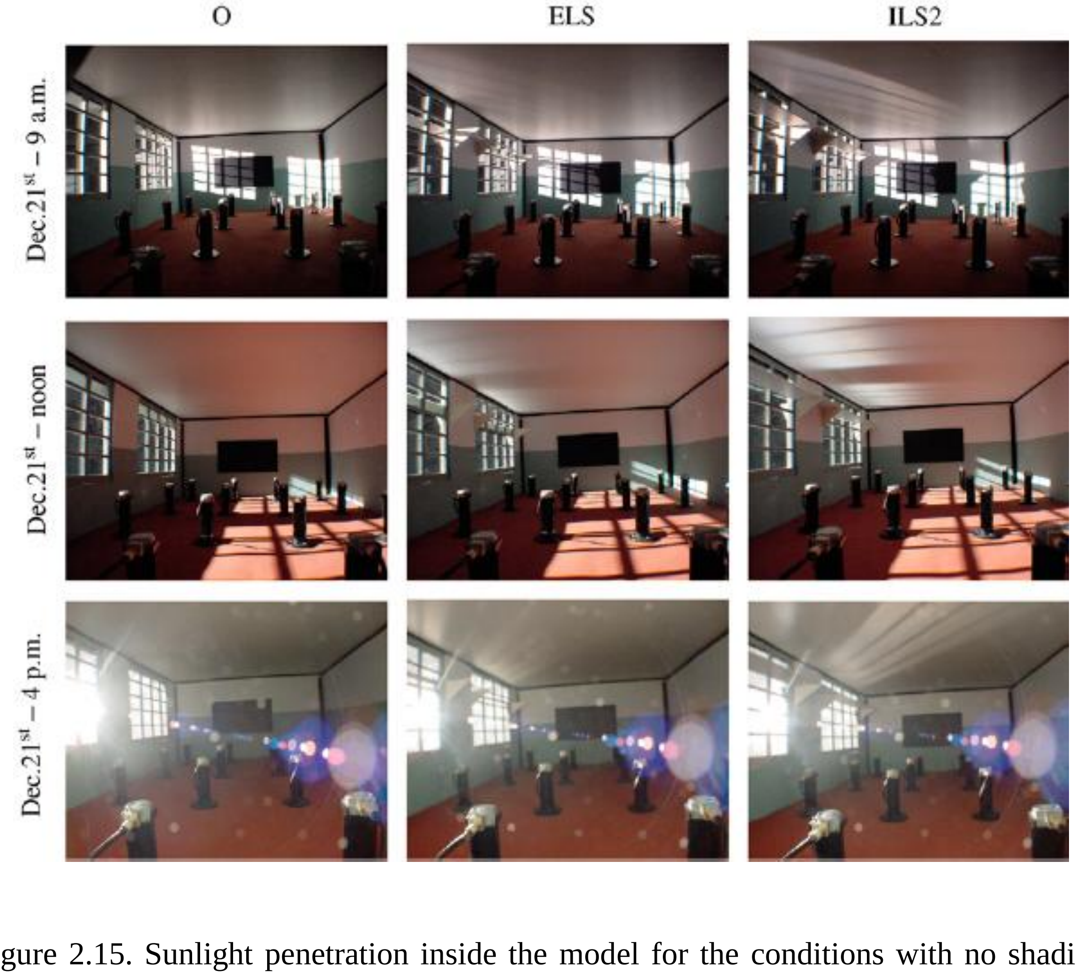


Figure 2.15. Sunlight penetration inside the model for the conditions with no shading systems (O), the condition with external light shelves (ELS) and the condition with internal light shelves (ILS2) (Source: Aghemo, Pellegrino, & Lo Verso, 2008)

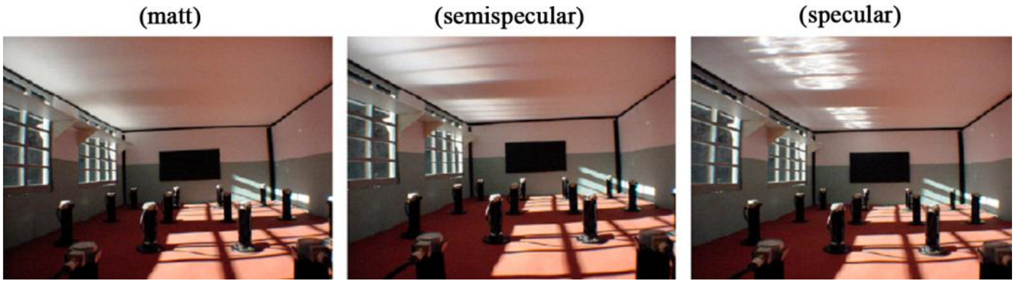


Figure 2.16. Daylighting conditions inside the model with the use of matt, semispecular and specular finishes on the internal light shelves (Source: Aghemo, Pellegrino, & Lo Verso, 2008)

In the last part of the research, Aghemo et. al. (2008) used matt, semispecular and specular finishes on the top surfaces of the internal light shelves aiming to comprehend their effects on the illuminance and sunlight penetration inside the model. According to the results, the illuminance and sunlight penetration increased with introducing the specular and semispecular finishes to the light shelves, as can be seen in Figure 2.16.

Lim, Kandar, Ahmad and Ossen (2012), conducted a research aiming to analyze and if necessary, improve the daylighting conditions of an existing government building in Malaysia. Field measurements were conducted in a south-west facing office located at the top floor of the selected government building with no remarkable outside obstructions. Findings regarding the measurements of illuminance indicated that, the daylighting condition of the room was inadequate. Existing shading device, consisting of an overhang and a vertical screen prevented the external illuminance, which was severely high, between 20 klx and 130 klx, at the time of the measurements; to illuminate the room adequately. Radiance based simulation software was used for modeling and simulating firstly the existing condition of the room and latter, the proposed systems. In order to improve the daylight performance, the existing window was replaced with a clear glazing (VT 75%) with no shading device. Internal – external light shelf was applied and positioned 1130 mm above the window sill. Lastly, partial blinds (45^o) were applied; just under the light shelf (Blind 1) and alternatively, just above the window sill (Blind2). All applied shading devices to the building are illustrated in Figure 2.17.

The results showed that, the application of the light shelf worsened the glare problem, but increased the uniformity ratio and reduced the severely high work plane

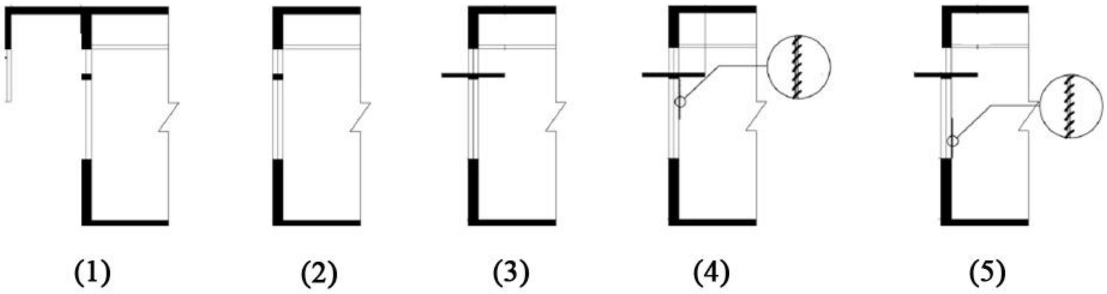


Figure 2.17. Applied shading devices; existing shading device (1), clear glazing (2), internal – external light shelf (3), internal – external light shelf with Blind1 (4), internal – external light shelf with Blind 2 (5) (Source: Lim, Kandar, Ahmad, & Ossen, 2012)

illuminance under tropical sky. The shelf directed daylight into deeper areas in the room and enhanced uniformity. In order to prevent the glare problem, the blinds were introduced to the system. The simulation findings pointed out that the vertical positioning of the blinds were critical at maintaining effective daylighting conditions. In the configurations mentioned above, Blind 1 which was located just under the light shelf was more successful at preventing glare than Blind 2 was.

2.3. An Overview of Daylighting Simulation Tools

This section is an overview of four recent simulation tools mostly used in daylighting design and performance studies. This overview is based on contemporary researches cited in literature and on inspection of simulation characteristics. Daylighting simulation tools have greater number of users when compared to the scale models and mathematical calculations. Their priority depends on being less-time consuming, and their ability to provide various visual scenes for various physical and sky conditions. By using daylighting simulation tools, it is possible to detect any deficiency in the design phase and provide solutions before its construction; which is cost efficient. In this section, the discussion is based on the physical correctness and usability of these tools for daylighting design decisions and performance analysis.

2.3.1. Desktop Radiance

Radiance is developed to assist designers in the prediction process of the lighting levels and the appearance of a space before application. The lighting simulator engine of the Radiance uses a hybrid approach of Monte Carlo and deterministic ray tracing in lighting calculations. The software is initially developed for the Unix environment and works on a text-based input format (Bhavani & Kahn, 2011; Kim & Chung, 2011; Minstrick, 2000). On the other hand, Desktop Radiance is a more user-friendly version of Radiance in terms of its graphical interface and ease of reach through the integrated pull-down menus within other programs such as AutoCAD, Autodesk Ecotect Analysis and DesignBuilder. Desktop Radiance works under the Windows operating system through these programs and its graphical user interface also allows using most of the key operating features of Radiance. It is also possible to reach the remaining Radiance features by modifying the original text-based inputs (Lim, Ahmad, & Ossen, 2010; Minstrick, 2000). The 3D model used in Desktop Radiance is created either in Radiance or in the above programs. It is also possible to import the model from other 3D modeling tools in compatible 3D formats.

To obtain proper photometric analysis, the model should include appropriate amount of details and the exterior should be modeled closely enough to calculate amount of daylight striking an opening adequately. Before proceeding to simulations, the complete 3D model should be edited by assigning Radiance materials onto each surface. These materials can be chosen from the Desktop Radiance Library or the Material Editor can be used for creating user-defined materials (Minstrick, 2000). The site location (entering longitude-latitude values or choosing from one of the available cities), the date, the time and sky condition should also be defined too, before running a simulation. The sky models used by the Desktop Radiance are the models of International Commission on Illumination (CIE) which are CIE clear sky, CIE intermediate sky, CIE overcast sky and uniform sky. It is also possible to discard daylight computations by entering the time as the middle of the night (Kim & Chung, 2011; Minstrick, 2000). The Desktop Radiance can make analysis on “single reference points” or “grids of reference points”; the latter is used to compute the horizontal illuminance. It is also possible to produce “detailed renderings” of the 3D model through which the illuminance or luminance values of each rendered surface can be learned. The Desktop Radiance has two alternative rendering modes; batch processing and an interactive mode that utilizes the rview program (Minstrick, 2000).

2.3.2. DesignBuilder

DesignBuilder is a building simulation tool which carries out analysis on energy consumption, carbon emissions, occupant comfort, daylight availability and works as an evaluation tool on determining the current conditions of the buildings with regard to several building regulations and certification standards.

DesignBuilder was launched as the first Graphical User Interface to the EnergyPlus simulation engine and the latest version of the program (Version 3) includes the first advanced Graphical User Interface to EnergyPlus HVAC systems and a daylight evaluation tool that uses the advanced Radiance ray-tracing engine (DesignBuilder, 2012).

The 3D model used in DesignBuilder can be created by an integrated OpenGL solid modeler or can also be imported from 3rd party BIM tools supporting the gbXML standard like ArchiCAD, Microstation and Revit. Imported 2D CAD floor plan data can be traced by DesignBuilder and used as a base for modeling. DesignBuilder provides three types of daylighting calculations; “daylight contour plots, average daylight factor and uniformity outputs by using the Radiance simulation engine”, “reduced electric lighting and consequent energy and carbon savings through EnergyPlus simulations” and “photo-realistic renderings by Radiance” (DesignBuilder, 2012). By using the Radiance simulation engine, it is possible to calculate daylight factors and illuminance as well as to generate high quality illuminance contour plots within the zones, the blocks or for a slice through the whole building. The sky models are similar to the ones used by Radiance (DesignBuilder, 2012). DesignBuilder uses also EnergyPlus simulations to determine the impact of daylighting strategies (decrease in electric lighting usage) on energy and carbon savings based on analysis of available daylight, site conditions, window management regarding solar gain and glare, and various lighting strategies (DesignBuilder, 2012).

2.3.3. Autodesk Ecotect Analysis

Autodesk Ecotect Analysis is a sustainable design analysis tool that provides a wide range of simulation and building energy analysis functions by using desktop and web-service platforms. The program uses Green Building Studio web-based service to carry out whole-building energy, water and carbon analysis and integrates them with desktop tools for visualizing and simulating building's performance. The program aims to help the designers in the schematic phases of their designs and guide their design decisions on orientation, floor plan depth, glazing sizes, etc. Regarding this purpose, the 3D model used in the software needs to be as simple as possible with no non-essential details; almost like a massing model with defined zones for air-conditioning or daylighting (Ecotect, 2012; Green Building Studio Manual, 2011). Ecotect Analysis together with Green Building Studio can produce data on whole-building energy analysis, thermal performance, water usage and cost evaluation, solar radiation, daylighting and shadows and reflections (Ecotect, 2012).

Ecotect Analysis carries out lighting analysis by several different methods. The program can create daylighting information by using the BRE daylight factor calculations integrated into Ecotect Analysis or by exporting the model to Radiance. Autodesk Green Building Studio also performs daylighting calculations using the LEED prescriptive method for evaluating the buildings for LEED Daylighting Credit Potential. It is also possible to calculate electric lighting as footcandle levels by BRE daylight calculation or by Radiance exports (Ecotect, 2012).

2.3.4. Velux Daylight Visualizer

Velux Daylight Visualizer is a daylighting design and analysis tool aiming to increase the use of daylight in buildings and help designers to predict the daylight quality of their designs before construction stages. The program runs on both Mac OSX and Windows7 platforms. The integrated modeling tool of Velux Daylight Visualizer can be used for creating quick and simple 3D models. The modeler only permits creating orthogonal shapes as well as the exception of the rotatable custom object entity, so it can be inflexible and inadequate when trying to model complex geometries. By using the 3D importer feature, it is possible to import 3D models. The imported 3D models should only be made of polygons and to prevent light leaks, the polygons should be attached together properly. Furniture created with other programs can be used in the imported models if they are inserted before importing the model to Daylight Visualizer. There are some other restrictions in Daylight Visualizer like the textures can only be applied to horizontal surfaces and there is no undo function in the program. In the simulations, Velux Daylight Visualizer uses sky types defined by CIE. By utilizing Velux Daylight Visualizer, the simulation outputs that can be acquired are; luminance, illuminance, daylight factor and daylight animation (Velux, 2012).

2.3.5 Physical Correctness and Adaptability for New Technologies

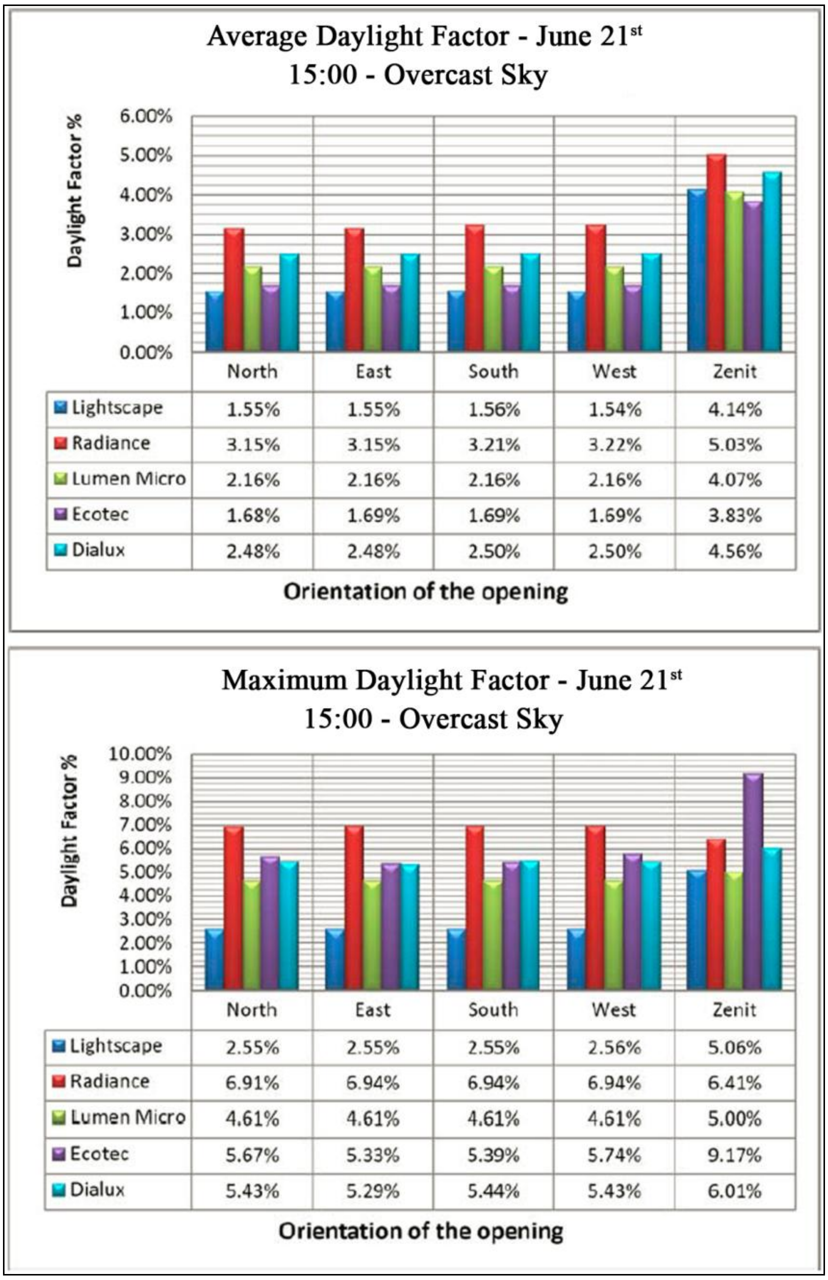
In recent years, daylighting simulation tools have become commonly used by lighting designers and professionals. Increasing trust in their accuracy and decreasing use of scale models may result in their wider use. However, their users still remain less than the others using other building simulation software. Since, users may tend to use easy, practical and reliable daylighting tools and when they cannot reach adequate information, self-teaching materials, convenient databases, practical user-interface or reliable analysis results; they avoid using them (Reinhart & Fitz, 2006; Reinhart & Wienold, 2011). In this section, “physical correctness” and “adaptability to new technologies” and in the following chapter, “usability” of four programs; Desktop Radiance, DesignBuilder, Ecotect and Velux Daylight Visualizer, were discussed through a review of related previous studies. A summarized comparison of the working principles of these four programs is given in Table 2.1.

Physical correctness depends on competence of 3D models, the various characteristics of materials, sky conditions and external obstructions. Various sky model types are used by these tools to indicate different sky conditions. However, it is almost impossible to cover all real sky conditions since they vary unpredictably due to time, location and occlusion. This inconsistency between the real sky conditions and the sky models of daylighting tools cause simulation errors and affect physical correctness of the tools.

Table 2.1. An overview of daylighting simulation tools

	Desktop Radiance	**DesignBuilder**	**Autodesk Ecotect Analysis**	**Velux Daylight Visualizer**
References	Kim and Chung 2011; Minstrick 2000; Bhavani and Kahn 2011; Lim et.al. 2010; Acosta et al. 2011; Ng 2001; Christakou and Silva 2008.	DesignBuilder 2012	Ecotect 2012; Green Building Studio Manual 2011, Acosta et al. 2011, Attia et.al. 2009; Christakou and Silva 2008.	Velux 2012; Labayrade et al. 2010.
Available daylighting calculations	reference points detailed renderings	reference points detailed renderings	reference points detailed renderings by Radiance; evaulation for LEED Daylighting	reference points detailed renderings
Daylighting Outputs	illuminance, luminance, daylight factor, photo-realistic renderings, daylighting contour plots	daylighting contour plots, average daylight factor, illuminance, and photo-realistic renderings by Radiance; electric and carbon savings by EnergyPlus	daylighting contour plots, average daylight factor, illuminance, uniformity outputs and photo-realistic renderings by Radiance; results for LEED Daylighting Credit potential	daylighting contour plots, average daylight factor, illuminance
Available sky models for daylighting calculations	CIE clear sky, CIE intermediate sky, CIE overcast sky and uniform sky	CIE sunny clear day, CIE clear day, CIE sunny intermediate day, CIE intermediate day, CIE overcast day, CIE overcast day (10000 lux) and uniform cloudy sky.	CIE clear sky, CIE intermediate sky, CIE overcast sky and uniform sky	CIE Standart Overcast Sky, Partly Cloudy Sky , CIE Standard Clear Sky
3D Modeling	in Radiance or in the programs DR is a plug-in. Importing is allowed.	by integrated OpenGL solid modeler or importing from programs	in Ecotect or importing in compatible formats	by the integrated modeler or by importing

To show these dependencies, a study by Acosta, Navarro and Sendra (2011) tried to identify how the sky models of the different tools affect daylighting calculations. To achieve this, a simple room with a square opening on one side was modeled identically in five tools; Lightscape, Desktop Radiance, Lumen Micro, Autodesk Ecotect Analysis and Dialux. Overcast sky conditions and a common day were selected for each simulation. Firstly, the researchers changed the opening orientation in each simulation (north, east, south, west, zenith) to understand how each tool responded to this variation. Findings showed significant differences in daylight factor results, illuminance levels, and coefficients of uniformity for each simulation tool (Figure 2.18).



	North	East	South	West	Zenit
Lightscape	1.55%	1.55%	1.56%	1.54%	4.14%
Radiance	3.15%	3.15%	3.21%	3.22%	5.03%
Lumen Micro	2.16%	2.16%	2.16%	2.16%	4.07%
Ecotec	1.68%	1.69%	1.69%	1.69%	3.83%
Dialux	2.48%	2.48%	2.50%	2.50%	4.56%

	North	East	South	West	Zenit
Lightscape	2.55%	2.55%	2.55%	2.56%	5.06%
Radiance	6.91%	6.94%	6.94%	6.94%	6.41%
Lumen Micro	4.61%	4.61%	4.61%	4.61%	5.00%
Ecotec	5.67%	5.33%	5.39%	5.74%	9.17%
Dialux	5.43%	5.29%	5.44%	5.43%	6.01%

Figure 2.18. Distribution of daylight factors obtained from each software due to orientation (Source: Acosta, Navarro, & Sendra 2011)

Highest illuminance levels were obtained by Desktop Radiance for all orientations. Ecotect results were almost half of them. But they were in acceptable limits for all software. The understanding of overcast sky by each tool was differed from each other. So, physical correctness of each tool varies due to their sky interpretation.

Secondly, distribution of light according to time was analyzed in the same study. Only the uniformity coefficients of Desktop Radiance varied with the time remarkably. Thus, Desktop Radiance was sensitive to time variation due to the addition of sky-turbidity-factor in its algorithms. Ecotect results had very small shifts in daylight factor values for the same time interval, but Desktop Radiance showed inconsistent and relatively greater values when compared to the other tools. Consequently, in overcast sky conditions, Desktop Radiance was found to be more sensitive to time when compared to Ecotect and other tools. Its daylight factor values tend to be higher than Ecotect in all conducted simulations in that study.

With a similar purpose, another study compared Desktop Radiance results with scale-model measurements conducted under intermediate and overcast tropical sky conditions in Malaysia. The simulated results showed high mean differences from the scale-model measurements such as 81.63%, 71.06% and 49.71% with external illuminance, absolute work plane illuminance and absolute surface illuminance respectively (Lim et. al., 2010). Daylight factor and luminance ratios were better comparisons with 26.06% and 29.75% mean differences. These errors basically based on the inconsistencies between the tropical sky and CIE sky models. Desktop Radiance failed to predict the external illumination in acceptable limits, though results were closer to the actual conditions under the CIE overcast sky when compared to CIE intermediate sky. According to Lim et al (2010), this was due to the luminance distribution of the tropical sky being more uniform during overcast conditions (Figure 2.19).

It is challenging for daylighting simulation tools to use sky models that are in complete harmony with extreme and rapidly changing real sky conditions. One reason for that may be the tendency of the software developers to constitute sky models that imitate general sky characteristics worldwide. Using these sky models for extreme sky conditions like tropical sky, the inconsistencies in the simulation results are inevitable.

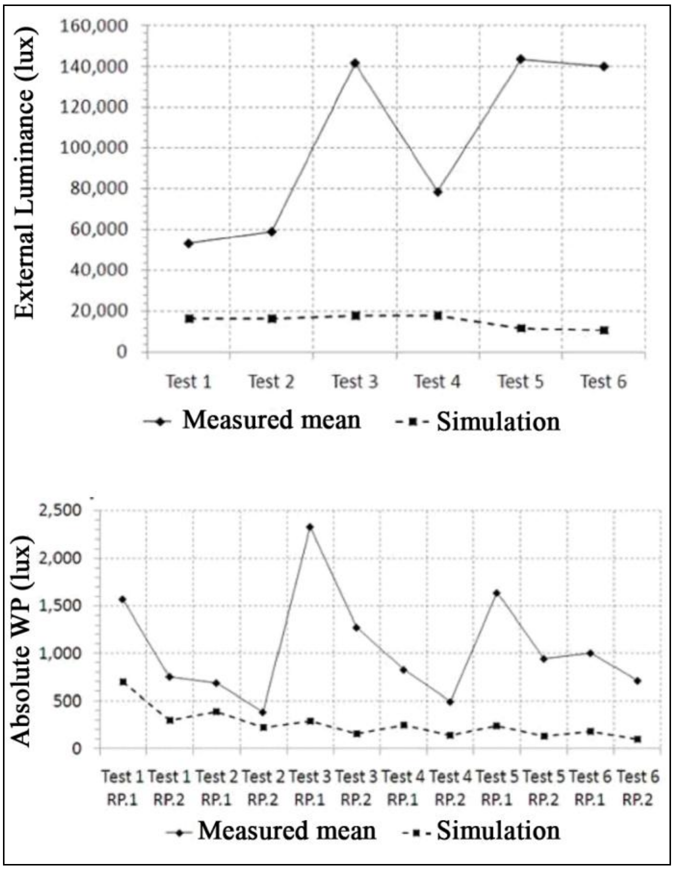


Figure 2.19. Measured and simulated illuminance
(Source: Lim, Ahmad, & Ossen, 2010)

High external obstructions affect the amount of daylight striking to openings. In some cases that may lead computational errors due to the distorted local sky conditions, and affect the physical correctness of daylighting tools. Regarding these concerns, in a research by Ng (2001), the simulation abilities of Radiance and Lightscape under conditions with high external obstructions were tested. Simulations carried out with the two tools were compared with the calculated results and the on-site measurements in an extremely dense urban environment in Hong Kong. The on-site measurements were carried out in three apartments located at different levels in a building block between June – October 2000, on cloudy days. For the simulations, the CIE Standard Overcast Sky was used. It was concluded that, on-site measurements substantially matched with the calculation results. Desktop Radiance simulations were similar to the calculation results at higher floor levels and with obstructions less than 30 degrees angles. At lower floor levels or with greater obstruction angles, both Desktop Radiance and Lightscape overestimated the daylight availability. The Desktop Radiance errors increased when the angle was greater than 35 and the error was close to 50% at 60 degrees. It was derived from trial-error simulations that, by lowering the reflectance to 0.2 from 0.4, Desktop Radiance could minimize the errors.

It was proved that external obstructions caused remarkable inconsistencies on daylighting simulation results and affected physical correctness. The obstruction angle and height of the simulated environment does also affect the results and may increase the errors. Under overcast sky conditions Desktop Radiance simulation results can be remarkably manipulated by external obstructions. Desktop Radiance overestimates daylight availability with an increasing error at lower floor levels and with obstruction angles higher than 35 degrees.

The comparison and validation studies of simulation programs in the literature that could be attained for this thesis mainly included Radiance, testing it alone or among other simulation tools or simulation results that were validated with measurements. Any studies of validation or comparison with Velux Daylight Visualizer or with Ecotect and DesignBuilder could be hardly reached, apart from the ones that are testing the programs with their Radiance based simulation capabilities. The dominance of Radiance on these studies can be explained by the previously mentioned survey (Reinhart & Fitz, 2006) results. Among 42 different daylighting simulation programs that the survey participants routinely used; over 50% of these programs were the ones that operated with the Radiance simulation engine.

However a study by Labayrade, H.W. Jensen and C.W. Jensen (2010) aimed to validate Velux Daylight Visualizer against CIE 171:2006 test cases. The validation results showed an average error of 1.8% and a maximal error of below 6% with respect to the reference for eight identified settings proving the accuracy of Velux Daylight Visualizer.

In designing low-energy buildings, material selection becomes an important criterion. By modifying the material characteristics like transparency, reflectivity or absorptivity, architects aim to design high energy performance buildings. To evaluate their daylighting performance, such tools should be adaptable to accurately simulate these complex new materials. For example, Thanachareonkit, Scartezzini and Robinson (2006) conducted an error analysis on the complex fenestration systems (prismatic films and laser-cut panels) simulation techniques by using Radiance. A 1:10 scale model under a scanning sky simulator and an identical Radiance model under CIE overcast sky were compared while both equipped with conventional glazing, laser-cut panel and prismatic film on the side opening respectively. With conventional glazing, the results showed a relative divergence of 1 - 9.2 % proving high accuracy of Radiance. With a laser-cut panel mounted to the window, it was 0.5 - 16%, while with prismatic film; it was 2.2 - 35%. Secondly, a sensitivity analysis of surface reflectance was carried out. 10 - 50% overestimation of surface reflectance caused 5 - 52 % relative deviation above the scale model values, while a similar underestimation range of surface reflectance caused 10 - 40% lower values. Laser-cut panel and prismatic film results were slightly differed from each other and both results were comparable with the glazing model. Thus, simulation techniques of laser-cut panels and prismatic films by using Radiance were validated.

A similar research was conducted aiming to validate trans and transdata Radiance material types and to constitute corresponding Radiance material from a translucent panel by using goniophotometer and integrating sphere measurements. After adjusting indoor illuminance simulation results with a ratio of measured to simulated façade illuminance, the errors were under 8% and 10% for transdata (Reinhart& Andersen, 2006).

As mentioned above, daylighting designers have been rapidly using the complex materials and advanced daylighting systems in their designs recently. Apart from the design decisions like orientation, amount of openings, floor plan depth, etc; using these modified materials and advanced daylighting systems provide remarkable energy savings. To evaluate the daylighting performance of the buildings with these new technologies, simulation tools should be adaptable to these consistent changes. As can be derived from the mentioned studies, simulation techniques of Radiance for complex fenestration systems (in this case laser-cut and prismatic panels) as well as the trans and transdata Radiance material types has been verified recently. Also, the ability of Radiance; constituting corresponding Radiance material from a translucent panel by using goniophotometer and integrating sphere measurements has been validated. With the new technological progresses in daylighting systems, materials and co-elements like paints or isolative films; the adaptability of the simulation tools to new technologies is crucial.

2.3.6. Usability of Simulation Tools

Researchers pointed out that, professionals, in general, prefer to learn the daylighting simulation tools by themselves. The ones which are easily understood by intuition and provide easy operation decrease learning period of time for the users. Even, the longer the time spent in self-teaching, the faster the users avoid from using these tools. Thus, daylighting simulation tools should offer efficient tutorial options and simple simulation environment (Reinhart & Fitz, 2006; Reinhart & Wienold, 2011). User interface is the center of interest for architects, since it is the link between them and digital processes in the background (Christakou & Silva, 2008).

Related studies mostly based on users' opinion and preferences, and the concept named here as "usability"(or user-friendly) involved criteria such as being intuitive and simple, having less learning time and user manual and data output options. This term mainly depends on the interface operation (graphical based or text based) and capability. Menus, on screen clickable items which are perceived immediately are requisite. Usability secondly based on information management of interface (Attia, Beltrán, Herde, & Hensen, 2009). In relation to this, Reinhart and Wienold (2011) defined barriers such as the misleading interpretation of simulation results or outdated evaluating schemes. Visually accessible simulation results are preferable.

According to the research conducted among users' opinion about simulation software (Attia et. al., 2009), usability is related to "better graphical representation, of simulation input and output, simple navigation and flexible control". Ecotect and Design Builder fully matched these criteria except "easy follow up structure" for the former and "graphical representation of results in 3D spatial analysis" for the latter. Due to the criteria concerning information management, users considered Ecotect as insufficient in creation of comparative reports and Design Builder as unsuccessful in the quality control of simulation input (Figure 2.20).

On the other hand, Radiance's interface was not defined as friendly by a reference cited in Christakou and Silva (2008). Their research included both users' opinion and the application of software in a design process. Findings showed that Ecotect was not the most suitable software and not intuitive when compared to Relux, but had user friendly interface.

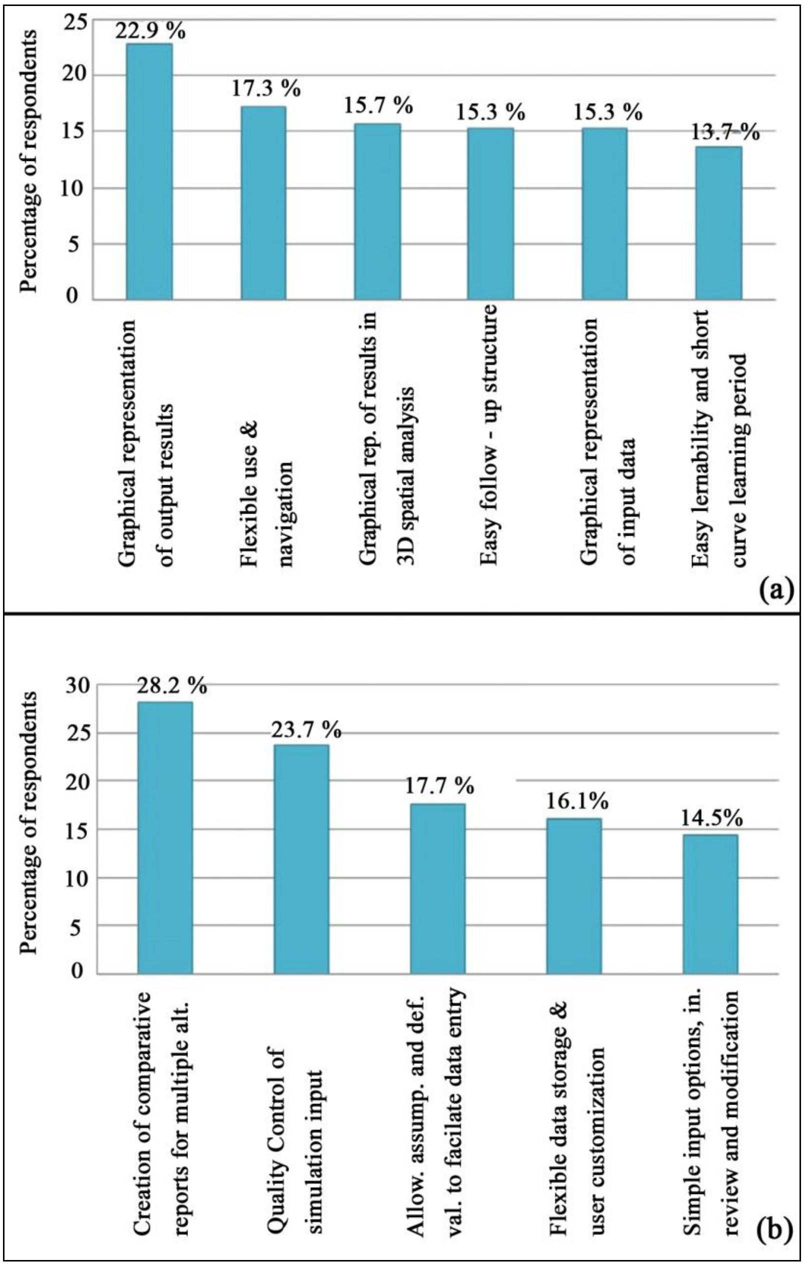


Figure 2.20. Criteria concerning (a) usability and graphical visualization usage pattern, (b) information management according to user's opinion (Source: Attia, Beltrán, Herde, & Hensen, 2009)

The study by Reinhart and Ibarra (2009) supported the usability of Ecotect due to users' preferences. According to this study about beginners' choice for using a software (Ecotect versus Radiance), it was stated that none of them preferred to run simulations by exporting to Radiance, but they used Ecotect analysis instead. However, a large number of students imported their model into Ecotect after modeling it with another program due to limitations of modeling capabilities of Ecotect. This showed that inappropriateness in flexible data storage and input options affected user's choice of simulation tool. Users in this study also paid attention to simulation tips which can be useful for the instructors. Regarding these, it can be derived that, easy learnability and simple navigation were suitable features in Ecotect. Literature about the usability of Velux was not cited.

Consequently, a majority of the studies analyzed Radiance as the mostly used daylighting tool. Output results by Radiance were found to be within acceptable limits, although its physical correctness might fail in some cases due to real sky conditions (such as tropical). However, Radiance is sensitive to time variation when compared to Ecotect. In regard to usability, Ecotect seems to be a practical tool because of its shorter learning time and simple navigation, user friendly interface and better graphical representation. It is important to note that Desktop Radiance also uses Ecotect's user interface as a plug-in. It can be concluded that, determining the most accurate daylighting simulation tool among the four compared simulation tools is a complex task. Each one has its own strengths and weaknesses. And it is obvious that the developments in the field of simulation technologies will continue with a growing acceleration aiming to improve these weaknesses. This study suggests that; among the analyzed simulation tools, Radiance and Ecotect together might be preferred in daylighting calculations, especially when designing and examining the effects of advanced daylighting technologies such as laser-cut or prismatic panels (Table 2.2).

Table 2.2 Strengths / weaknesses of usability for Ecotect, Radiance and DesignBuilder

	Strengths	**Weaknesses**
Ecotect	Less learning time and simple navigation (simulation tips for instructors) user friendly interface better graphical representation	inappropriateness in flexible data storage and input options (Limitations in 3D modeling) not easy follow up structure not intuitive
Design Builder	simple navigation flexible control	graphical representation of results in 3D spatial analysis
Radiance		not user friendly not preferred by beginners

CHAPTER 3

MATERIAL AND METHOD

This chapter involves two subsections, namely, physical facility and the analysis of daylight illuminance and uniformity. The former is a description of the subject building where the field measurements were taken place. The analysis includes both the explanations of the measurement process and the steps of the modeling phase.

3.1. Physical Facility

The study was carried out in the educational building of the Faculty of Architecture in Izmir Institute of Technology. The building is situated in the west part of the campus on a hilly site (latitude 38° 19’ north, longitude 26°37’ east) and consists of classrooms, construction laboratories and design studios. The building has three stories, each covering 1600m^2. General layout of the building is shown in Figure 3.1.

3.1.1. Architectural Design Studios in IYTE

There are a total of eight design studios which are on the second and third floor and are occupied for the architectural education. Two of them are facing north and east, two are facing south and east, two are facing south and west and the last two are facing north and west. The story height for all studios is 3.20 m. The surface area of an identical double-glazed window in each studio is almost 4.00 m^2 (Table 3.1). The subject studios in this study are located on the third floor. They are designated with codes; namely, S01, S02, S03 and S04. Each studio has two exterior walls; for example, the longer façade of the studio S01 facing east has three windows and its shorter façade facing south has two windows as the schematical expression of this studio is shown in Figure 3.2. The window ratio (the window area / the floor area) is 11% for S01 and S02, while it is 9% for S03 and S04 both of which have one window in their shorter facade.

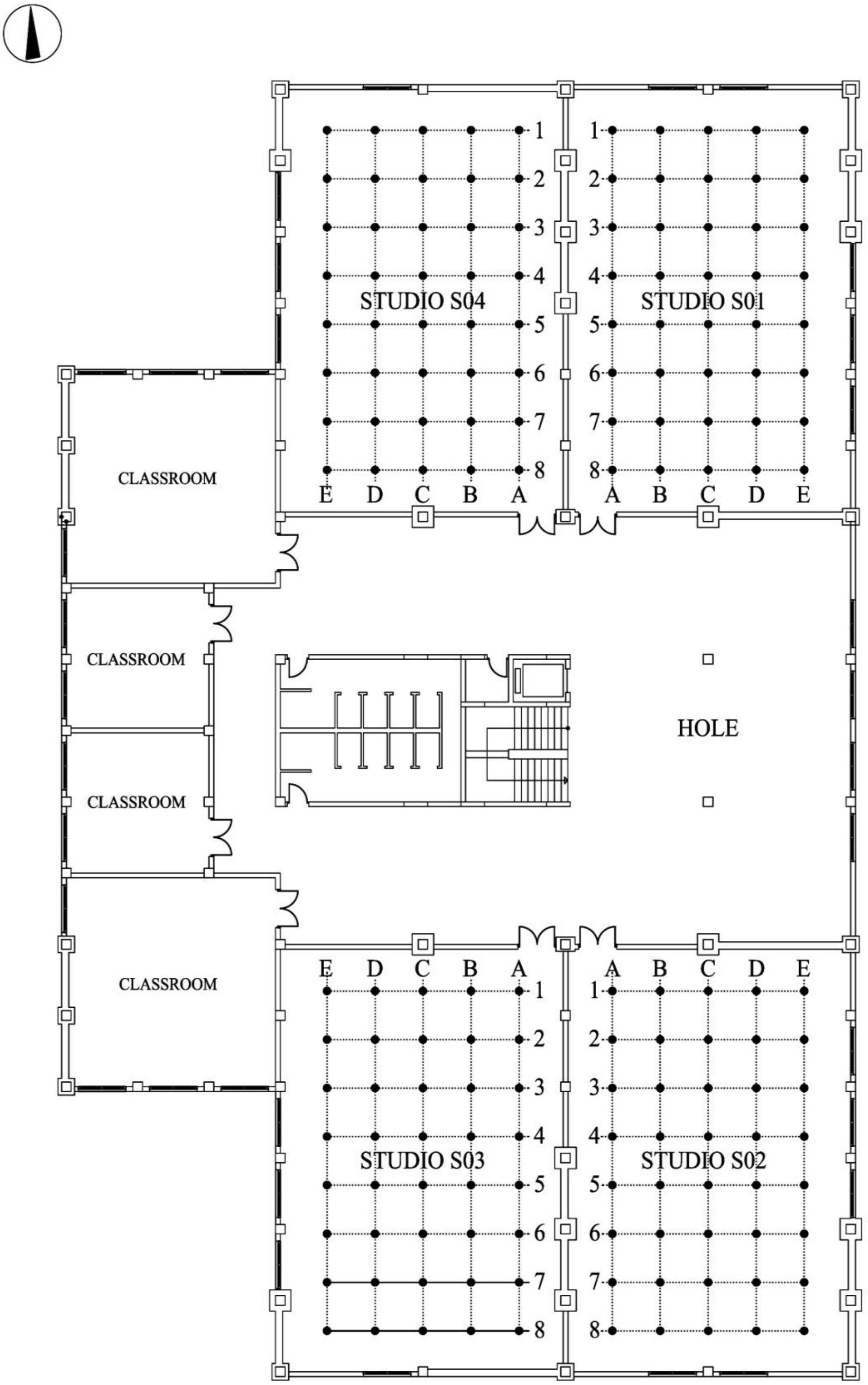


Figure 3.1. General layout of the building (3rd floor) and the measurement points

Table 3. 1. Geometrical properties of the studios

Geometry	**Studio - S01**	**Length (m)**	17.65
		Width (m)	11.25
		Height (m)	3.20
		Facade Area (m2)	92.5
		Glazed Area (m2)	21
		Window Ratio (%)	11
	Studio - S02	**Length (m)**	17.65
		Width (m)	11.25
		Height (m)	3.20
		Facade Area (m2)	92.5
		Glazed Area (m2)	21
		Window Ratio (%)	11
	Studio - S03	**Length (m)**	17.65
		Width (m)	11.25
		Height (m)	3.20
		Facade Area (m2)	92.5
		Glazed Area (m2)	16.8
		Window Ratio (%)	9
	Studio - S04	**Length (m)**	17.65
		Width (m)	11.25
		Height (m)	3.20
		Facade Area (m2)	92.5
		Glazed Area (m2)	16.8
		Window Ratio (%)	9

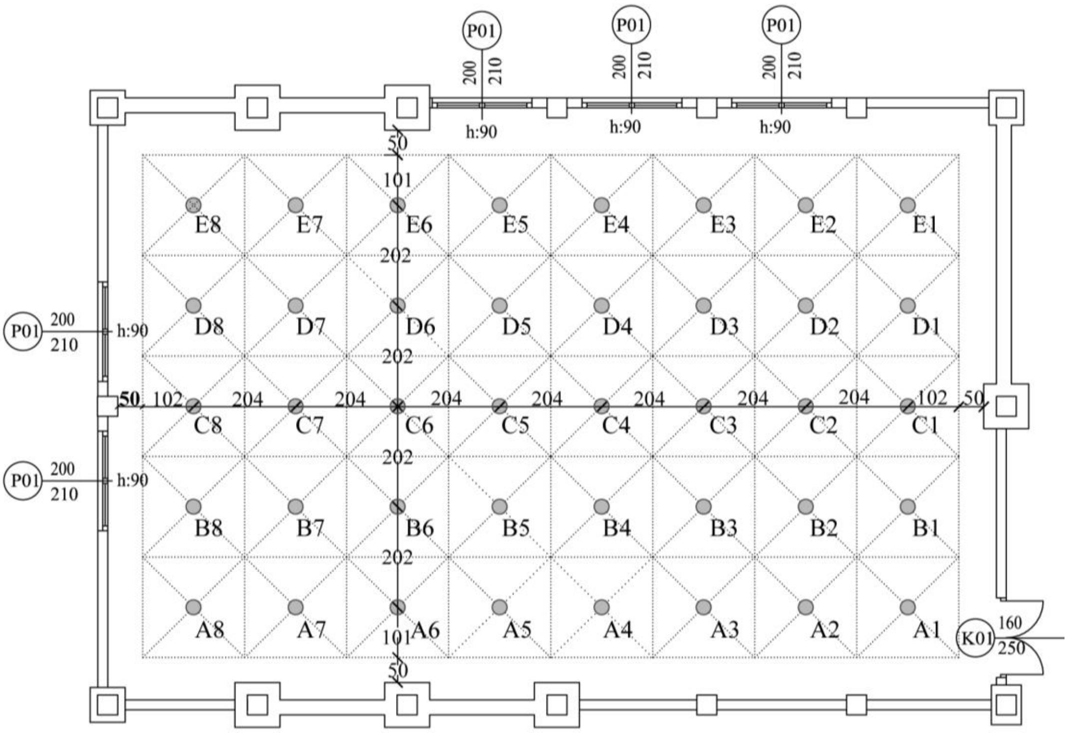


Figure 3.2. Layout of Studio S01

3.1.2. Climatic Data for Izmir

The climate type of İzmir is described as humid subtropical which is mild with no dry season, hot summer. According to the monthly statistics showing dry-bulb temperatures (°C) for İzmir, May and June have the highest daily average temperatures following the values obtained in July and August (World Climate Design Data 2001 ASHRAE Handbook). The sun position for the two selected dates for this thesis for daylight simulations, May 4th and June 21st, is identified with the azimuth and altitude angles obtained by Ecotect. These angles are 105.5^0 and 42.8^0 at 9:00; -150.2^0 and 64.5^0 at 13:00; and -97.6^0 and 34.7^0 at 16:00 on May 4th. However, on the summer solstice, the sun is at the highest level. The angles are 95.7^0 and 46.4^0 at 9:00; -143.4^0 and 72^0 at 13:00; and $-89.8^0$and 40^0 at 16:00 on June 21st. Direct solar exposure (radiation) may be obtained as 750 W/m^2, 845 W/m^2, and 360W/m^2; and 780 W/m^2, 790W/m^2 and 580 W/m^2 respectively.

3.2. Analysis of Daylight Illuminance and Uniformity

In this study, the output parameters obtained from the field measurements and the simulation model were daylight illuminance and uniformity ratios. They were evaluated in accordance with daylighting design norms. Daylight illuminance defines the amount of light intensity which penetrates inside through the glazed surfaces. While daylight illuminance provides information about the amount of light at specific points, the uniformity gives an idea about the distribution of light intensity throughout the horizontal working area. It is a measure of the balance of daylight illuminance inside.

3.2.1. Field Measurements

By following certain practical guidance offered by Chartered Institution of Building Services Engineers [CIBSE] (1996), field measurements were carried out to determine daylight illuminance at reference points. The number of measurement points and their locations were also determined according to the recommendations of the CIBSE Code 1994. The number of measurement points is related with the Room Index (ratio between room size and height) and their locations should be defined at the centre of equal small areas which are divisions of the floor area of the room (divided regarding the number of measurement points needed), each of which are as close to square as possible. The measurement is taken at the centre of each small area which is defined by grid points (CIBSE, 1996).

The measurements were carried out in the period between the months of May and June 2012. It covered mainly such prevailing conditions as clear sky and partly cloudy sky. A digital light meter with a silicon photo diode detector was used for the measurements. Measurements were taken 0.5 m away from walls / columns / partitions and grid points were positioned with equal spacing (Fig. 3.2). The constant height for each reading was 0.8 m high from the floor level.

According to DIN 5034 (Licht, 2006), the uniformity values for the daylit interiors should satisfy the equations of $D_{min} / D_{max} > 0.67$ and $D_{min} / D_{ave} > 0.5$. In addition, minimum illuminance values should be 500-750 lux for studios in educational buildings regarding the CIBSE standards (CIBSE, 1994).

3.2.2. Modeling in Autodesk Ecotect / Desktop Radiance

Ecotect modeling was developed for the studio by utilizing building dimensions, materials, location and weather data for İzmir. The consideration was to resemble the actual physical properties of the studios. Each studio was arranged as one zone including glazed openings which are made of single glazing and white aluminum frame. The partitions of the fenestration system were modeled similarly. RAL colour chart was taken into consideration in the selection of surface reflectance values in order to attain physical conditions as close to the existing conditions of the studios as possible (Table 4). The calibration and validation of the model were attained by the comparison of actual daylight illuminance with the model outputs. Climate data for İzmir was uploaded to Ecotect and sun position was calculated in accordance with this weather file and location of the city.

Lighting analysis tool was first used in Ecotect. Model was exported to the Desktop Radiance for more detailed analysis. Daylighting measurements were then compared with the simulation results of Desktop Radiance. A schematic perspective of the Ecotect model is displayed in Figure 3.3.

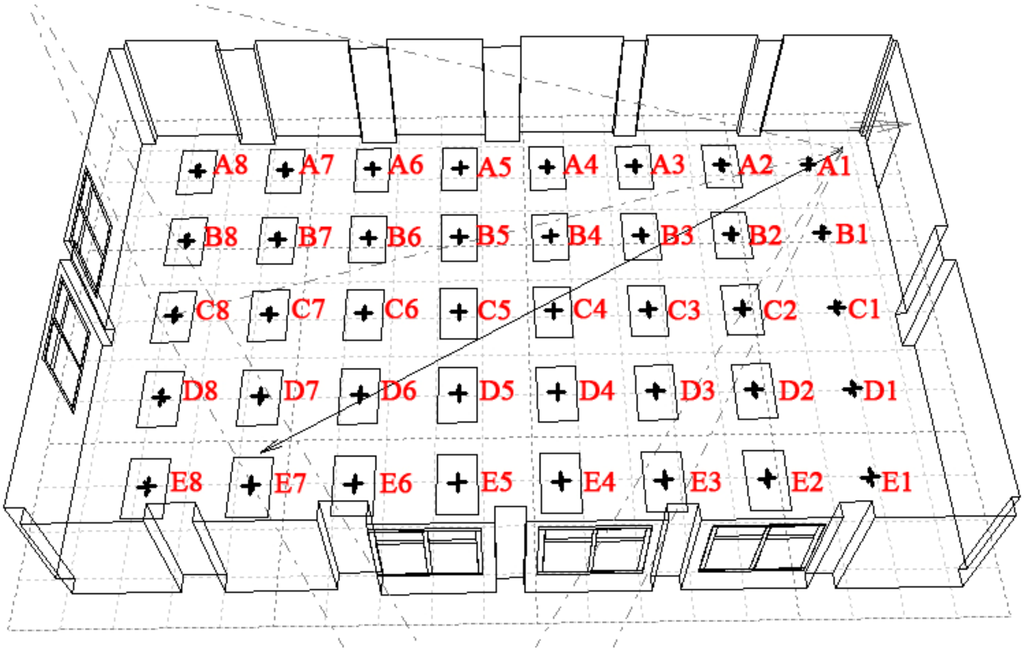


Figure 3.3. Basic layout of the studio S02 displaying measurement points, drawing tables and openings as modeled in Ecotect.

Table 3. 2. Material characteristics of the Ecotect model

Model Characteristics				**Colour Reflectivity**	**Visible Transmittance**
Material	**Interior Environment**	**Wall**	Brick Plaster cream white (RAL 9001)	0.79	-
		Floor	Marble Tiles traffic white (RAL 9016)	0.85	-
		Ceiling	Suspended Concrete Ceiling Signal White (RAL 9003)	0.84	-
	Glazing System	**Window**	Single Glazed (average dirty)	-	0.85
		Frame	Aluminium white	0.84	-
	Daylighting Systems	**Laser Cut Panel**	Acrylic (Parallel cuts)	-	0.92
			Mirror (Optically reflective surface)	0.83	-
		Prismatic Panel	Acrylic (Sawtooth surfaces)	-	0.92
			Mirror (Optically reflective surface)	0.83	-
		Light Shelf	Aluminium	0.83	-

CHAPTER 4

RESULTS

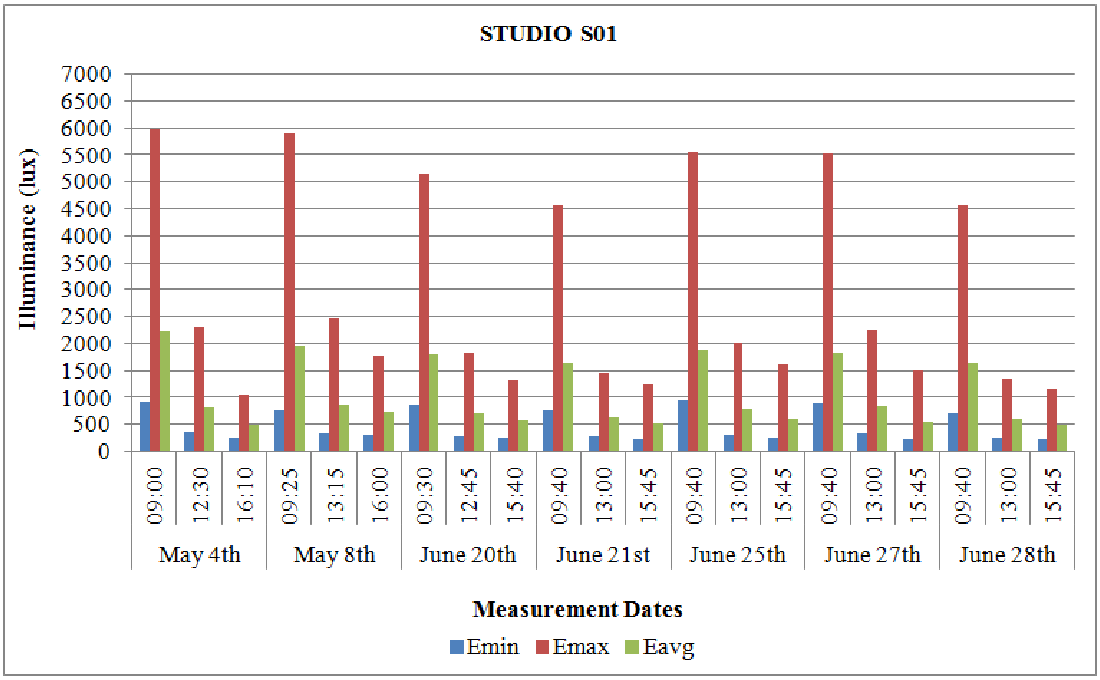
This chapter involves four subsections; general findings obtained from field measurements conducted in architectural design studios, findings regarding simulations based on the field measurements, application of the proposed daylighting systems and a discussion subsection evaluating all results in regard to literature and general daylighting design norms.

4.1. Findings Regarding Field Measurements

All measurements of daylight illuminance were conducted in four architectural design studios in the morning, at noon and in the afternoon. A total of 40 measurement points were determined at each studio and measurements were carried out on certain days in May (i.e. May 4th, May 8th) and June (i.e. May 4th, May 8th, June 20th, June 21st, June 25th; June 27th and June 28th) 2012. The reason why the field measurements were conducted on May and June based on the observation of the highest impact of sunlight on these months during the educational season in Izmir.

The average, minimum and maximum daylight illuminance at four studios for each measurement day and the external horizontal illuminance at the time of the measurements are presented in Figures 4.1 – 4.4.

The average daylight illuminance was in accordance with the external horizontal illuminance as known from literature. However, the inclination line of the external horizontal illuminance depicted several divergences from the average internal horizontal illuminance. For example, although the average illuminance (E_{avg}) in studio S02 on June 27th decreased gradually by time, the same pattern cannot be observed in the external horizontal illuminance for the same day. There was no strict and stable daylight factor throughout the studios during the measurement days.



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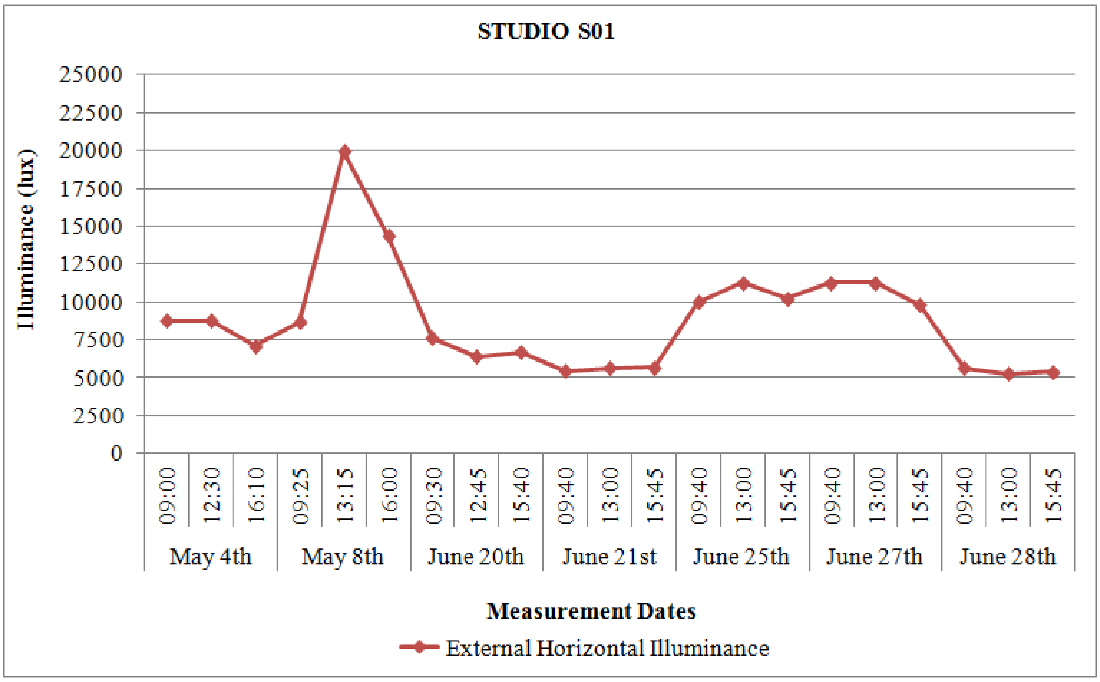
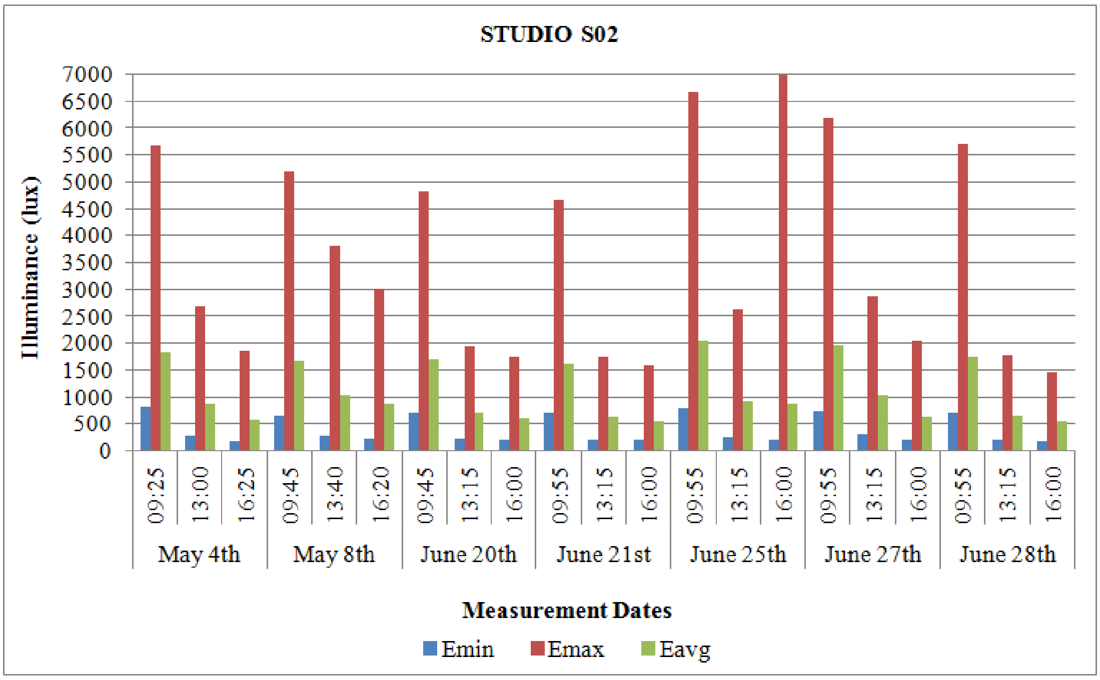


(b)

Figure 4.1. (a) The average, minimum and maximum illuminance in Studio S01 and (b) external illuminance at time of measurements



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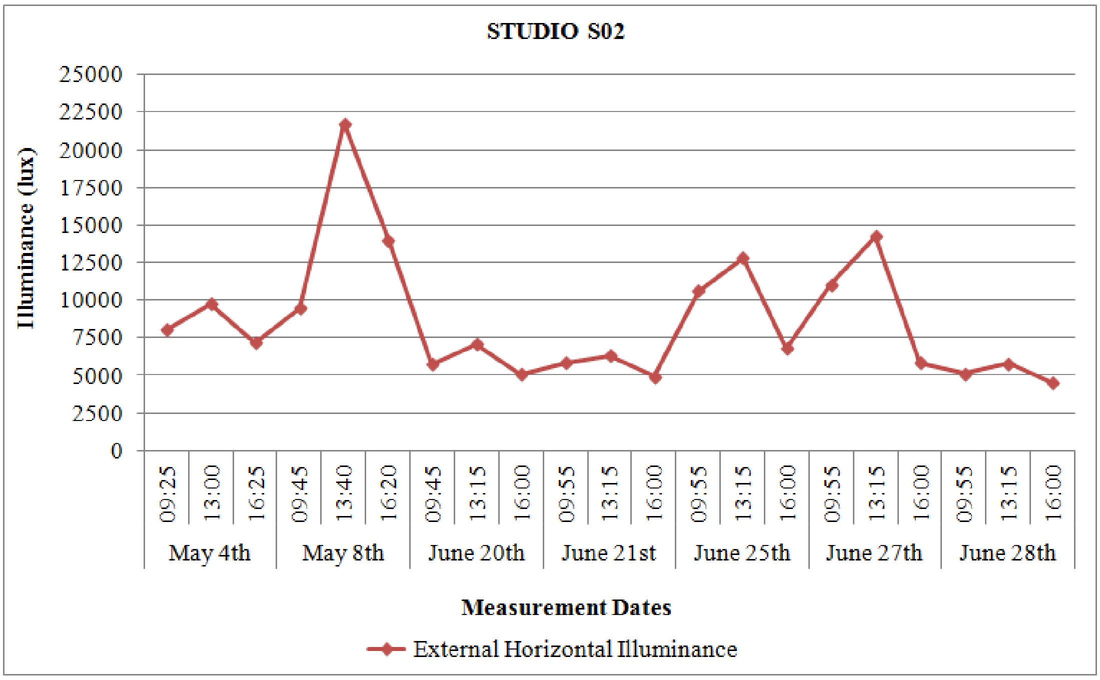
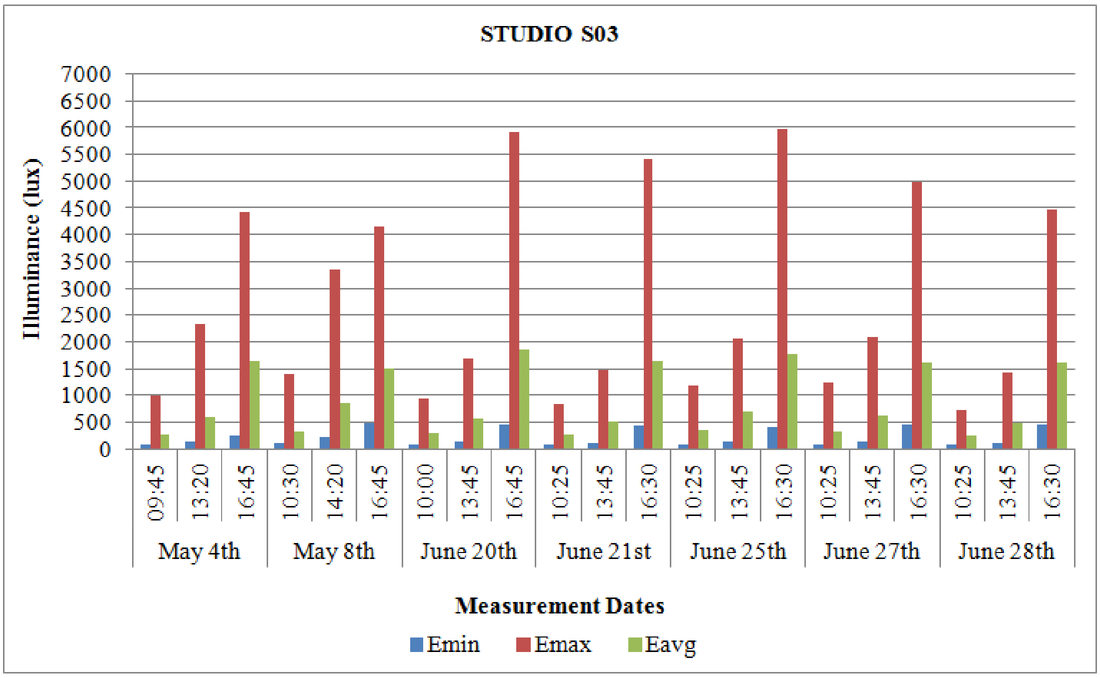


(b)

Figure 4.2. (a) The average, minimum and maximum illuminance in Studio S02 and (b) external illuminance at time of measurements



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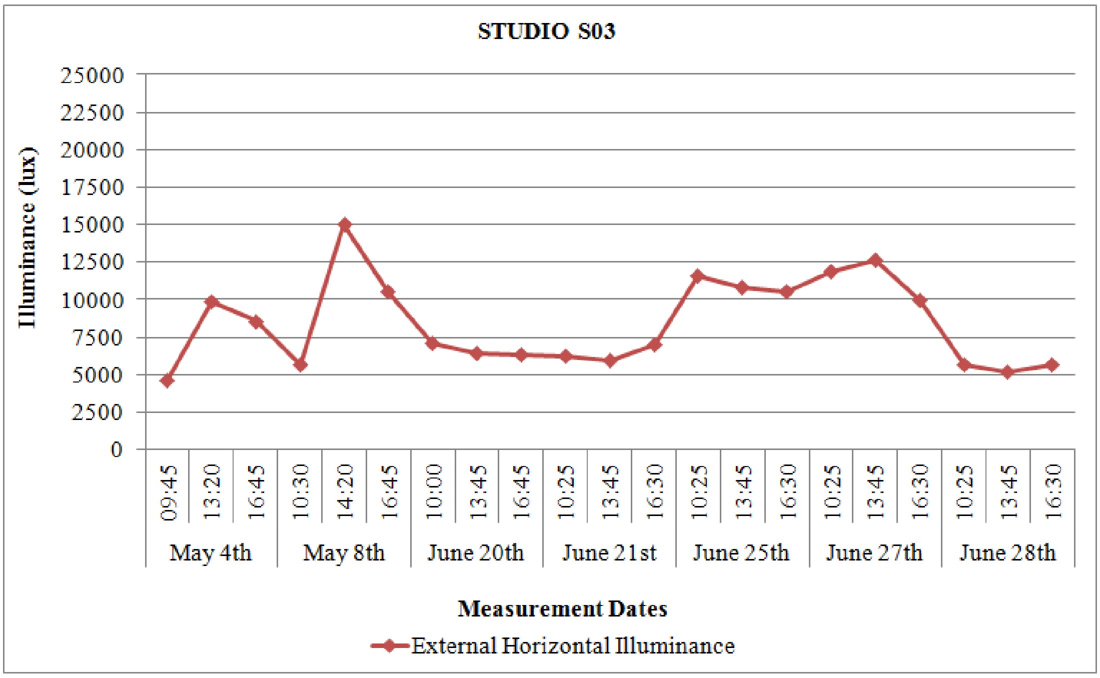
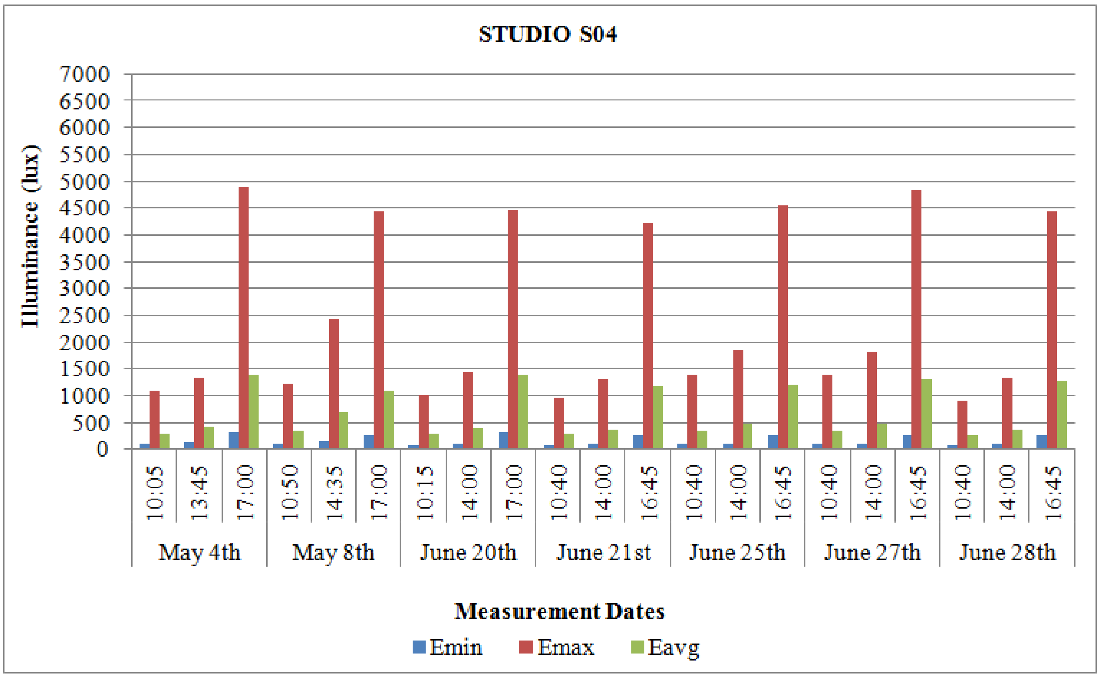


(b)

Figure 4.3. (a) The average, minimum and maximum illuminance in Studio S03 and (b) external illuminance at time of measurements



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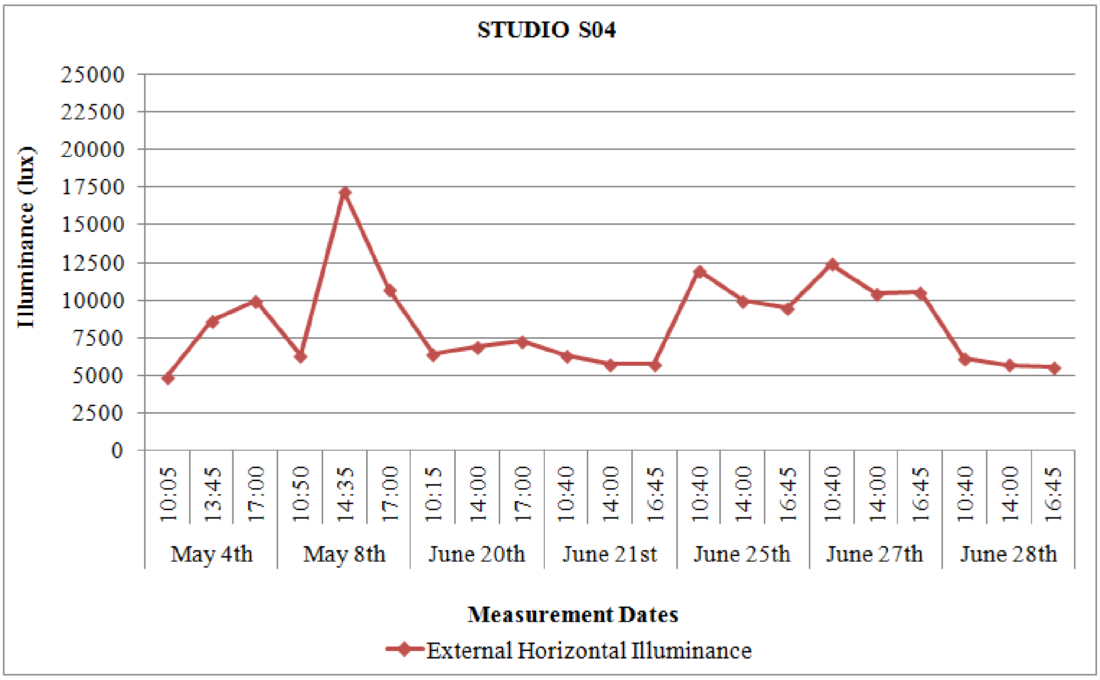


(b)

Figure 4.4. (a) The average, minimum and maximum illuminance in Studio S04 and (b) external illuminance at time of measurements

Such daily and hourly variations in the daylight illuminance at the studios point out the unstable nature of daylight as a light source which is known from the literature. Unpredicted sky conditions and the orientation of the studios were the main causes of these variations.

In this thesis, findings of two selected days were explained thoroughly; namely, May 4th and June 21st 2012. June 21st, when the sun was at its highest position, the summer solstice in the Northern Hemisphere; and May 4th, when the sun was about at its lowest position during these two months. To demonstrate the daylighting conditions of the four architectural design studios on these two days; the distribution of daylight illuminance at each of them is displayed in Figure 4.5 and 4.6.

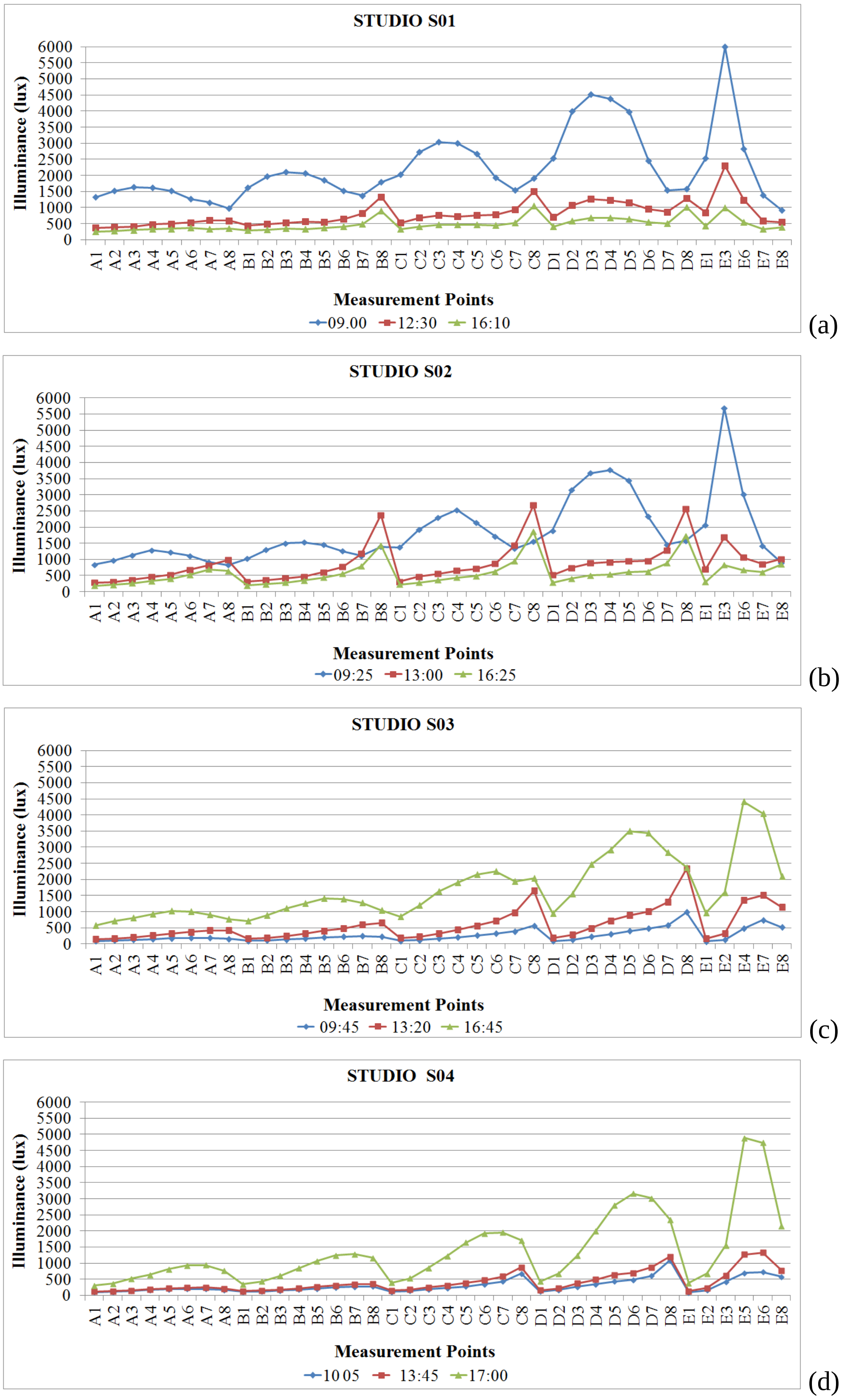


Figure 4.5. Distribution of daylight illuminance at measurement points on May 4th for (a) S01, (b) S02, (c) S03, (d) S04

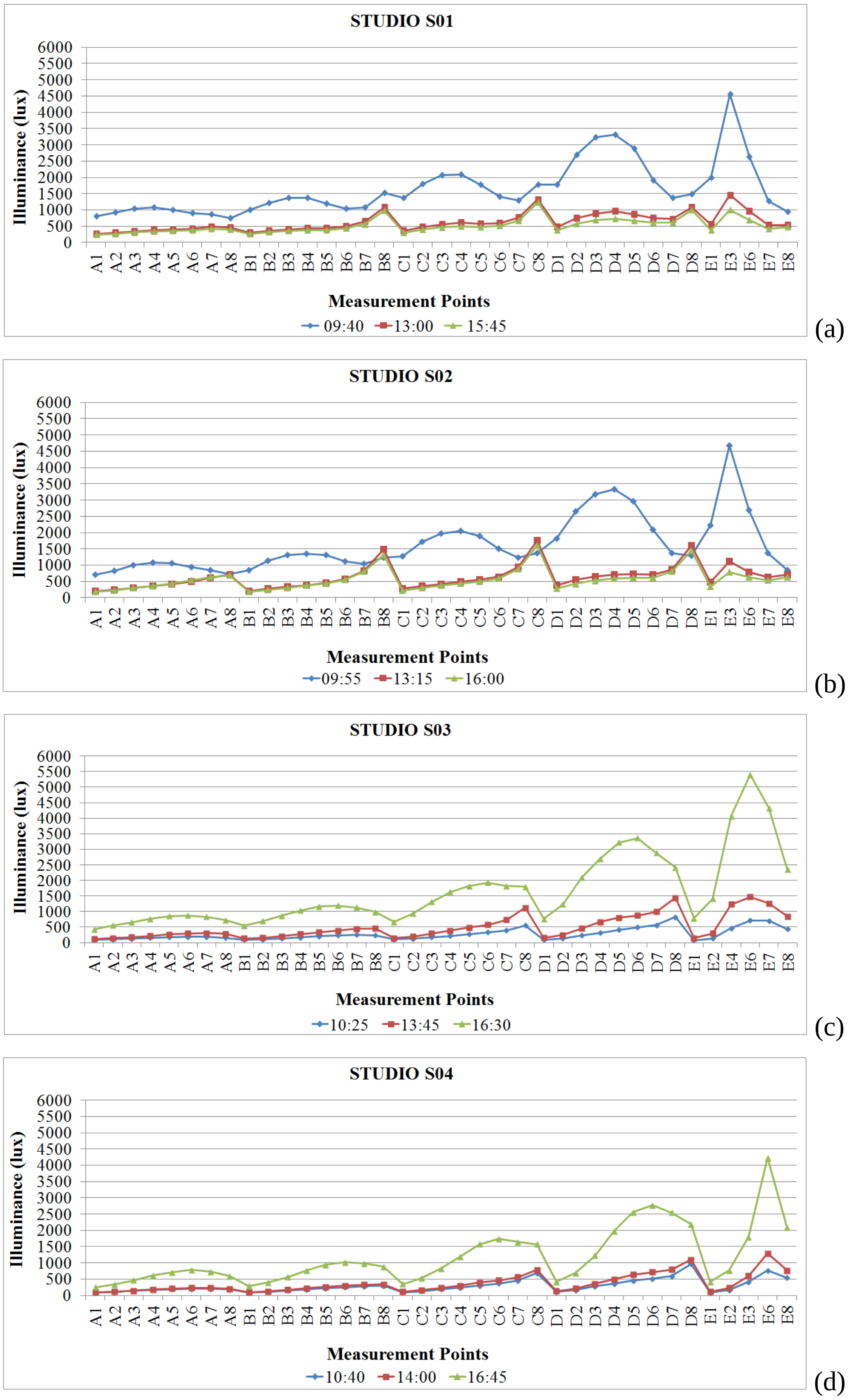
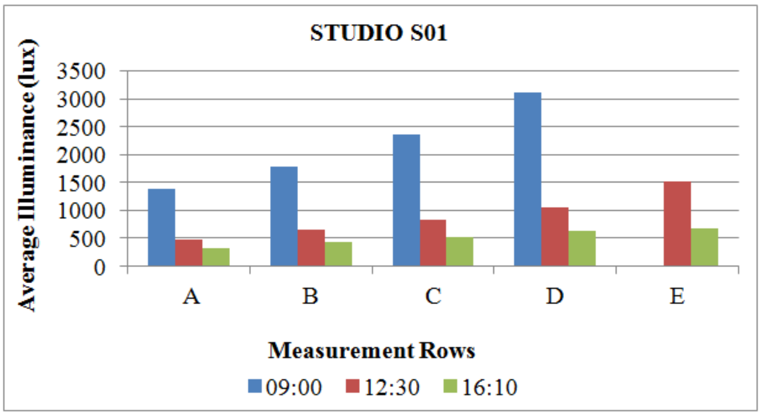


Figure 4.6. Distribution of daylight illuminance at measurement points on June 21st for (a) S01, (b) S02, (c)S03, (d) S04

4.1.1 Studio S01

According to Figure 4.5, on May 4th, in the north and east facing studio S01, the measured daylight illuminance was relatively higher in the measurements at 09:00, than the measurements at noon (at 12:30) and in the afternoon (at 16:10). In the studio, the average illuminance continually increased regardless of time while approaching from row A towards row E, which was the closest row to the main wall which has the highest amount of window area, facing east (Figure 4.7). Sun patches were also observed at 09.00 at three measurement points; namely, E2, E3 and E5 on row E.



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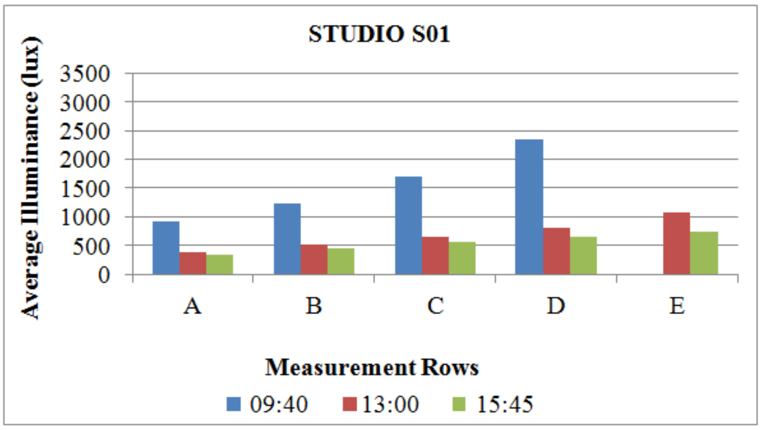


(b)

Figure 4.7. Average daylight illuminance at measurement rows on (a) May 4th and (b) June 21st for S01

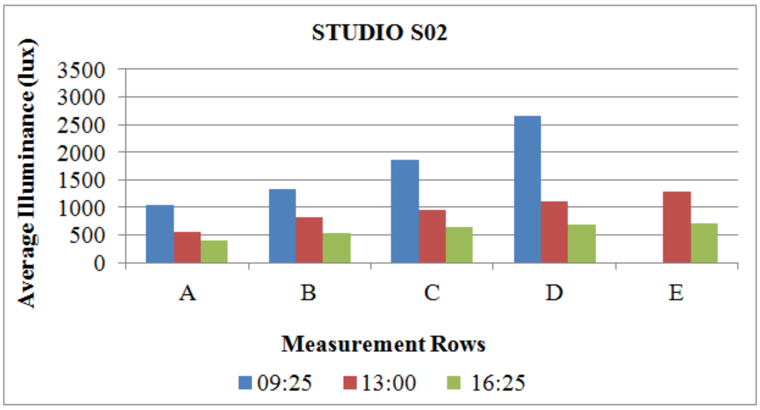
The daylight illuminance at 09:00 was higher at the middle area of the studio (columns 3, 4 and 5) at each row, affected by the east facing windows. At 12:30 and 16:10 measurements, at rows A, B and C; the values tended to peak at the 8th column which was the closest column to the north façade. At rows D and E, the values were higher both at the middle area and at the 8th column, showing the illuminance distribution of the two rows was affected by both facades.

The uniformity ratio D_{min} / D_{max} at 09:00, 12:30 and 16:10 on May 4th was 0.15, 0.16 and 0.24 respectively; far below the suggested ratio of 0.67. The second uniformity ratio, D_{min} / D_{ave} was 0.41 at 09:00, 0.46 at 12:30 and 0.53 at 16:10. This calculated ratio according to the measurements satisfied the recommended ratio of 0.5 at 16:10. Also, the daylight illuminance at more than half of the measurement points was below the recommended illuminance of 750 lux at 12:30 and 16:10. At 09:00, it was above 1000 lux for all points. All these measurements showed significant inefficiencies at the daylight illuminance distribution in the studio S01 on May 4th, for the occupants to conduct the tasks of an architectural design studio.

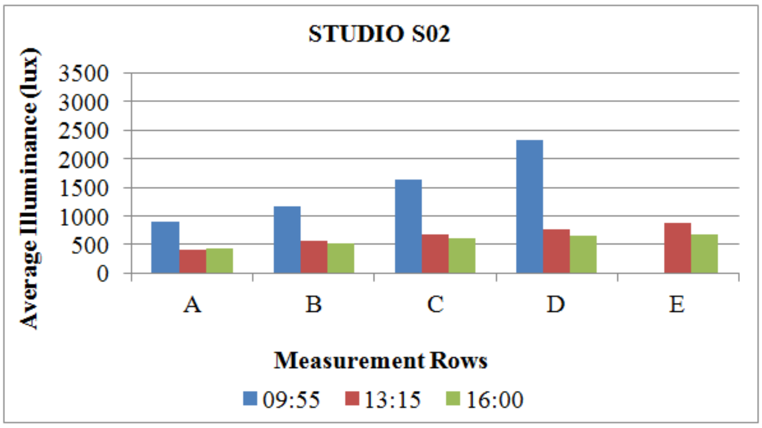
The illuminance distribution on June 21st was quietly similar to the distribution on May 4th for studio S01, as shown in Figures 4.5 and 4.6. However, the average daylight illuminance of June 21st was lower at 09:40 and at 13:00, as the altitude of the sun is at the highest level. The uniformity ratio D_{min} / D_{max} was 0.17 at 09:40, 0.19 at 13:00 and 0.19 at 15:45. Similarly with the ratios calculated for May 4th, they were below the recommended ratios. And the second uniformity ratio D_{min}/D_{ave} was 0.45, 0.43 and 0.46 respectively.

4.1.2 Studio S02

The daylight illuminance distribution of studio S02 on May 4th and June 21st showed similarities with studio S01. The average illuminance increased towards the East façade (from row A towards row E) on both days, regardless of time; as shown in Figure 4.8. Sun patches were observed on the E row at measurement points E2, E4 and E5 at 09:25 on May 4th and 09:55 on June 21st. (The average illuminance of row E obtained from morning measurements on both days are excluded from the Figure 4.8 because of the sun patches.)



(a)



(b)

Figure 4.8. Average daylight illuminance at measurement rows on (a) May 4th and (b) June 21st for S02

The daylight illuminance was higher at the middle area of the studio (columns 3, 4, 5) at each row in the morning measurements, on both days. At the rows A, B, C and D in the noon and afternoon measurements, the values peaked at the 8th column, which was closest to the south façade.

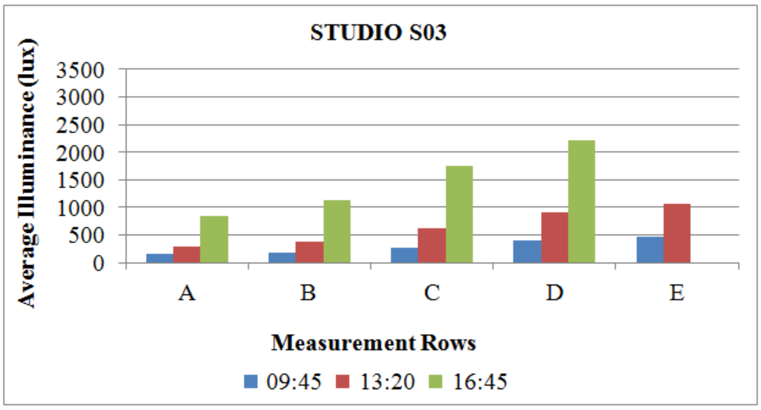
The daylight illuminance at more than half of the measurement points were below 750 lux in the noon and afternoon measurements, while the values were greater than 1000 lux at most of the points in the morning measurements; on both days. The uniformity ratio D_{min} / D_{max} was 0.15 at 09:25, 0.10 at 13:00 and 0.09 at 16:25 on May 4th, indicating a severe divergence from the suggested ratio. D_{min} / D_{ave} ratio was 0.45, 0.31 and 0.39 respectively for the same measurements. The results were almost the same with the uniformity values obtained at June 21st. D_{min} / D_{max} and D_{min} / D_{ave} results showed similar but more unbalanced distribution of daylight illuminance for the studio S02 than the distribution at the studio S01. Like it was at the studio S01, the daylight illuminance distribution at the studio S02 was inefficient on both days, for the tasks of an architectural design studio.

4.1.3 Studio S03

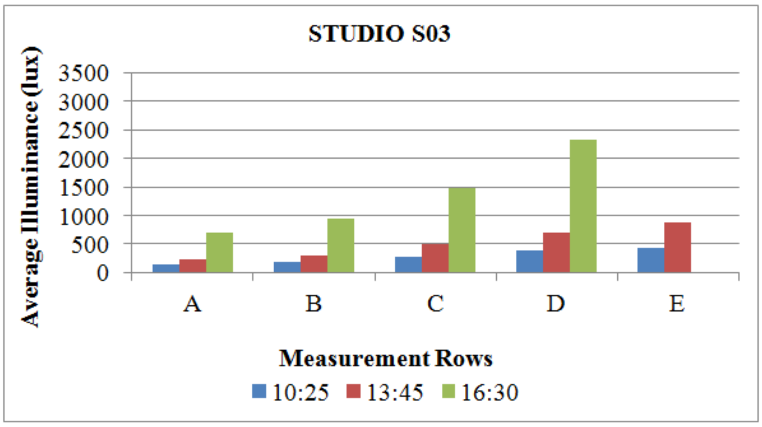
According to the measurements conducted on May 4th, the daylight illuminance of the south and west facing studio S03 was severely insufficient at 09:45 and 13:20. The daylight illuminance at more than 50% of the studio was below 300 lux at 09:45 and below 500 lux at 13:20. Only 5% floor area of the studio in the morning, 22.5% at noon and 82.5% in the afternoon had adequate daylight illuminance to satisfy the recommended illuminance of 750 lux. The average daylight illuminance at the studio was 266.68 lux at 09:45, 597.24 lux at 13:20 and 1700.52 lux at 16:45.

On both days, the illuminance was higher at the middle area of the studio, columns 5 and 6 had greater values at each row, in the afternoon measurements; showing the effects of the west facing windows. The average daylight illuminance at the studio increased towards the west façade (from row A towards row E), regardless of time, on both days (Figure 4.9). This increase was observed in all four studios, affected by the dominant window façade of each studio. Sun patches were observed on the E row, at points E3, E5 and E6 on May 4th at 16:45 and at points E3 and E5 on June 21st at 16:30. On both days, in the morning and noon measurements, except row E, daylight illumination peaked at the column 8, which was the closest column to the south façade.

The uniformity ratio D_{min} / D_{max} of the studio on May 4th was 0.08, 0.06 and 0.06 respectively at 09:45, 13:20 and 16:45, which were severely lower than the recommended ratio of 0.67; pointing out the high illumination discrepancies between measurement points within the studio. The second uniformity ratio D_{min}/D_{ave} was 0.29 at 09:45, 0.25 at 13:20 and 0.15 at 16:45, all of which were almost half of the recommended ratio. On June 21st, the uniformity ratios were quietly close to the ratios obtained at May 4th.



(a)



(b)

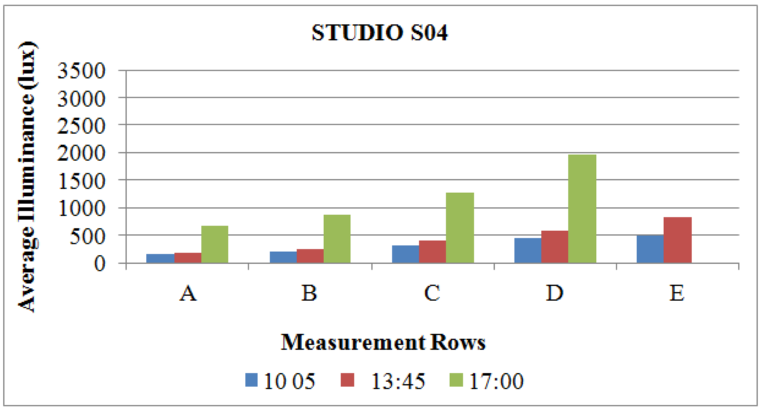
Figure 4.9. Average daylight illuminance at measurement rows on (a) May 4th and (b) June 21st for S03

4.1.4 Studio S04

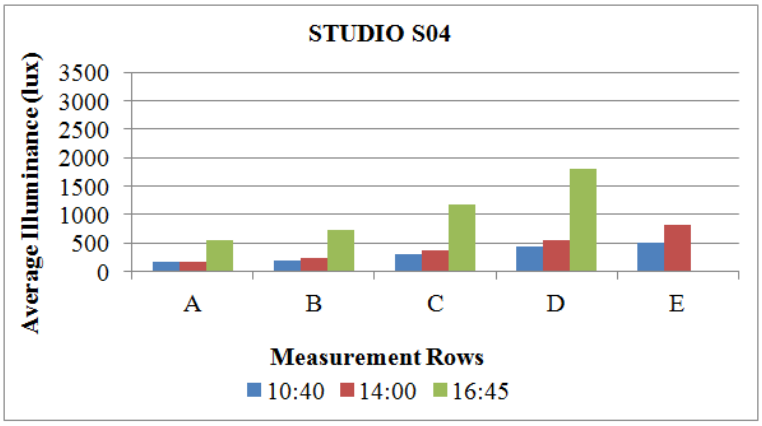
The daylight illuminance distribution at the north and west facing studio S04 on May 4th and June 21st showed similarities with studio S03. But the values were a little lower than the studio S03 in general. The daylight illuminance was below 300 lux at about half of the measurement points at 10:05 and 13:45 on May 4th, severely lower than the recommended illuminance of 750 lux. The average daylight illuminance in the studio on May 4th was 302.05 lux at 10:05, 413.58 lux at 13:45 and 1383.38 lux at 17:00, pointing out the high differences in daylight quality. The uniformity ratio D_{min} / D_{max} on May 4th was 0.09 at 10:05 and 13:45, 0.23 at 17:00, quietly unstable during the day and below the recommended ratio. D_{min}/D_{ave} ratio at the same day was 0.31 at

10:05, 0.29 at 13:45 and 0.23 at 17:00, about half of the recommended ratio of 0.50. The results were very close on June 21st, both pointing out the deficiencies at daylight illuminance distribution in the studio throughout the day.

The illuminance was higher at the middle area of the studio in the afternoon; columns 6 and 7 had greater illuminance at each row, affected by the west facing windows. The average daylight illuminance at the studio also increased towards the West façade (from row A towards row E), regardless of time, on both days (Figure 4.10). The sun patches were also observed on row E, at points E4 and E7 on May 4th at 17:00 and E4, E5 and E7 on June 21st at 16:45.



(a)

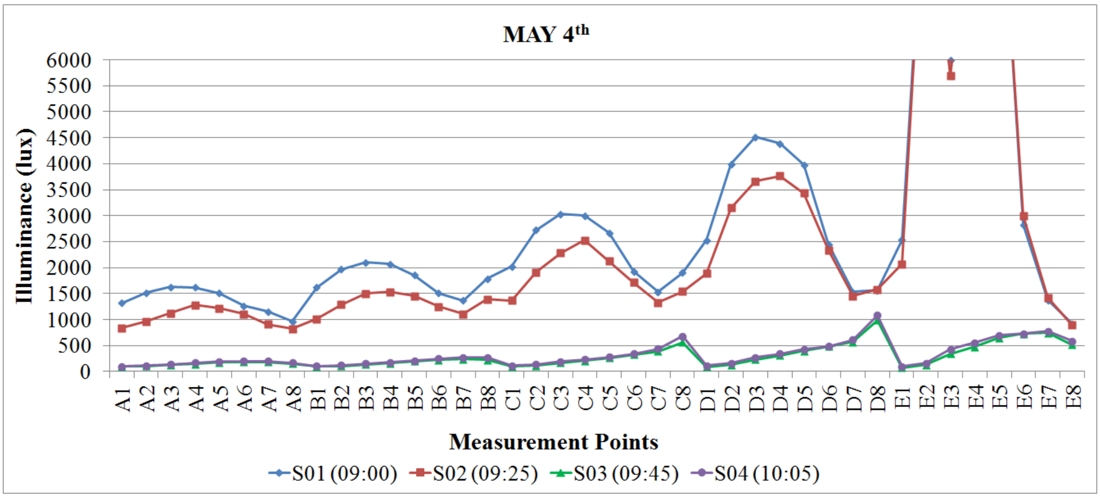


(b)

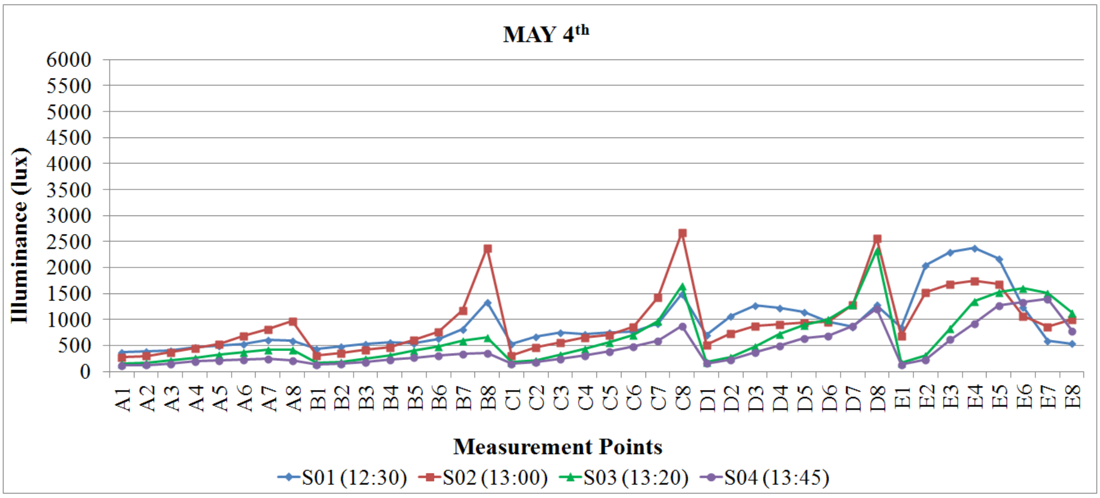
Figure 4.10. Average daylight illuminance at measurement rows on (a) May 4th and (b) June 21st for S04

4.1.5 Overview

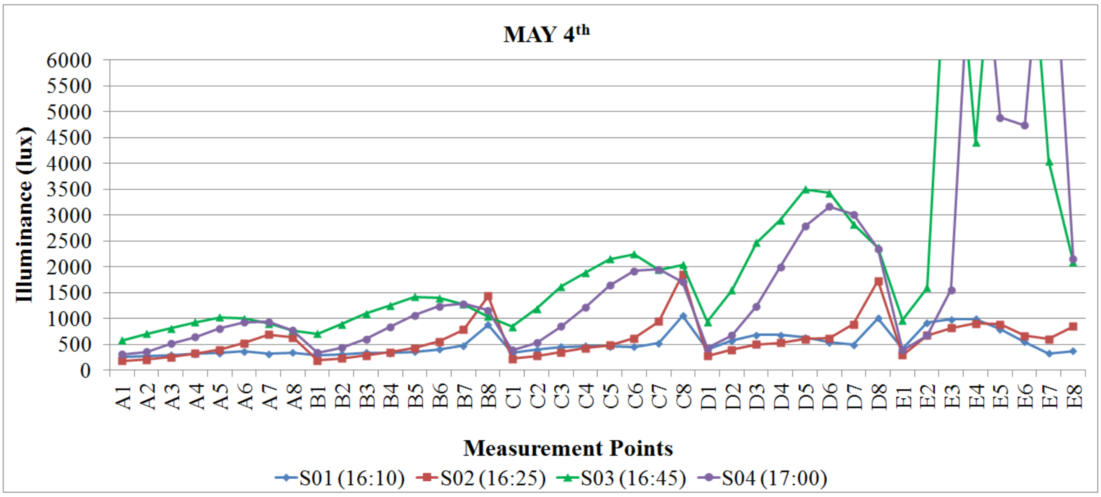
The distribution of the daylight illuminance at four studios was severely unstable on daily and hourly basis as can be derived from the Figures 4.11 and 4.12. In addition, the daylight distribution among the studios for the same time interval showed remarkable variations. Regarding the measurements in the morning, the daylight illumination in the west facing studios S03 and S04 were seriously insufficient for the required daylighting norms of a design studio in an educational building. The values were greater in the east facing studios S01 and S02, but severely non uniform; additionally, at the most of the measurement points, they were far greater than the desired values. Regarding the measurements at noon, the illuminance distribution showed similarities among the studios, but uniformity was inadequate and the values did not reach to the desired interval. According to the measurements in the afternoon, the east facing studios S01 and S02 showed a similar distribution, and had lower and more inadequate values than the other studios had. On the other hand, the average daylight illuminance in S03 and S04 was greater than the illuminance in S01 and S02, but severely non uniform and mostly far greater than the desired values (Figure 4.11 and 4.12).



(a)

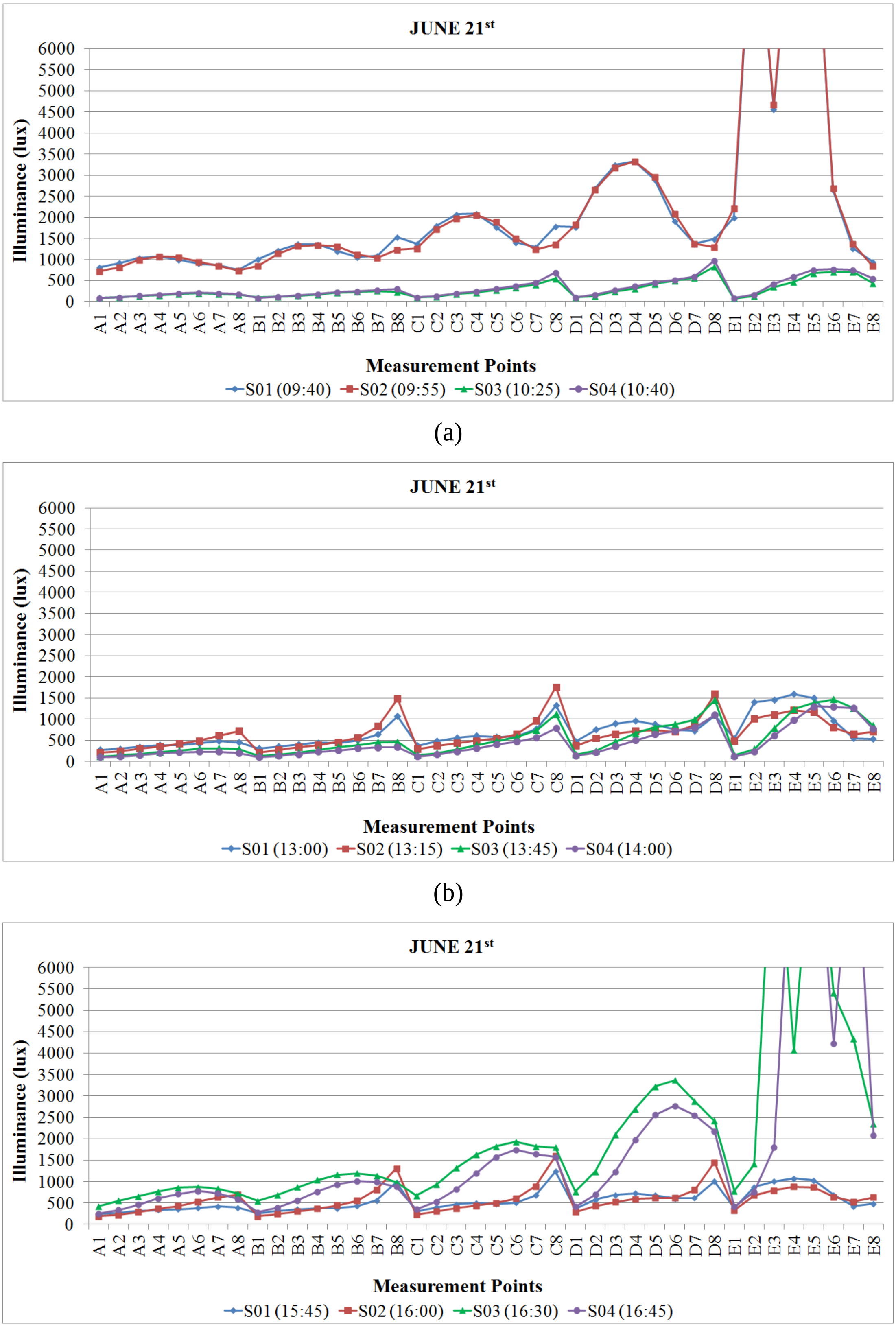


(b)



(c)

Figure 4.11. Distribution of daylight illuminance measured at studios S01, S02, S03, S04 on May 4th (a) in the morning, (b) at noon and (c) in the afternoon



(a)

(b)

(c)

Figure 4.12. Distribution of daylight illuminance measured at studios S01, S02, S03, S04 on June 21st (a) in the morning, (b) at noon and (c) in the afternoon

4.2. Findings Regarding Simulation

The simulation model of the four studios was built using Autodesk Ecotect Analysis, as mentioned before. The actual locations of the drawing tables and openings were modeled. The color and reflectance of surface materials were selected carefully in order to resemble the actual materials correctly. The daylight simulations for the selected two days, May 4th and June 21st, were conducted on this model, on Autodesk Ecotect Analysis platform; using Desktop Radiance.

The simulation outputs of Desktop Radiance (daylight illuminance at measurement points) were compared with the field measurements in order to validate and finalize the Ecotect model. Linear regression analysis was used to estimate the relationship between the field measurements and simulation results, and to validate the model. The coefficient of determination (R^2) values ranged between 88% and 98% for all simulations of May 4th and between 78% and 97% for June 21st; showing the high accuracy of the simulation model. Here, only the comparison of May 4th simulations with the field measurements are given in detail as shown in Figures 4.13 - 4.15.

According to the simulations which were conducted in the morning on May 4th, the daylight illuminance distribution and the field measurements matched mostly. It was observed that the values were closer at the west facing studios. So, it was thought that the indirect and diffuse illumination caused by the sky luminance in the morning might be the reason of this situation in these studios. For all four studios, the simulation results were greater than the field measurements in the morning as shown in Figure 4.13. In east facing studios, this difference was greater; however, the distribution remained very close, as mentioned.

Simulations conducted at noon also slightly overestimated daylight illuminance for all studios. The illuminance distribution of the simulation results and field measurements matched very closely at the majority of the points; however they showed some variations at S02 and S03, at row E, on the points close to the south facing windows as displayed in Figure 4.14. These areas were exposed to direct sunlight at the time of the measurements. So, this might cause these divergences.

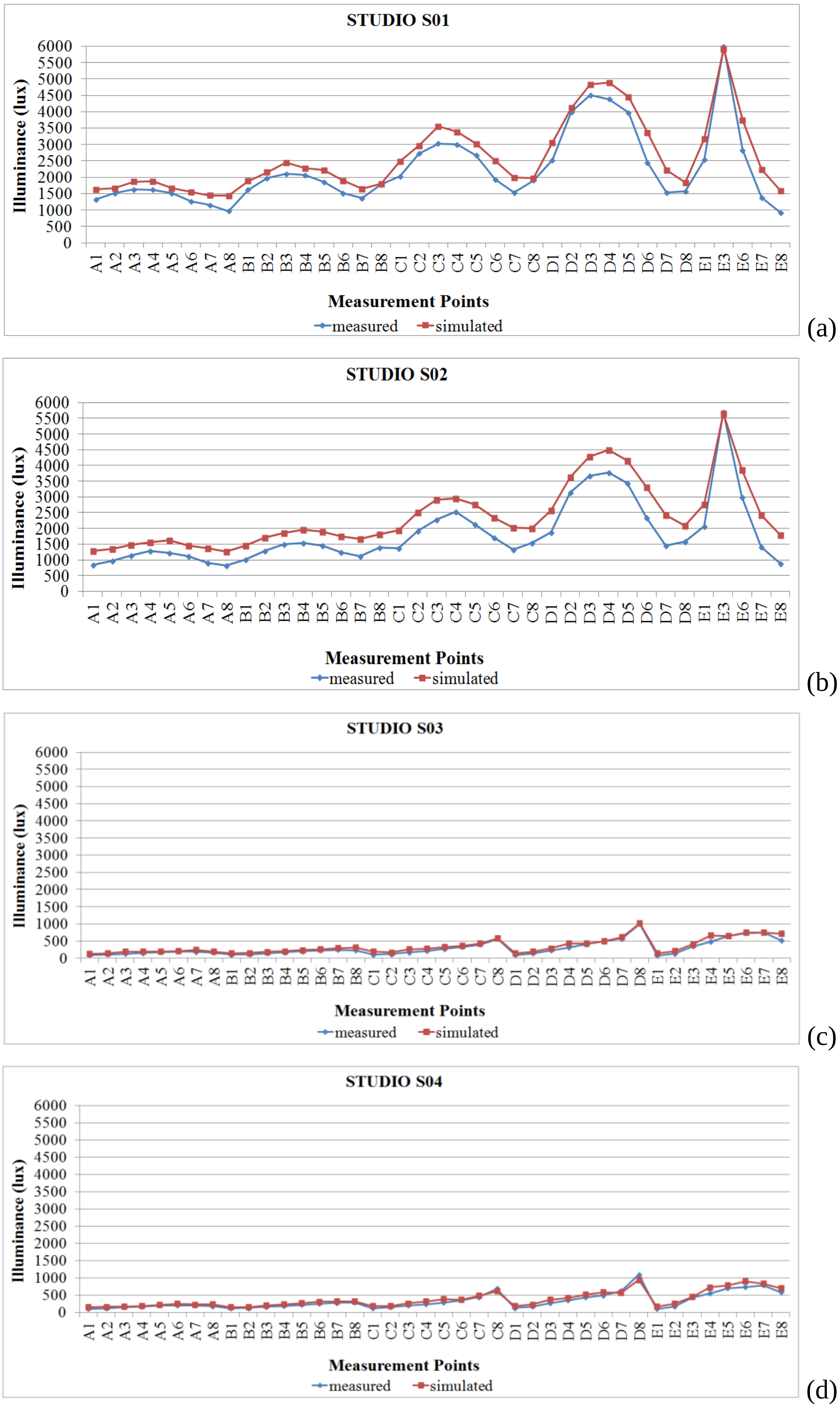


Figure 4.13. Measured and simulated results at (a) 09:00 for S01, R^2=0.96; (b) 09:25 for S02, R^2=0.96 (c) 09:45 for S03, R^2=0.97; (d) 10:05 for S04, R^2=0.95; on May 4th

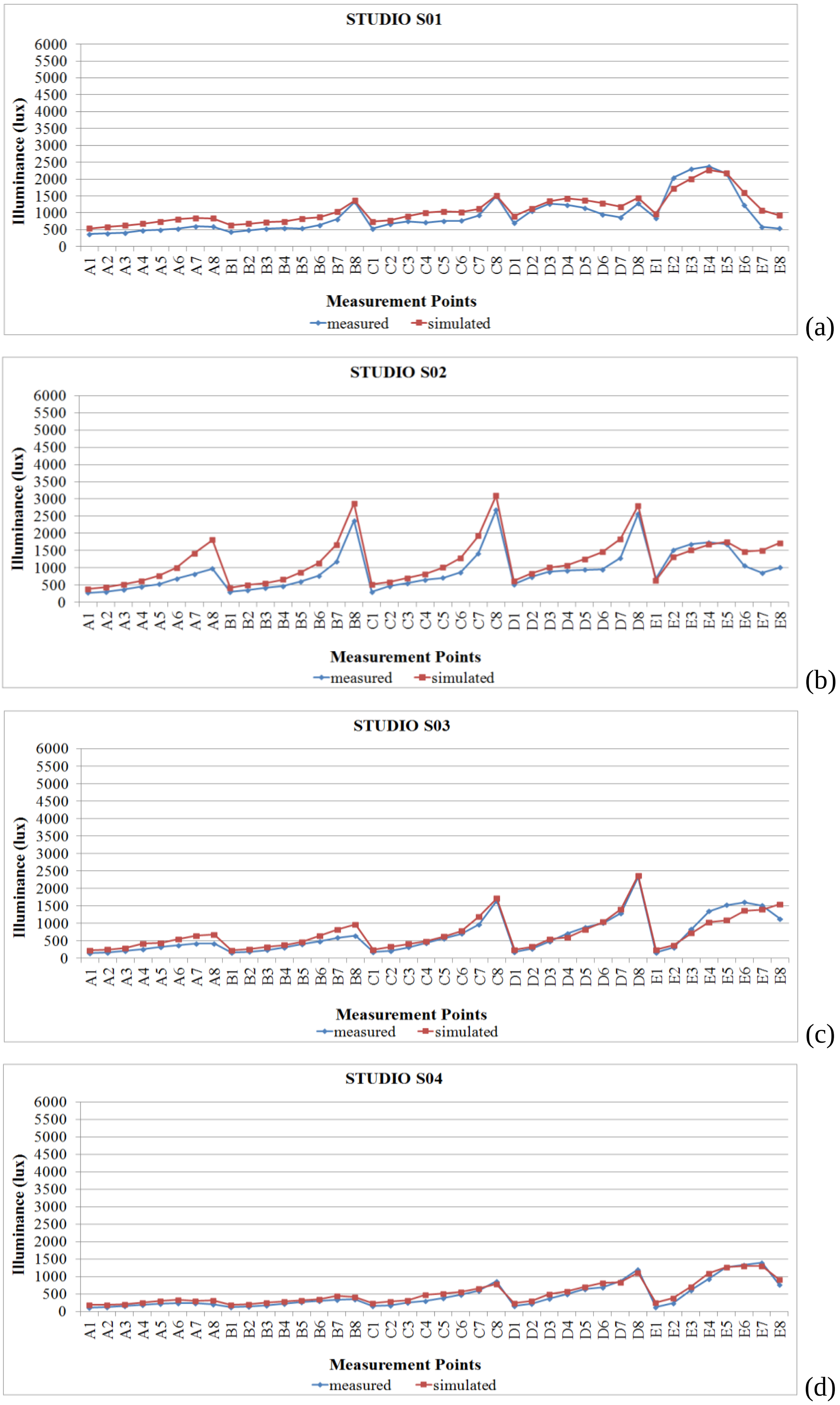


Figure 4.14. Measured and simulated results at (a) 12:30 for S01, R^2=0.94; (b) 13:00 for S02, R^2=0.89; (c) 13:20 for S03, R^2=0.92; (d) 13:45 for S04, R^2=0.98 on May 4th

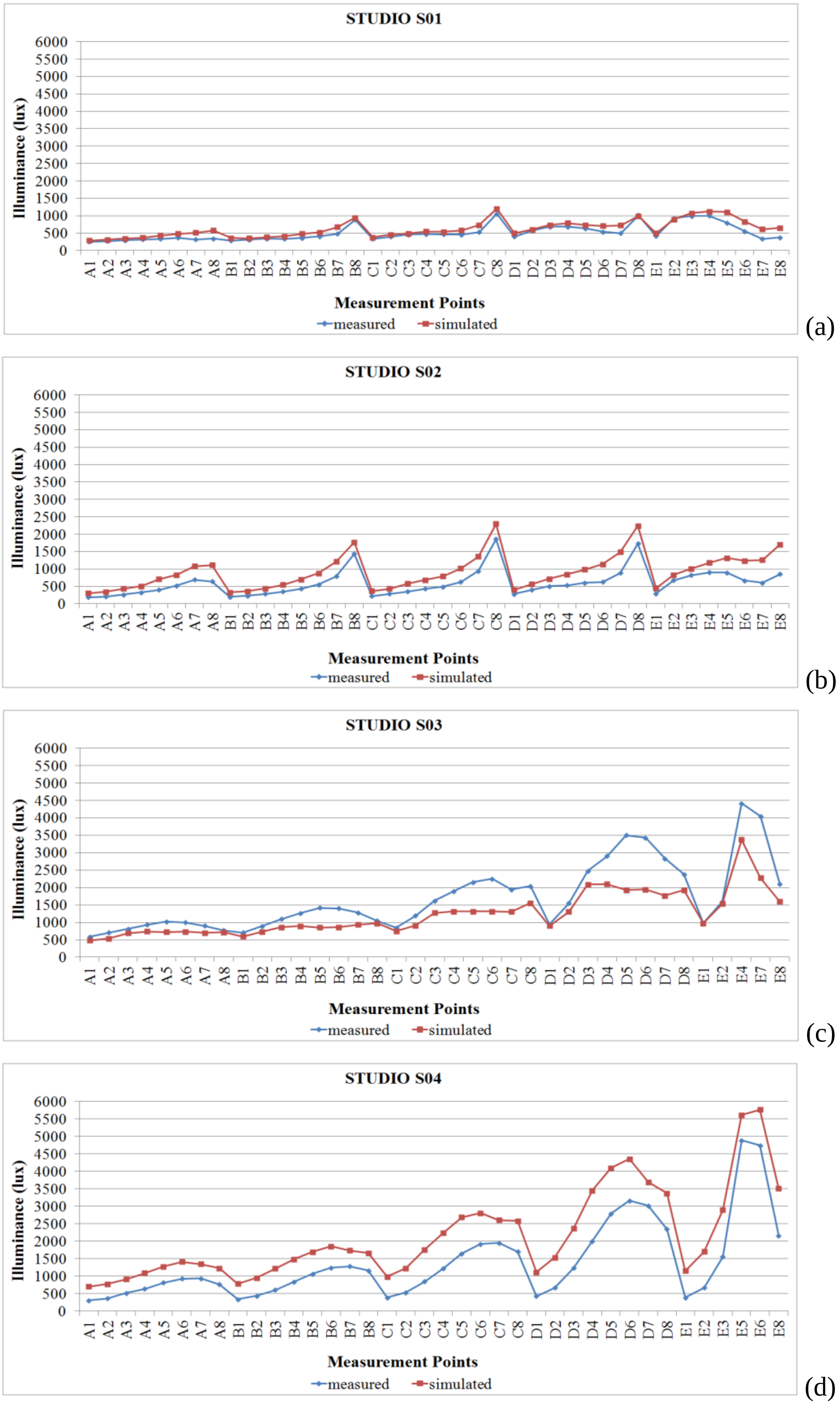


Figure 4.15. Measured and simulated results at (a) 16:10 for S01, R^2=0.88; (b) 16:25 for S02, R^2=0.92 (c) 16:45 for S03, R^2=0.90; (d) 17:00 for S04, R^2=0.96; on May 4th

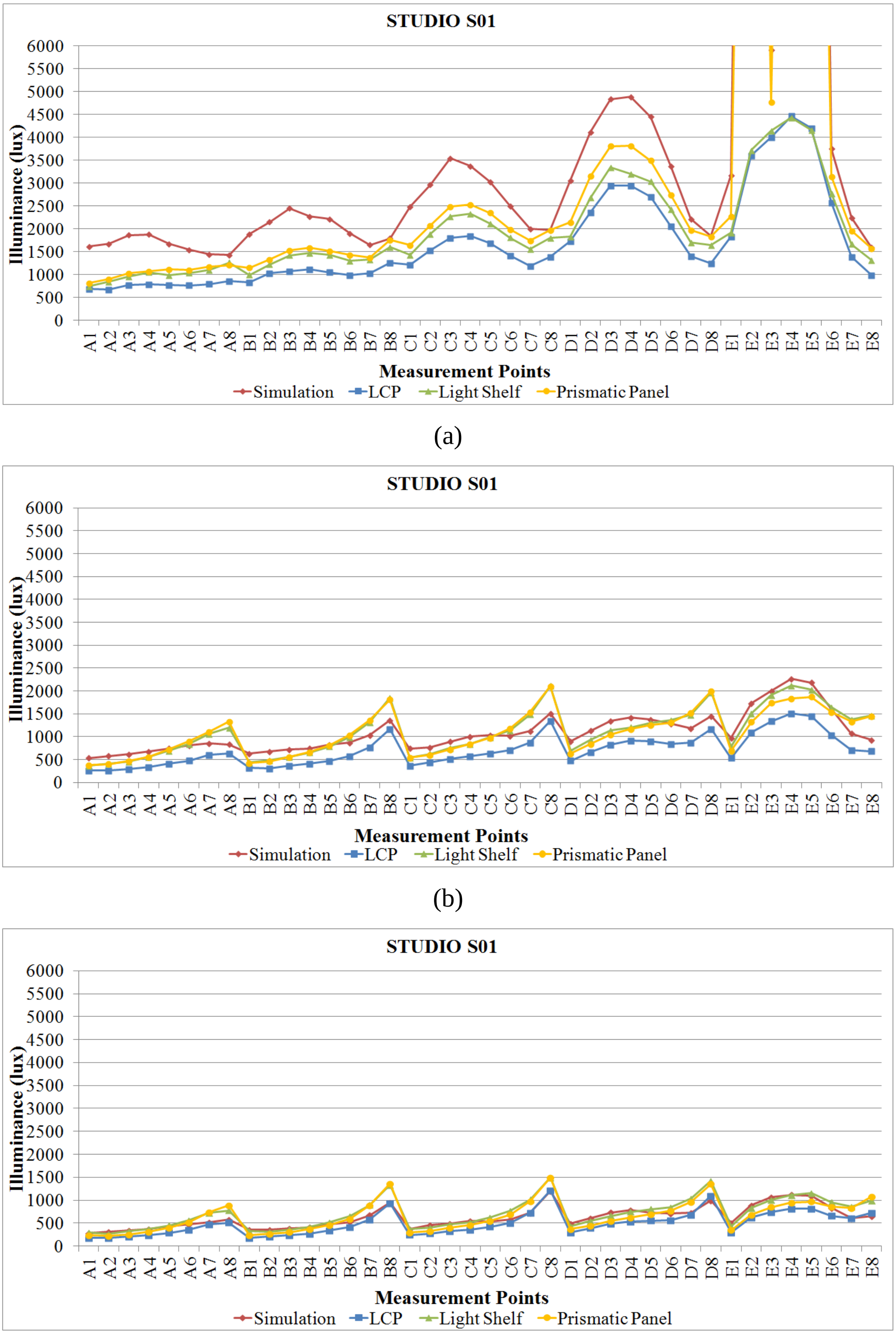
Regarding the simulations carried out in the afternoon, the illuminance distribution of the simulation results was very close to the measurements at the studio S01 and S02. However, the differences between them were slightly higher on the rows A and E, columns 6, 7, 8. On the other hand, the illuminance distribution of the studio S03 showed significant divergences when compared to other three studios. On the rows B, C, D and E, and on the columns 4, 5, 6, 7, the shift in the results was greater. Those points were exposed to direct illumination at the time of the measurements; so, again, that might have caused the differences. Apart from the simulations conducted in the other studios, the predicted illuminance by Radiance was lower than the field measurements in the studio S03. The simulations for the studio S04 also resulted similarly. In general, the daylight illuminance distribution of the simulation results showed inconstancies with the field measurements at the points which were exposed to direct sunlight. Otherwise, they might explicitly display more uniform daylight distribution than it was; and they would show closer matches to the field measurements (Figure 4.15).

4.3. Application of Proposed Daylighting Systems

As can be acquired from the findings of field measurements and Desktop Radiance simulations, the current daylighting condition of the four studios were severely insufficient for the norms of architectural design studios. The daylight illuminance distribution of the studios was not uniform and the values did not satisfy the recommended levels. The differences in the illuminance were remarkably high within the studios; the measurement points near the rear wall of the studios largely differed from the points near the exterior walls with the large glazed areas. The horizontal depth of the studios was 11,25m and the glazing ratio (the window area / the floor area) differed from 9% to 11% for each studio, strictly lower than the recommended ratios for educational spaces. The glazing area of the studios was not enough to illuminate the whole space uniformly.

In the light of all these considerations, this thesis aimed to propose a daylighting system to improve the daylight illuminance and uniformity in these studios. With regard to the all mentioned daylighting deficiencies of the studios, these systems should have light guiding capabilities in order to redirect daylight towards the low illuminated areas away from the window wall. These systems also should have sun shading capabilities in order to prevent the present sun patches and glare near the window wall.

Regarding these assessments, daylighting simulations were conducted with three selected advanced daylighting systems; laser cut panels, prismatic panels and lastly, light shelves in order to comprehend their effects on the daylight illuminance and uniformity of the studios. For the simulations, the material characteristics and dimensioning of the elements of the proposed daylighting systems were determined from the previous studies. Thus, it was aimed to make comparison between the findings of this study and the literature. The simulation results of the proposed systems for the four architectural design studios are given as Figures 4.16 – 4.19.

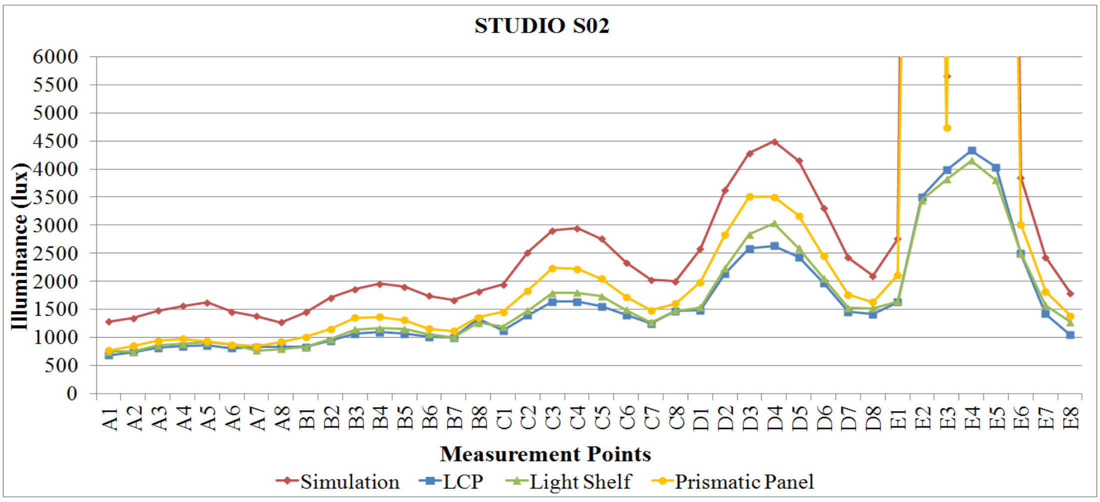


(a)

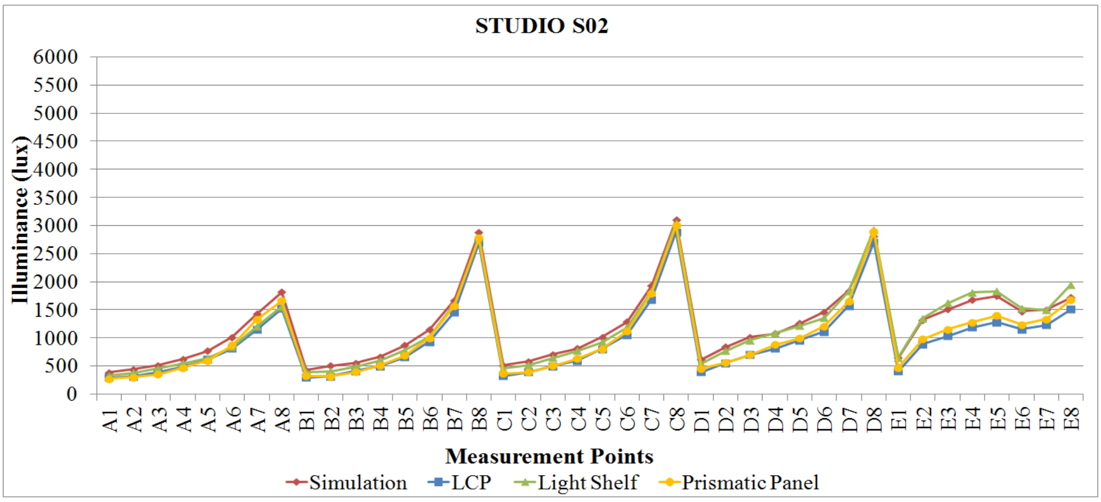
(b)

(c)

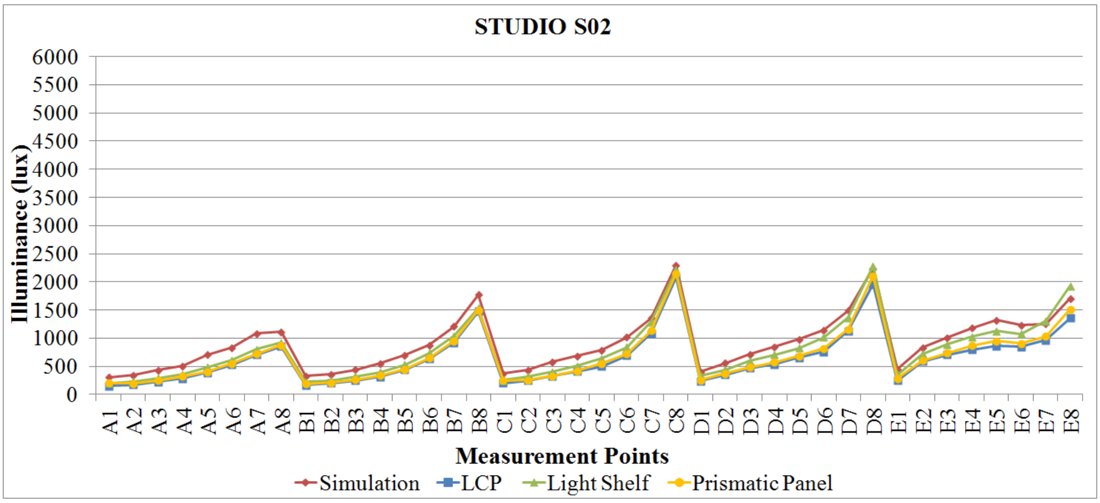
Figure 4.16. Simulation results of the proposed systems for May 4th; (a) 09:00, (b) 12:30, (c) 16:10 for Studio S01



(a)

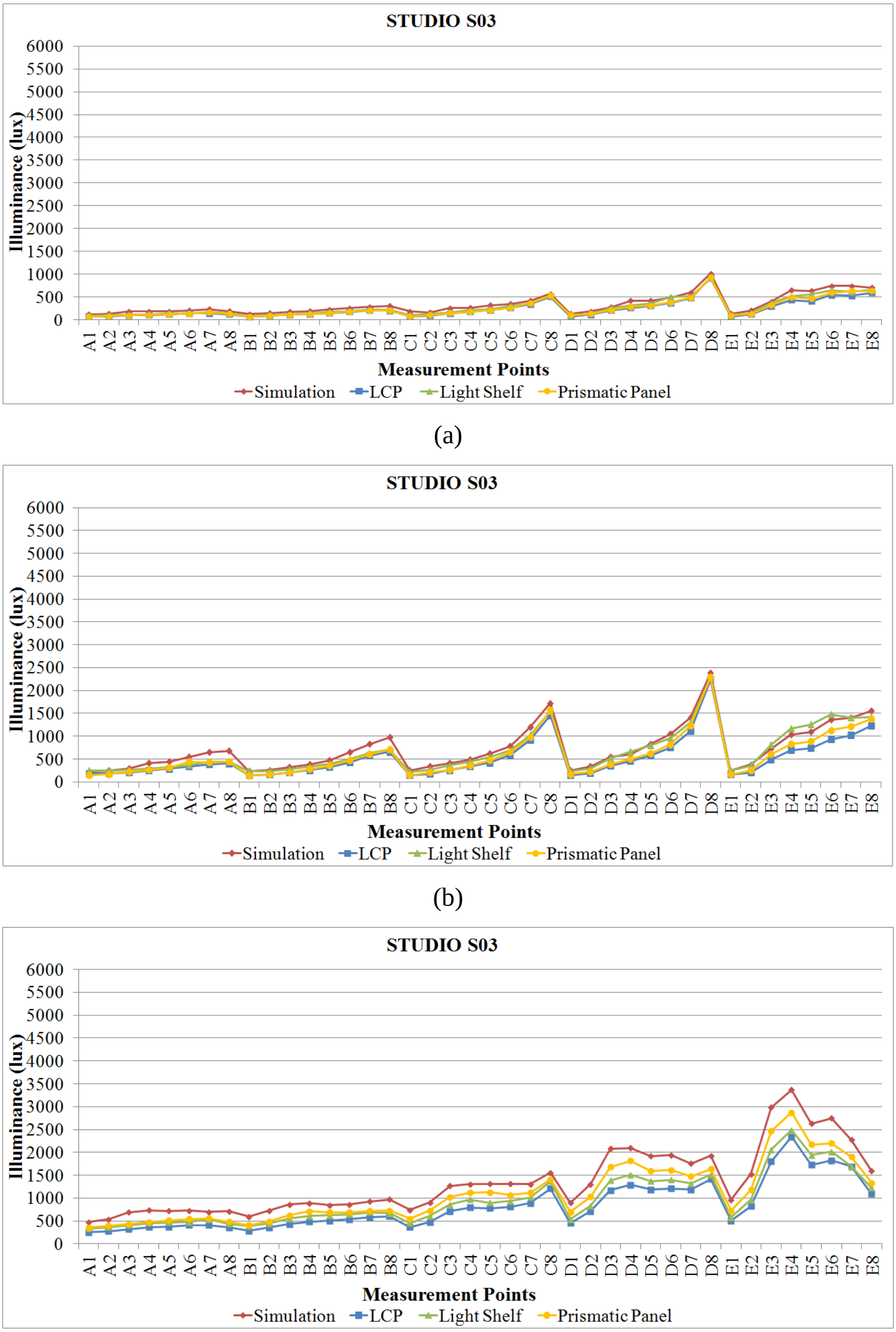


(b)



(c)

Figure 4.17. Simulation results of the proposed systems for May 4th; (a) 09:25, (b) 13:00, (c) 16:25 for Studio S02

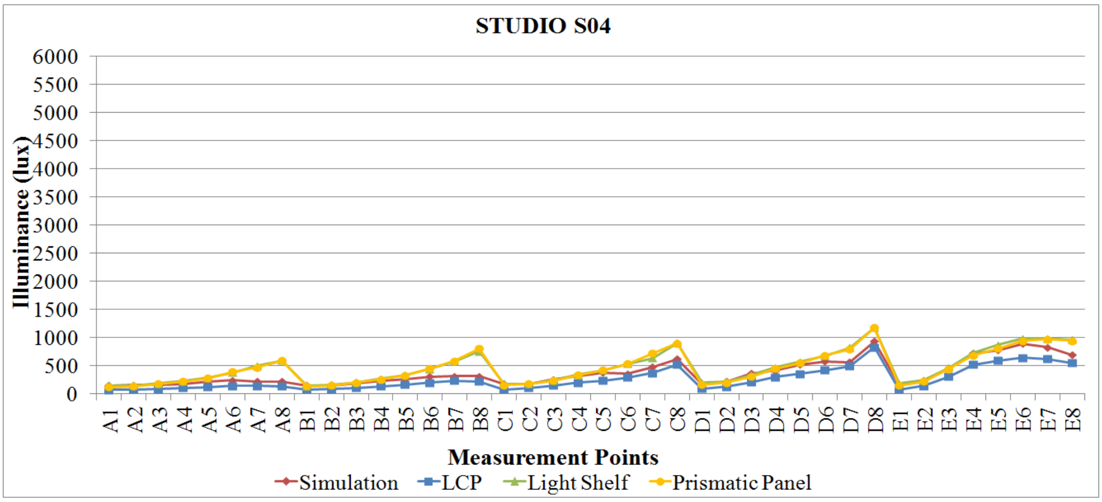


(a)

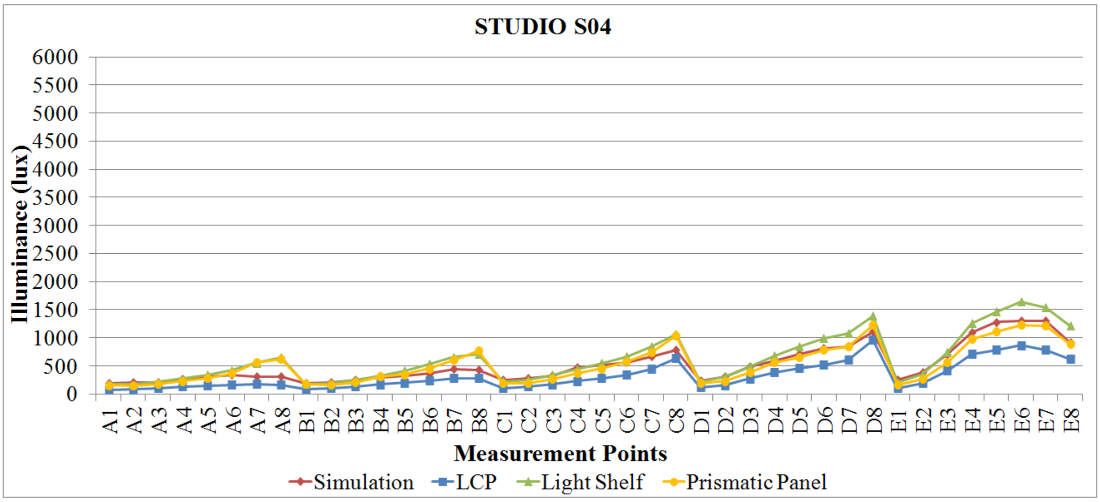
(b)

(c)

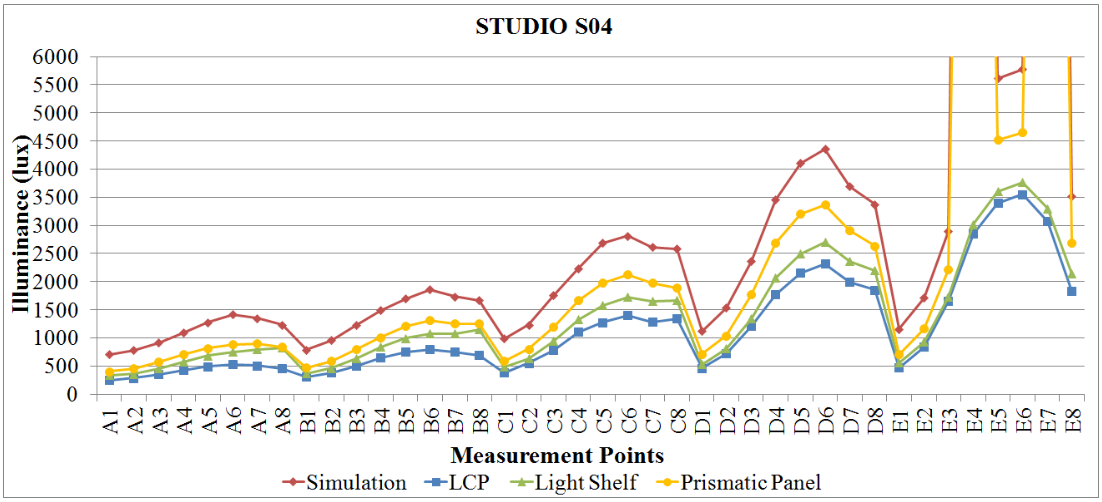
Figure 4.18. Simulation results of the proposed systems for May 4th; (a) 09:45, (b) 13:20, (c) 16:45 for Studio S03



(a)



(b)



(c)

Figure 4.19. Simulation results of the proposed systems for May 4th; (a) 10:05, (b) 13:45, (c) 17:00 for Studio S04

4.3.1. Laser Cut Panels

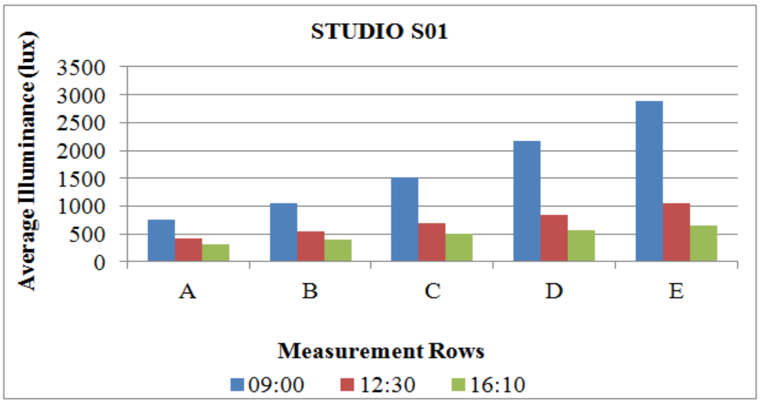
In order to comprehend if and how much the daylighting conditions of the studios could be improved with the application of laser cut panels (LCP), the daylight simulations were conducted by using Desktop Radiance. The panels were modeled in Autodesk Ecotect Analysis. The dimensioning of the panel cuts was adjusted according to a previous application established in St Paul's School, Brisbane, Australia (IEA, 2000). In the model, the panels were placed above eye level, 2 meters above the floor, aiming to prevent glare that might have occurred by the redirection of daylight and not to block the outside view. The daylight simulations of the laser cut equipped model were conducted for all studios for the two selected days, May 4th and June 21st.

A) Regarding the studio S01, the daylight illuminance distribution did not show remarkable changes when compared to the simulations conducted for the current condition of the studio, according to the simulations conducted for May 4th and June 21st with LCP equipped model. However, with laser cut panels, the illuminance was lower at all measurement points, regardless of time (Figures 4.16 – 4.19).

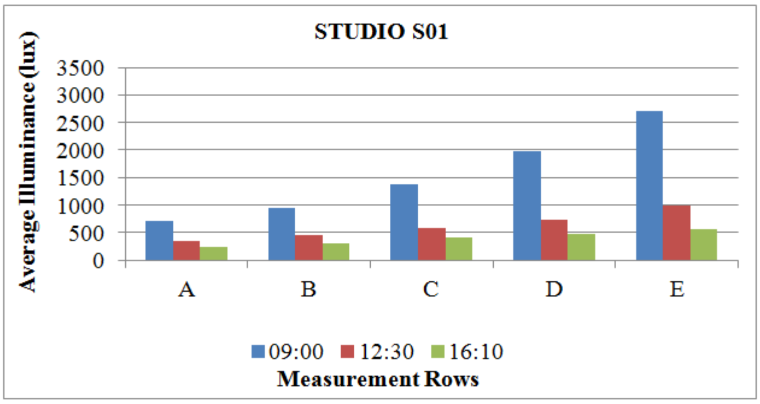
The illuminance distribution of the two rows closest to the rear wall, A and B, showed a more uniform distribution in the morning; and the illuminance was closer to the desired levels. But the distribution in the remaining area of the studio was not uniform; at each row, the columns 3, 4 and 5 still had remarkably higher illuminance than the rest, affected by the exterior wall with large glazed area. However, the previous sun patches was not observed at row E on measurement points.

There was not any improvement in daylighting conditions at noon and in the afternoon when compared with the previous condition. The illuminance distribution was still non uniform. The illuminance was lower than the recommended illuminance of 750 lux at some areas close to the rear wall in the current condition. With the light guiding characteristics of the laser cut panels, it was predicted that the illuminance in these areas would get higher by redirecting daylight into deeper areas in the studio. But the illuminance decreased severely at almost every measurement point, after the application of the panels. In the 12:30 simulations; the illuminance on 62.5 % of the measurement points for May 4th and 70% of the points for June 21st were below 750 lux. These ratios were 82.5% for May 4th, 90% for June 21st for the 16:10 simulations. The distance between the window wall and the rear wall being too deep might be the reason why applying LCP did not increase the illuminance in deep areas.

Also, in the simulations conducted at 12:30 and 16:10, the illuminance at the column 8, which was the closest column to the north façade, was still severely higher at the rows A, B, C and D. The reason of this outcome might be due to the application of LCP only on the east façade of the studio. As row E is the closest one to the main exterior wall which has the highest amount of window area, facing east, the average daylight illuminance of each measurement row still increased from row A towards row E as shown in Figure 4.20. It was still observed that almost 70% of the floor area was receiving insufficient amount of light intensity for an architectural design studio; i.e. at 9:00.



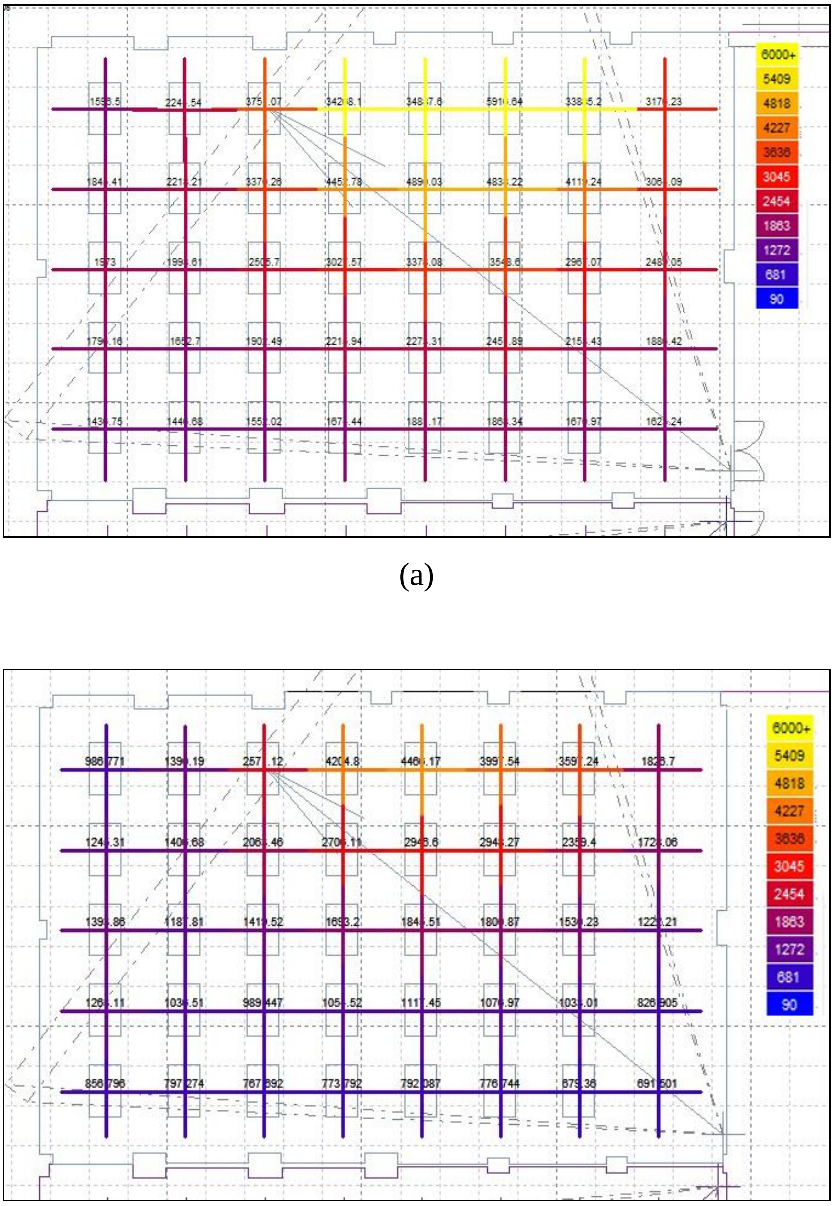
(a)



(b)

Figure 4.20. Average daylight illuminance at measurement rows for (a) May 4th and (b) June21st with LCP for studio S01

On the contrary that, approximately the total floor area was under the optimum daylighting level at noon and in the afternoon. The uniformity ratio D_{min} / D_{max} was 0.17 at 09:00; 0.17 at 12:30 and 0.15 at 16:10 on May 4th. These were severely lower than the recommended value of 0.67. D_{min}/D_{ave} ratio was closer to the recommended ratio of 0.50. It was 0.46 at 09:00; 0.37 at 12:30; and 0.36 at 16:10. For June 21st, the ratios were quietly close to the ratios obtained for May 4th.

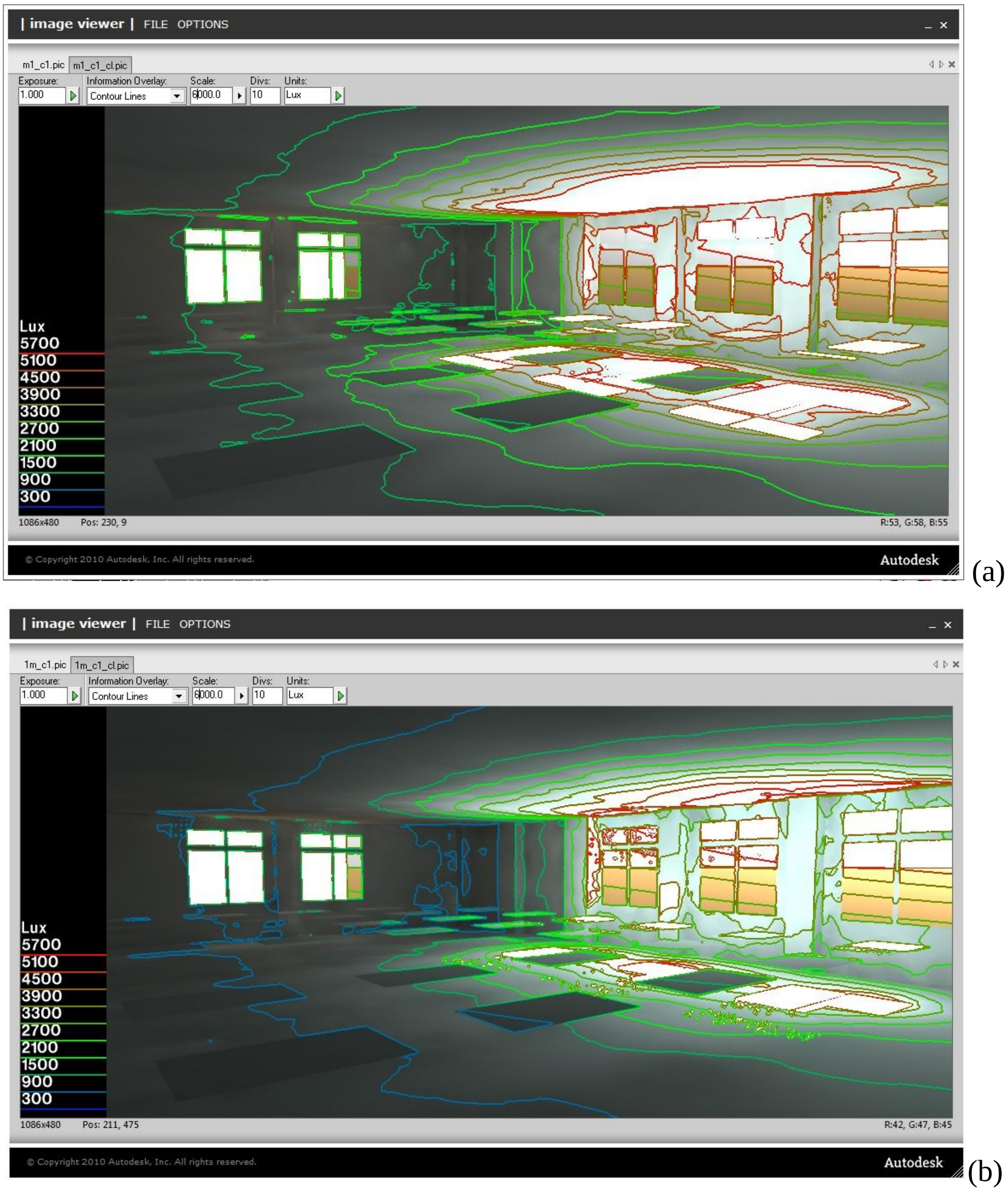


(a)

(b)

Figure 4.21. Simulated illuminance for May 4th, 09:00 for (a) the current condition and (b) the condition with LCP for Studio S01

The simulation outputs resulted from Ecotect/ Radiance for studio S01 were presented to comprehend the changes in the illuminance distribution with the application of LCP as displayed in Figures 4.21-4.24 with the help of a colored legend. Regarding these, the most day lit areas (points) were presented as yellow and orange which are near the main exterior wall. LCP decreased the horizontal daylight illuminance throughout the floor area and avoided the sun patches (Figure 4.21).

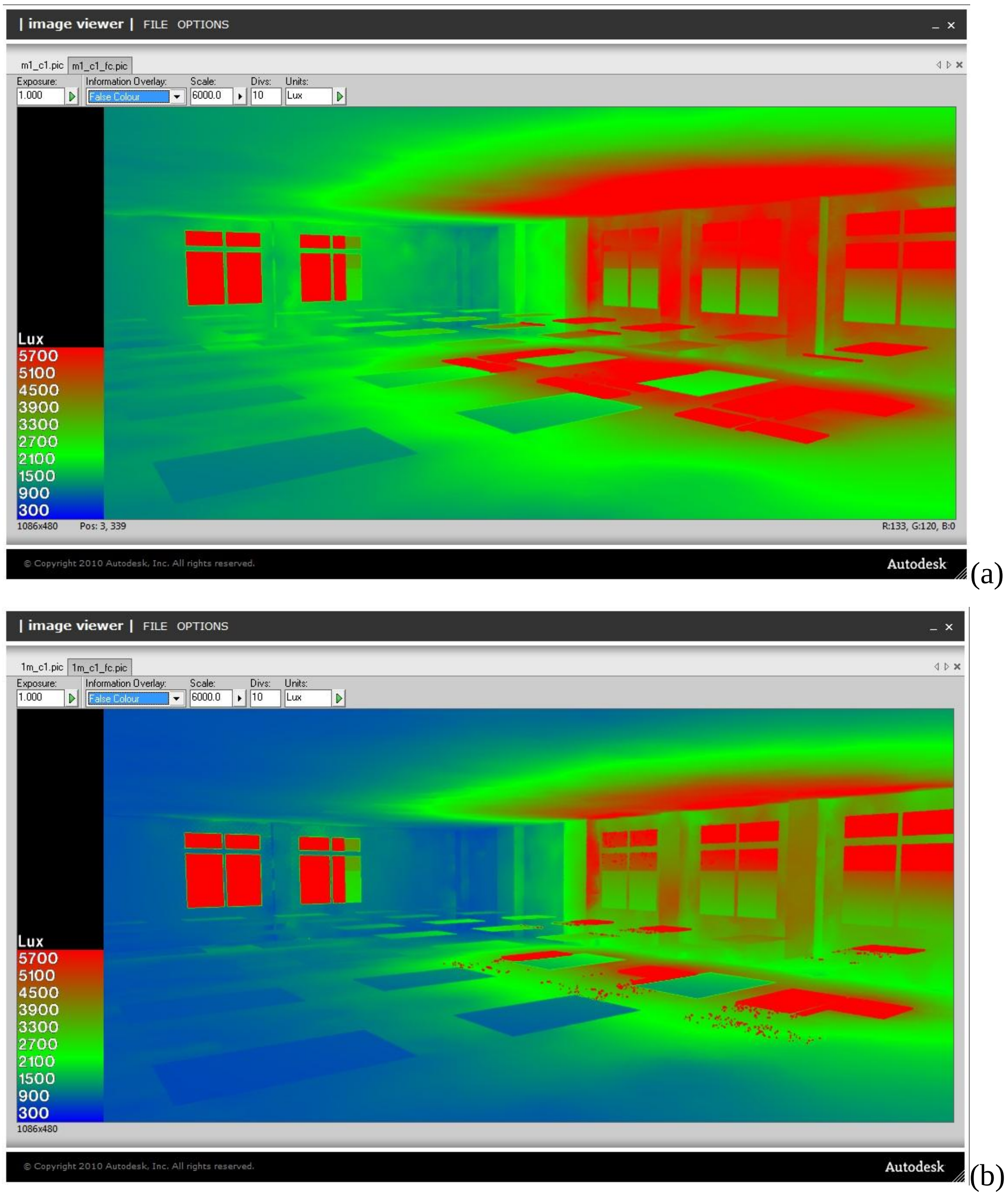


Exposure: 1.000
Information Overlay: Contour Lines
Scale: 6000.0
Divs: 10
Units: Lux

Exposure: 1.000
Information Overlay: Contour Lines
Scale: 6000.0
Divs: 10
Units: Lux

Figure 4.22. Illuminance contour lines showing distribution on May 4th, at 09:00 for (a) the current condition and (b) the condition with LCP for Studio S01

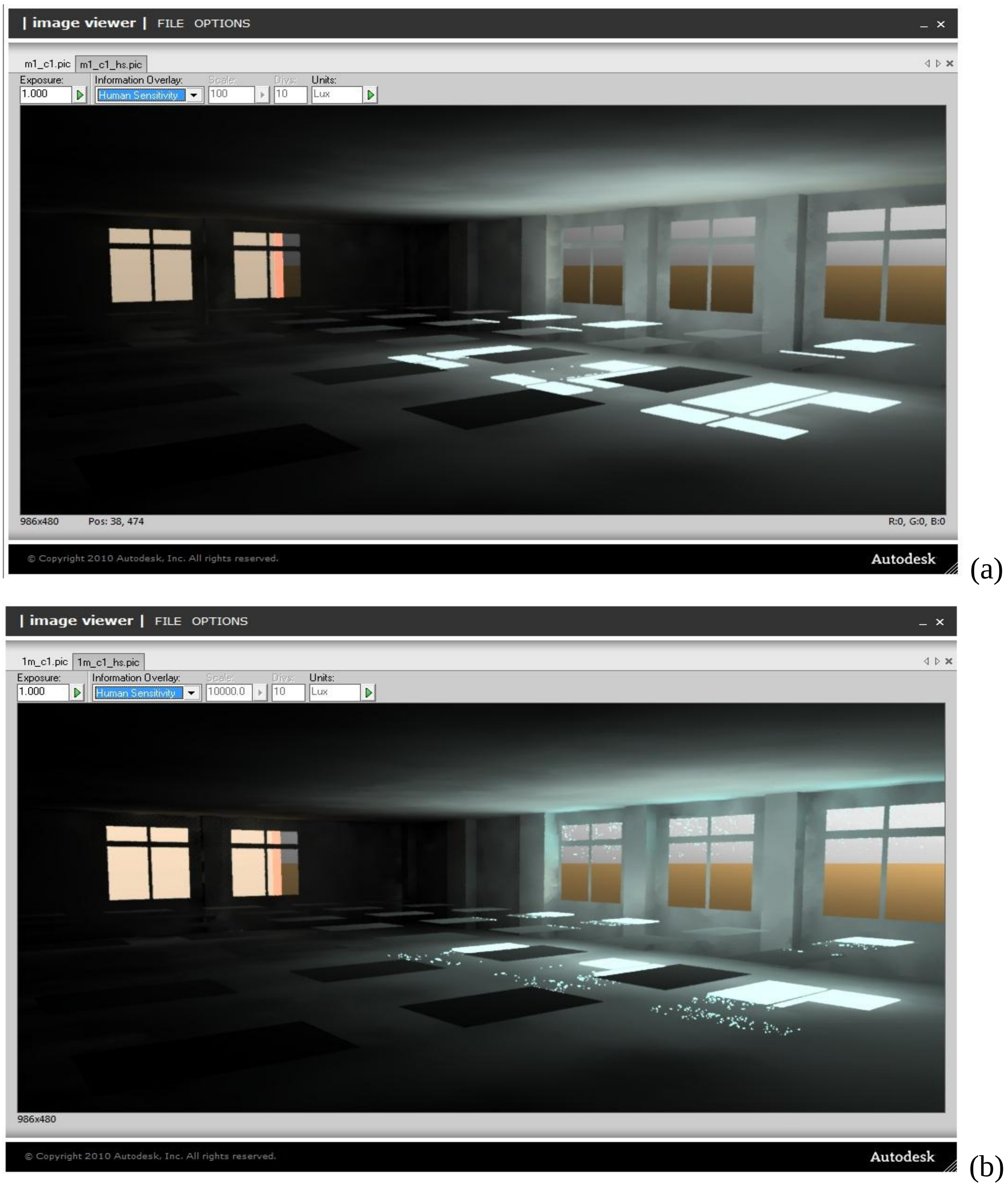
Illuminance contour lines displayed the daylight illuminance in a Radiance scene is shown in Figure 4.22. It was clear that LCP reduced the large sunny surfaces on the floor and the light intensity on the window surface. The illuminance of the middle and the rear areas dropped down, as well. These are clearer on the false colour representation of similar scenes by rendering the colour as the daylight illuminance. The amount of reddish areas in Figure 4.23 (b) is less than Figure 4.23 (a).



Exposure: 1.000
Information Overlay: False Colour
Scale: 6000.0
Divs: 10
Units: Lux

Figure 4.23. False colour representations on May 4th, at 09:00 for (a) the current condition and (b) the condition with LCP for Studio S01

Finally, the scenes of the human sensitivity emphasized how the human eye perceived the interior space under the current lighting condition (a) and the condition with laser cut panels (b) is shown in Figure 4.24. As can be seen from the images, majority of the floor area is dusk, while a minor area is very bright which explains the cause of unbalanced uniformity. These findings are very similar for the simulations in the studio S02.



Exposure: 1.000
Information Overlay: Human Sensitivity
Scale: 100
Divs: 10
Units: Lux

(a)

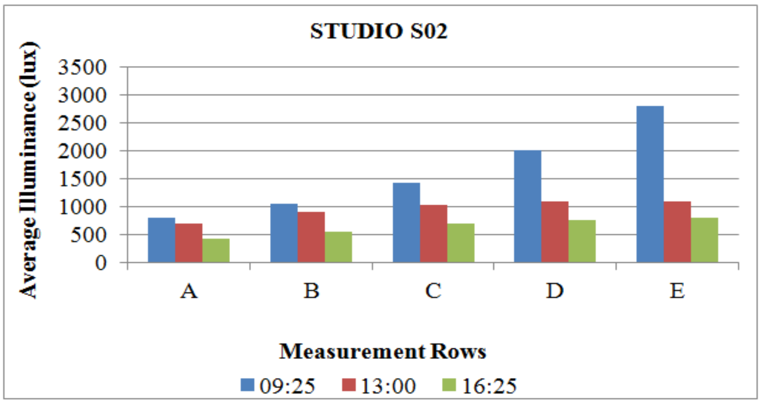
Exposure: 1.000
Information Overlay: Human Sensitivity
Scale: 10000.0
Divs: 10
Units: Lux

(b)

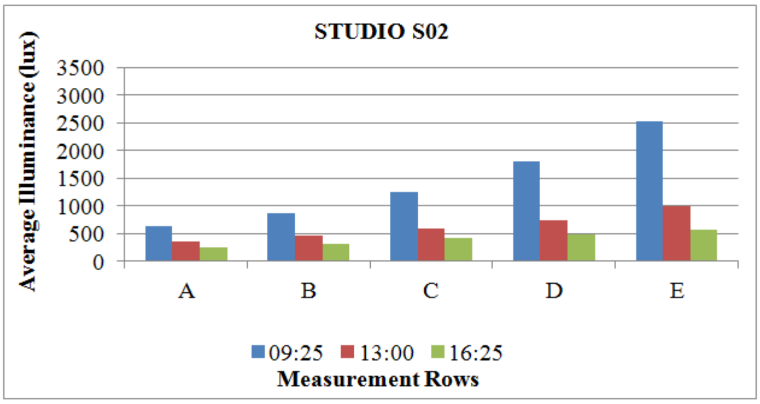
Figure 4.24. Radiance scenes showing human sensitivity of the studio S01 on May 4th, at 09:00 for (a) the current condition and (b) the condition with LCP

B) Regarding studio S02, the daylight illuminance distribution did not show remarkable changes either, when compared to the current condition; according to the simulations conducted for May 4th and June 21st with the laser cut panel equipped model. However, the illuminance was lower than the current condition at almost all measurement points, like it was in studio S01.

According to the simulations conducted with the LCP equipped model for morning, the daylight distribution in studio S02 showed similarities with the studio S01. The illuminance distribution on the rows A and B was more uniform than the current condition and the illuminance was closer to the desired levels. The daylight illuminance distribution got more irregular when moving towards row E, the closest row to the main external wall with the largest glazing area, facing east.



(a)

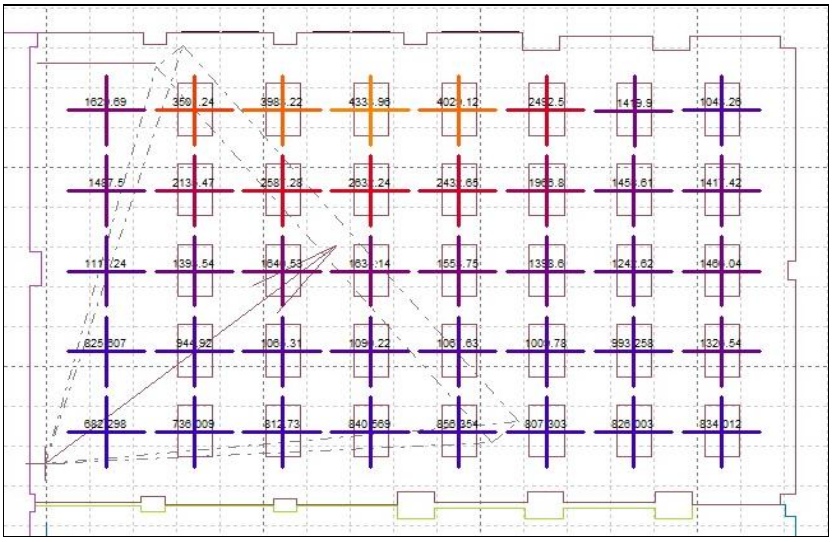


(b)

Figure 4.25. Average daylight illuminance at measurement rows for (a) May 4th and (b) June 21st with LCP for studio S02

However, the laser cut panels prevented the previous sun patches that were observed on row E in the current condition. But despite the panels, within each row, the illuminance was still higher at the middle area of the studio, columns 3, 4 and 5, like it was in the current condition. The reason to this increase might be due to the effects of the east glazed façade.

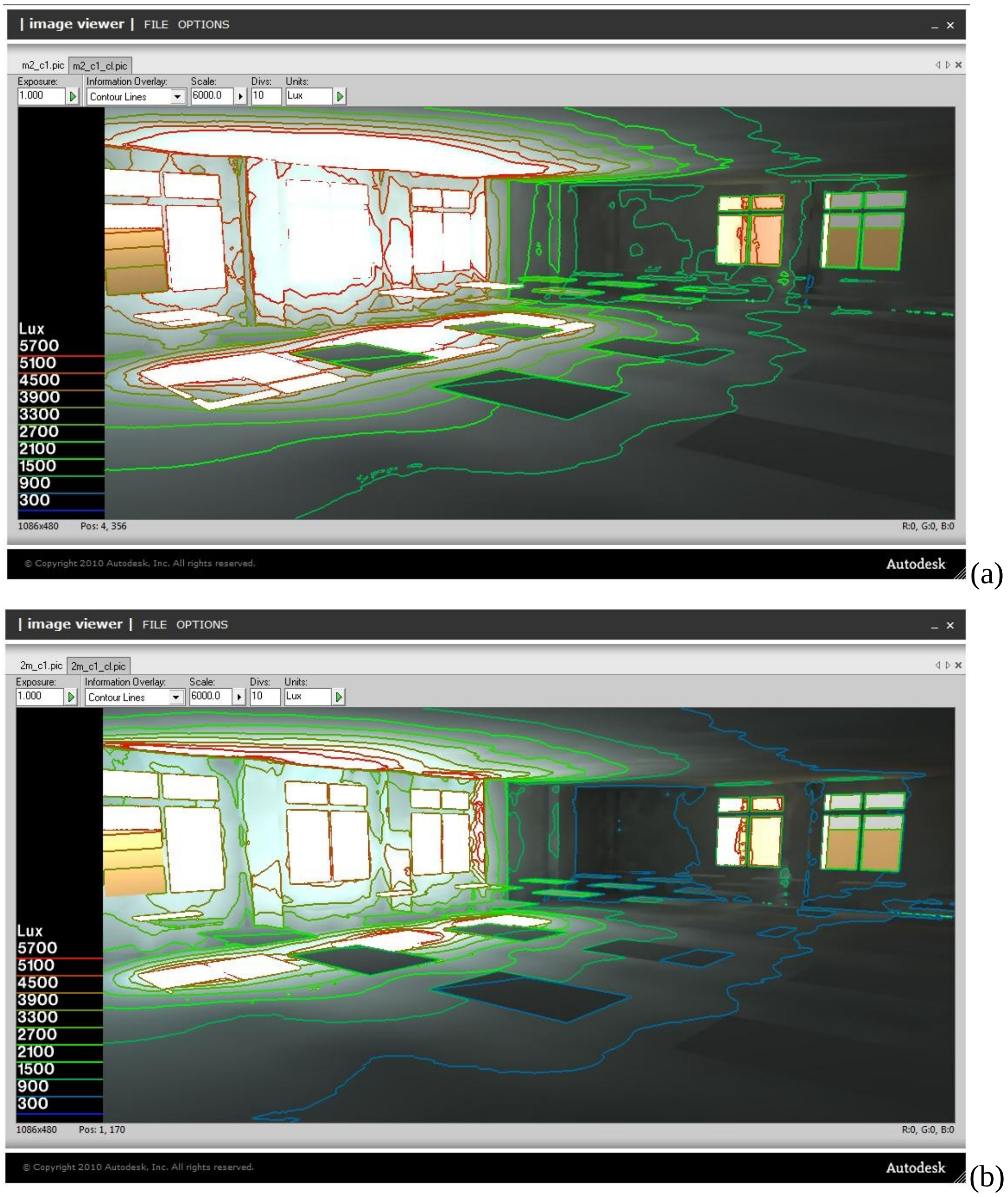
(a)



(b)

Figure 4.26. Simulated illuminance for May 4th, 09:25 for (a) the current condition and (b) the condition with LCP for Studio S02

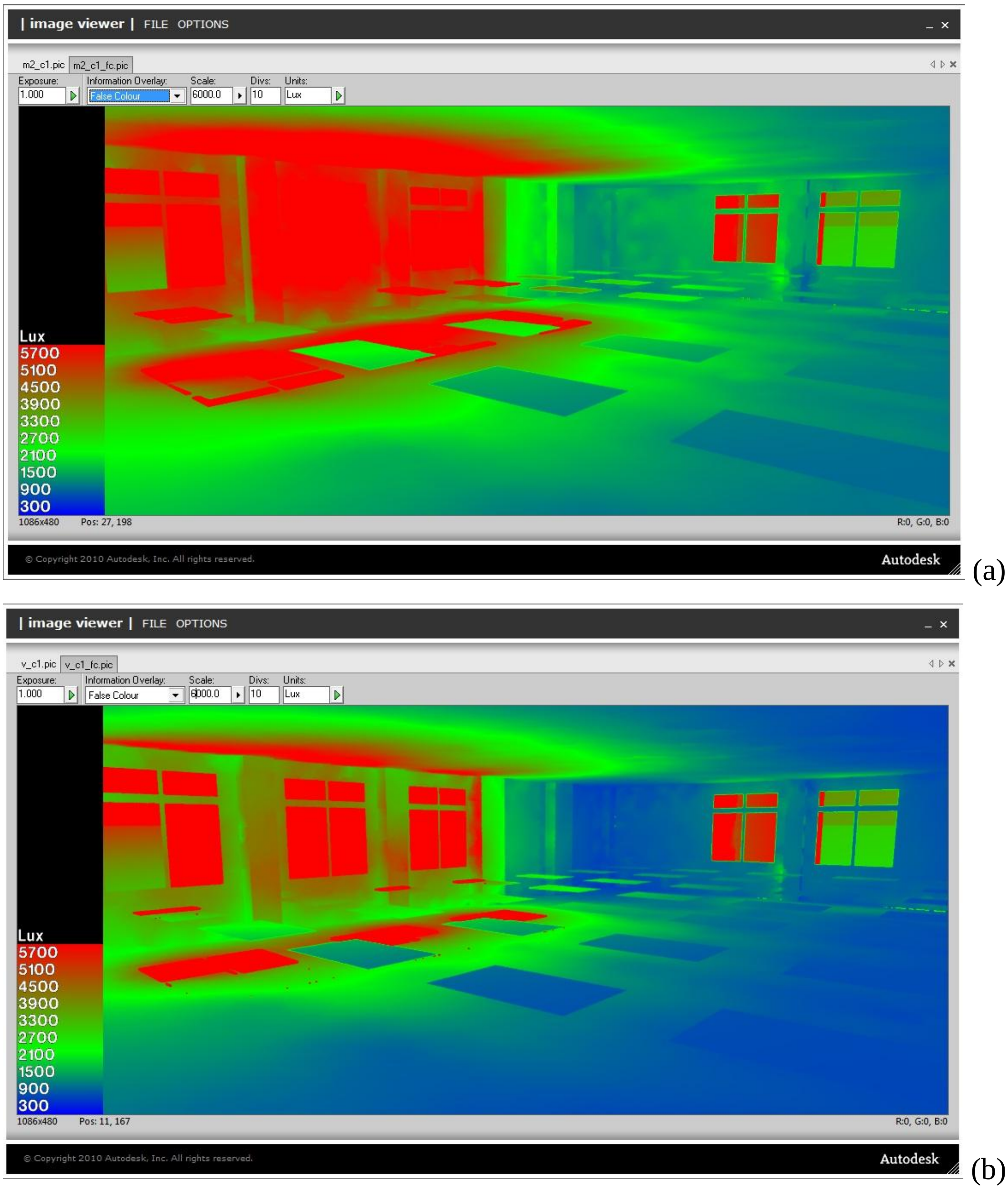
The application of laser cut panels did not provide much improvement on the daylight illuminance distribution in the studio at 13:00 and 16:25. The illuminance was a little lower than the current condition, but the distribution remained quietly similar. Low and peak illuminance at measurement points was observed for each row, like it was in the current condition. The average daylight illuminance at each row is given in the Figure 4.25, according to the simulation results of laser cut panel equipped model.


Exposure: 1.000
Information Overlay: Contour Lines
Scale: 6000.0
Divs: 10
Units: Lux
1086x480 Pos: 4, 356 R:0, G:0, B:0

Exposure: 1.000
Information Overlay: Contour Lines
Scale: 6000.0
Divs: 10
Units: Lux
1086x480 Pos: 1, 170 R:0, G:0, B:0

Figure 4.27. Illuminance contour lines showing distribution on May 4th, at 09:25 for (a) the current condition and (b) the condition with LCP for Studio S02

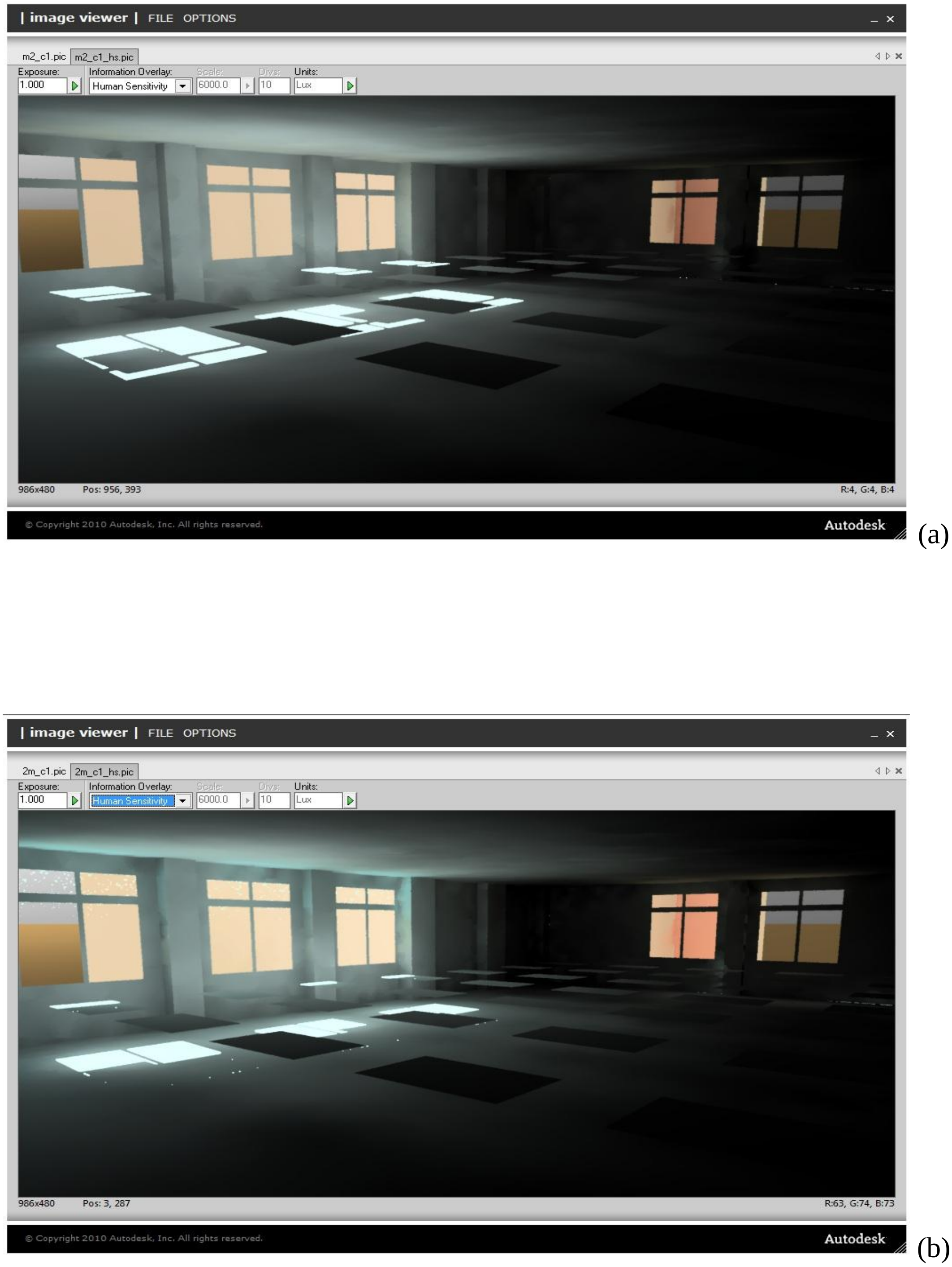
The uniformity ratio D_{min}/D_{max} was 0.17 at 09:25, 0.1 at 13:00 and 0.07 at 16:25 on May 4th, pointing out the high differences within the studio between the peak and low points. D_{min} / D_{ave} ratio was 0.48, 0.3, 0.24 at 09:25, 13:00 and 16:25 respectively. For June 21st was 0.13 at 09:25, 0.12 at 13:00 and 0.1 at 16:25 for D_{min}/D_{max} and 0.35 at 09:25, 0.34 at 13:00 and 0.29 at 16:25 for D_{min}/D_{ave}. The simulation outputs of Ecotect/ Radiance model with LCP in studio S02 were presented in the Figures 4.26 – 4.29.



Exposure: 1.000 Information Overlay: False Colour Scale: 6000.0 Divs: 10 Units: Lux

Exposure: 1.000 Information Overlay: False Colour Scale: 6000.0 Divs: 10 Units: Lux

Figure 4.28. False colour representations on May 4th, at 09:25 for (a) the current condition and (b) the condition with LCP for Studio S02



Exposure: 1.000
Information Overlay: Human Sensitivity
Scale: 6000.0
Divs: 10
Units: Lux

986x480 Pos: 956, 393 R:4, G:4, B:4

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(a)

Exposure: 1.000
Information Overlay: Human Sensitivity
Scale: 6000.0
Divs: 10
Units: Lux

986x480 Pos: 3, 287 R:63, G:74, B:73

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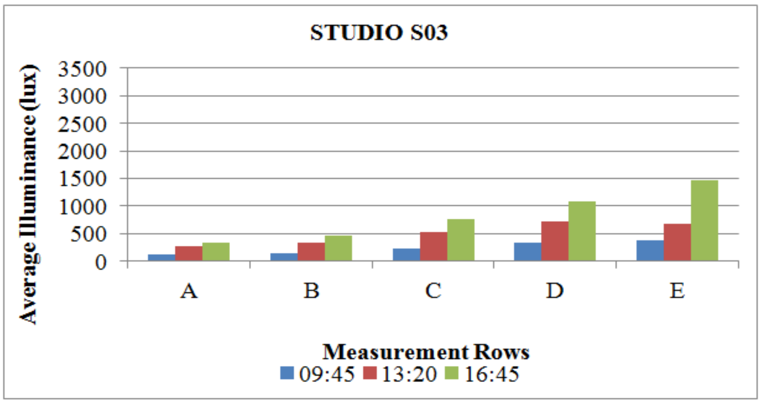
(b)

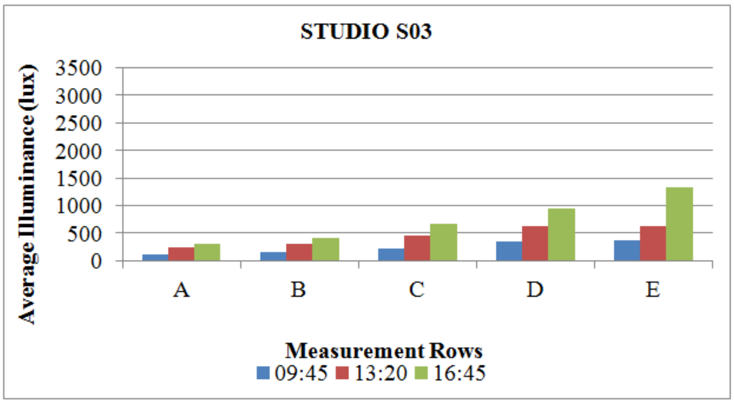
Figure 4.29. Radiance scenes showing human sensitivity on May 4th, at 09:25 for (a) the current condition and (b) the condition with LCP for Studio S02

C) Regarding the simulations of S03 with the LCP equipped model, the daylight illuminance distribution did not change noticeably after the panels were applied, but the illuminance was lower in almost all of the measurement points on both days. The difference between the illuminance of the current condition of the S03 and the condition with LCP was less on June 21st. Especially, on the 13:20 simulations of June 21st, the illuminance was almost identical with the current condition at the rows A and B.

The current daylight condition of the studio S03 was severely problematical, and the illuminance was remarkably lower than the recommended levels at most of the points, especially in the simulations conducted for morning and noon. The application of laser cut panels even lowered the illuminance in the studio more, disproving the predictions. The daylight redirection characteristics of the panels was not adequate for



(a)

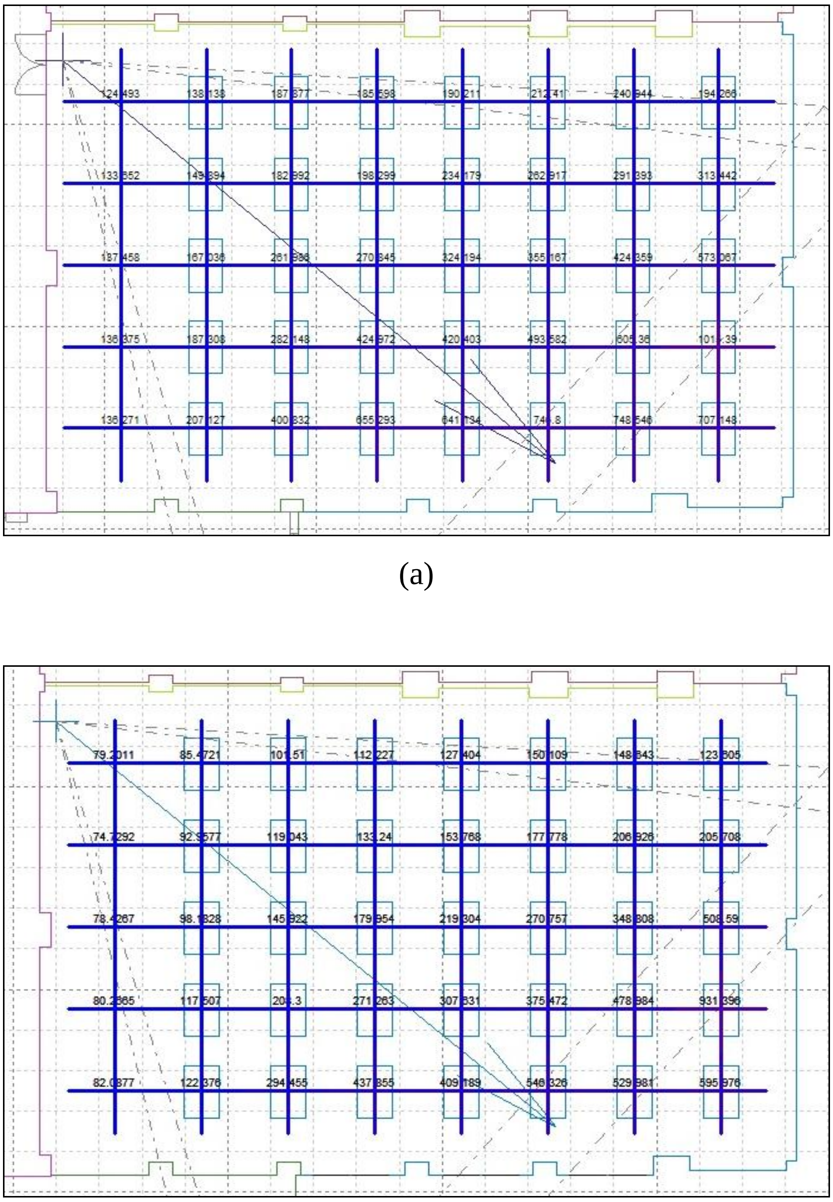


(b)

Figure4.30. Average daylight illuminance at measurement rows for (a) May 4th and (b) June 21st with LCP for studio S03

the selected studios, which very likely was due to the deep distance of 11.25m between the rear wall and the window wall. In Figure 4.30 is presented the average illuminance distribution according to measurement rows on May 4th (a) and June 21st (b).

The uniformity ratio D_{min}/D_{max} of the studio S03 was severely under the recommended ratio of 0.67 with 0.08 at 09:45, 0.06 at 13:20 and 0.07 at 16:45; according to the simulations conducted for May 4th with LCP equipped model.



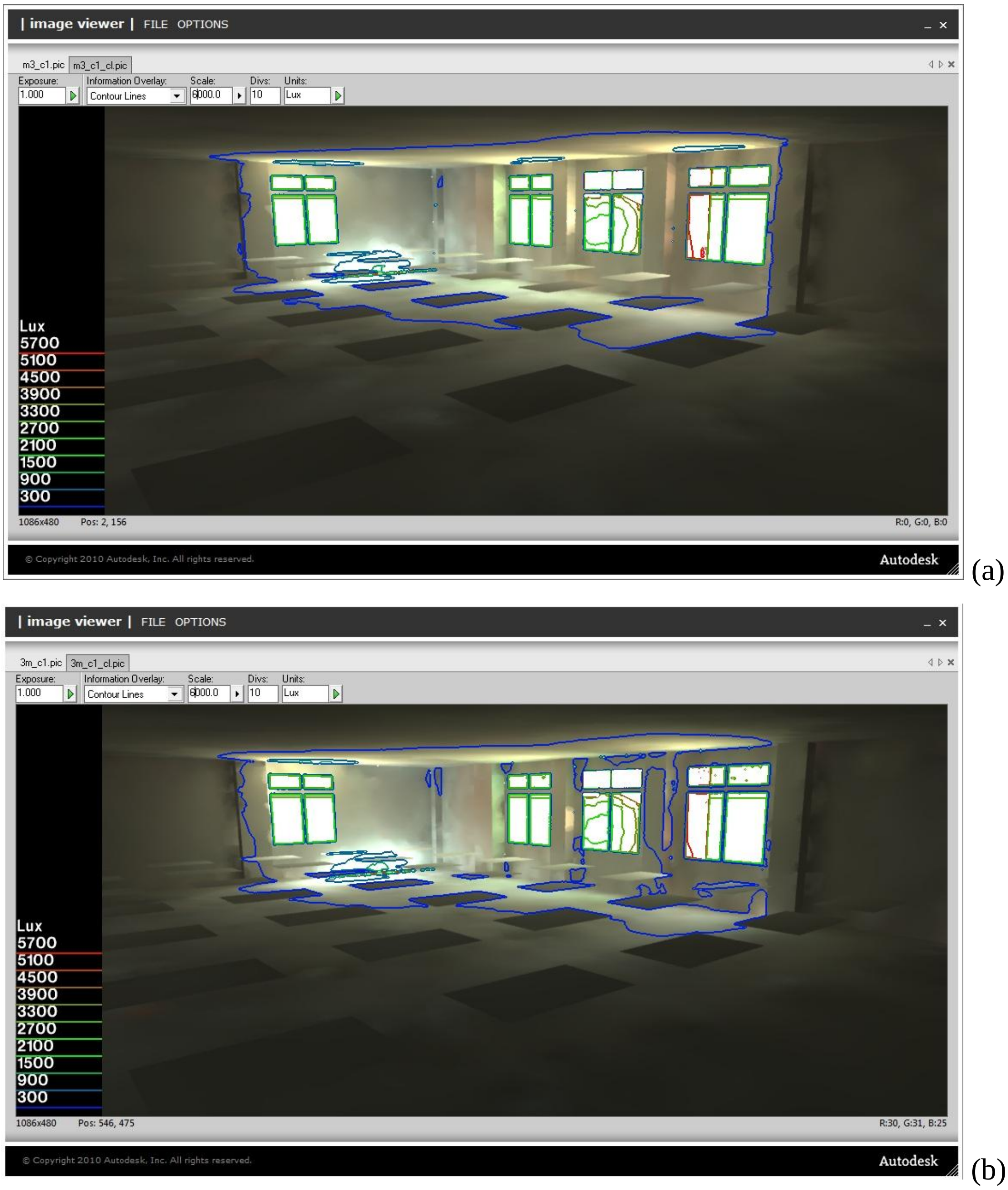
(a)

(b)

Figure 4.31. Simulated illuminance for May 4th, 09:45 for (a) the current condition and (b) the condition with LCP for studio S03

The other uniformity ratio D_{min} / D_{ave} for May 4th was 0.31, 0.28 and 0.23 at 09:45, 13:20 and 16:45; lower than the recommended ratio of 0.50. The uniformity ratios of the simulations conducted for June 21st was quietly similar with May 4th.

In the figures 4.31 – 4.34 are the simulation outputs of Ecotect/ Radiance model equipped with the laser cut panel in studio S03, in order to comprehend the condition of the studio with LCP at 09:45 on May 4th.



Exposure: 1.000 Information Overlay: Contour Lines Scale: 6000.0 Divs: 10 Units: Lux

1086x480 Pos: 2, 156 R:0, G:0, B:0

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Exposure: 1.000 Information Overlay: Contour Lines Scale: 6000.0 Divs: 10 Units: Lux

1086x480 Pos: 546, 475 R:30, G:31, B:25

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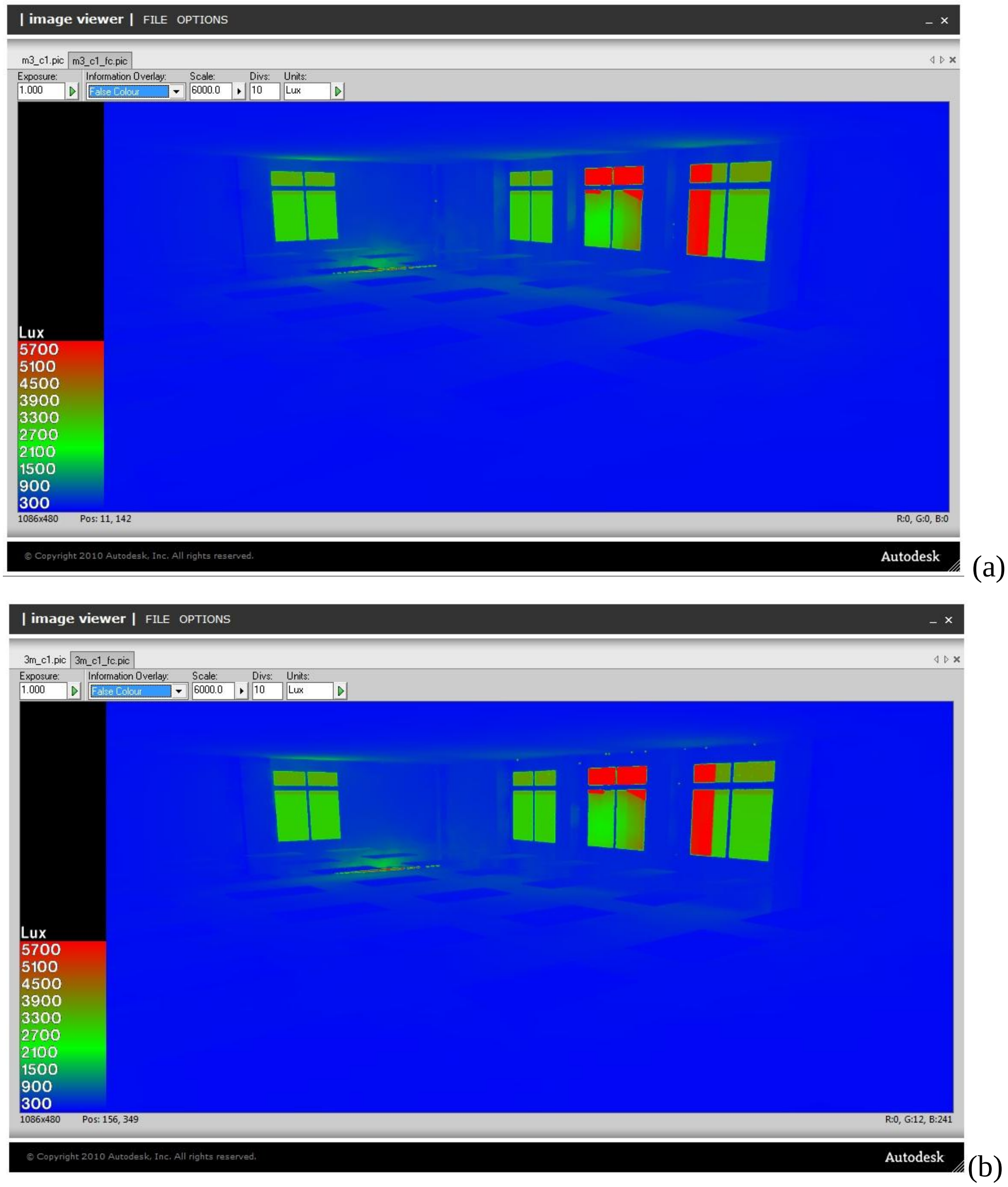
Figure 4.32. Illuminance contour lines showing distribution on May 4th, at 09:45 for (a) the current condition and (b) the condition with LCP for studio S03

According to the illuminance contour lines and false colour representation, it is notable to see more uniform but severely low illuminance distribution in the studio S03. As the orientation of this studio is totally different than the studio S01 and S02, direct sunlight is not abundant during the day. So, the application of LCP did not make any remarkable difference in lighting conditions. Besides, it obstructed some part of the light intensity falling on the horizontal working area.



Exposure: 1.000
Information Overlay: False Colour
Scale: 6000.0
Divs: 10
Units: Lux

Figure 4.33. False colour representations on May 4th, at 09:45 for (a) the current condition and (b) the condition with LCP for studio S03

Exposure: 1.000 Information Overlay: Human Sensitivity Scale: 6000.0 Divs: 10 Units: Lux

986x480 Pos: 0, 223 R:21, G:20, B:16

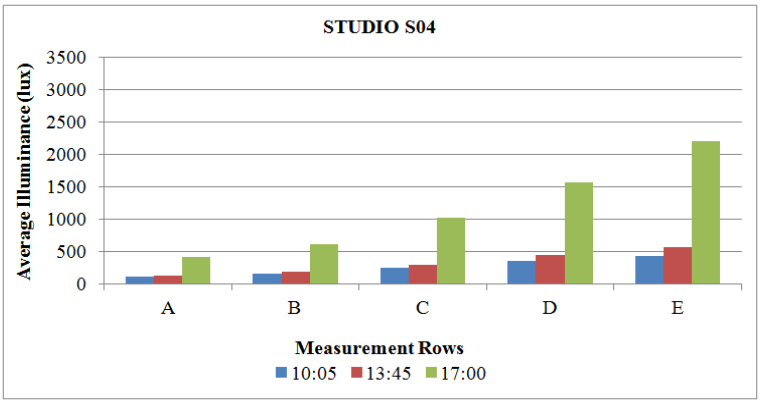
Exposure: 1.000 Information Overlay: Human Sensitivity Scale: 10000.0 Divs: 10 Units: Lux

986x480 Pos: 742, 479 R:1, G:1, B:1

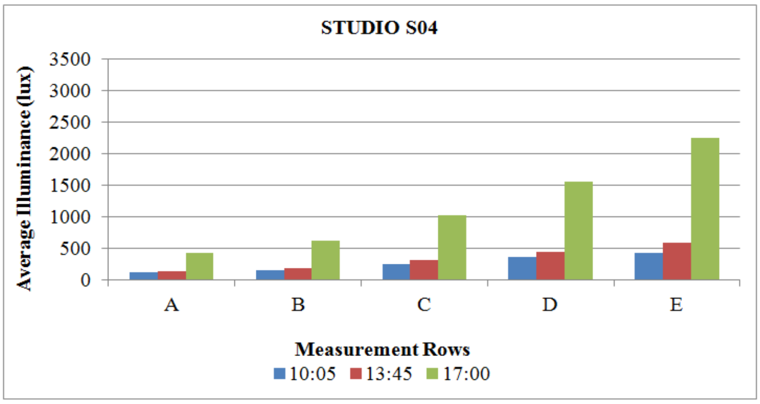
Figure 4.34. Radiance scenes showing human sensitivity on May 4th, at 09:45 for (a) the current condition and (b) the condition with LCP for studio S03

D) Regarding the studio S04, the daylight illuminance distribution of the simulation results of the model with LCP was quietly similar with the current condition at 10:05 and 13:45 on May 4th; only the illuminance was lower. The distribution on June 21st was more uniform on the rows A and B, for the same simulations.

The distribution was similar with the current condition at the rest of the studio. The illuminance at 10:05 and 13:45 at most of the measurement points were below 750 lux at the current condition on both simulated days. The laser cut panels even lowered the overall illuminance in the studio. The simulations conducted for 17:00 showed that the panels did not improve the uniformity much, the distribution was quietly similar with the current condition, only the illuminance was lower in all of the measurement points. Also, the previous sun patches were not observed at row E.



(a)

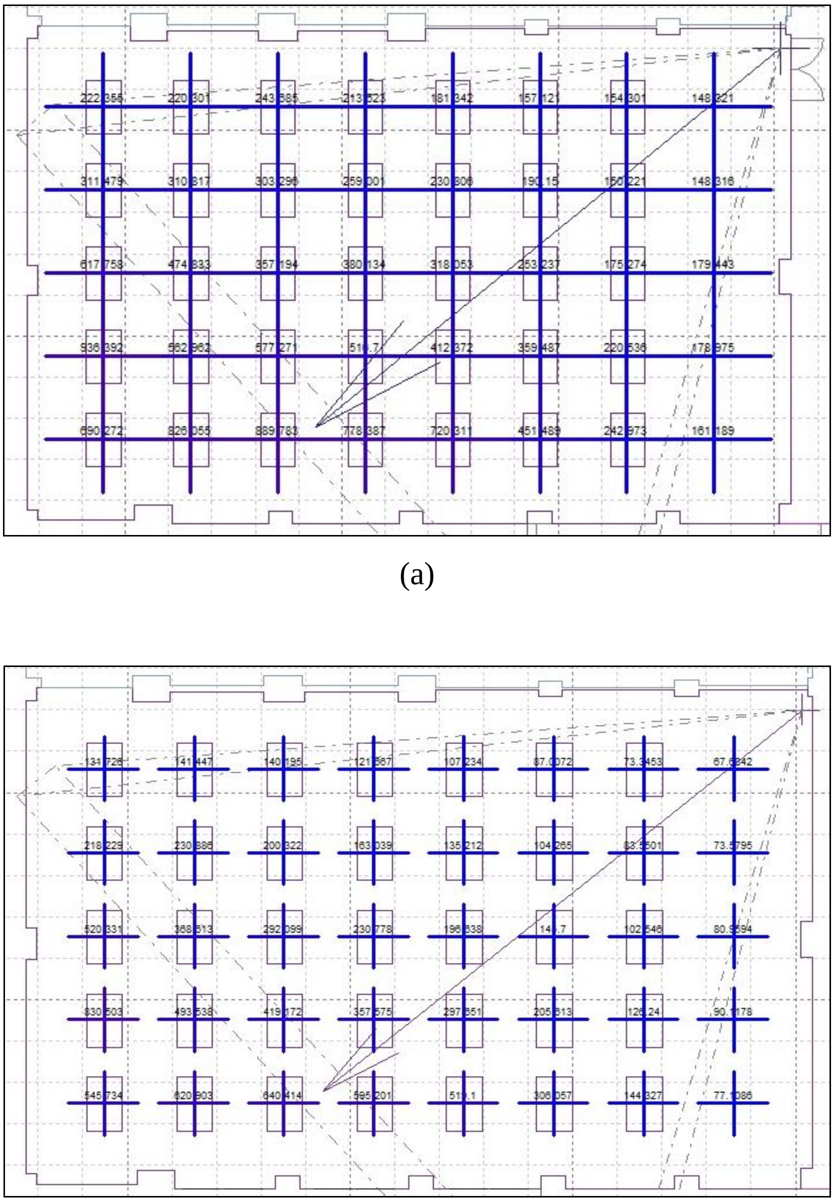


(b)

Figure 4.35. Average daylight illuminance at measurement rows for (a) May 4th and (b) June 21st with LCP for studio S04

In the Figure 4.35 is presented the average illuminance distribution according to measurement rows on May 4th (a) and June 21st (b).

The uniformity ratio D_{min}/D_{max} was 0.08 at 10:05 and 13:45 and 0.07 at 17:00 according to the simulation results of the model with LCP for May 4th. D_{min}/D_{ave} ratio of the same day was 0.26 at 10:05, 0.23 at 13:45 and 0.23 at 17:00. The uniformity ratios for June 21st were almost identical to May 4th.

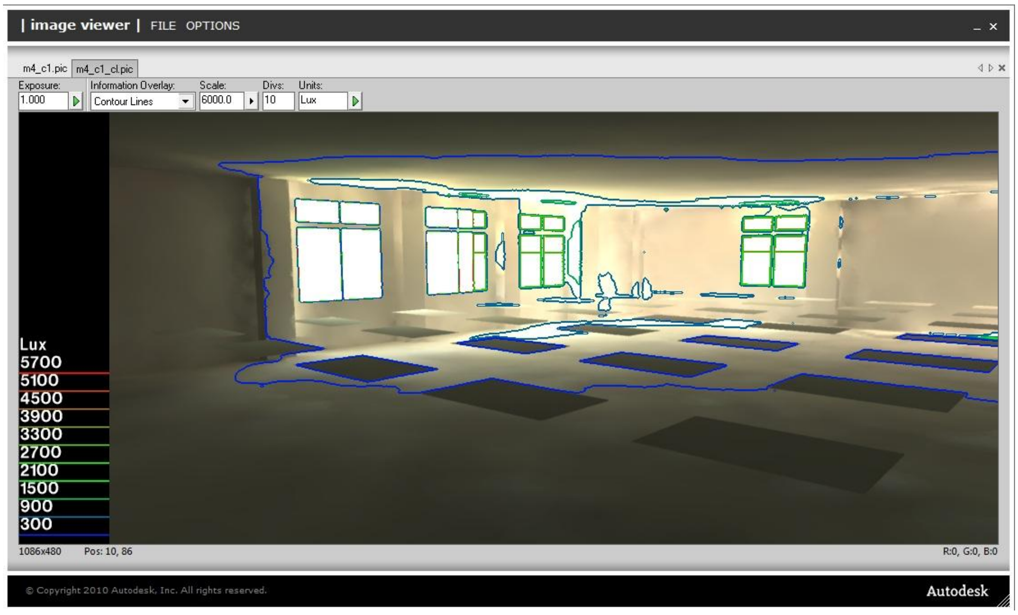


(a)

(b)

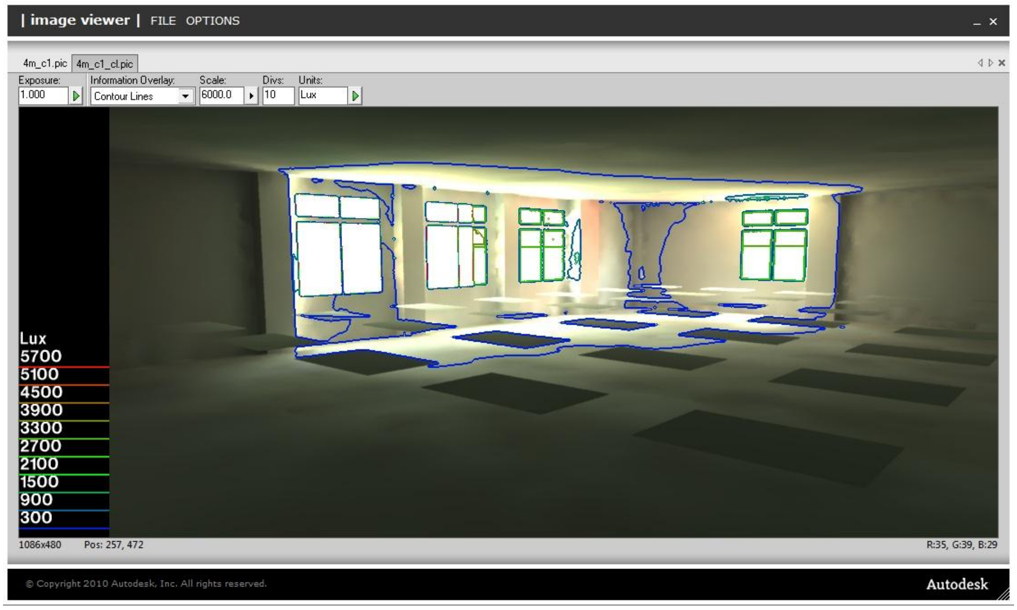
Figure 4. 36. Simulated illuminance for May 4th, 10:05 for (a) the current condition and (b) the condition with LCP for studio S04

In the Figures 4.36 and 4.39 are presented the simulation outputs of Autodesk Ecotect Analysis / Desktop Radiance in order to comprehend the distribution of daylight in the studio.



Exposure: 1.000
Information Overlay: Contour Lines
Scale: 6000.0
Divs: 10
Units: Lux

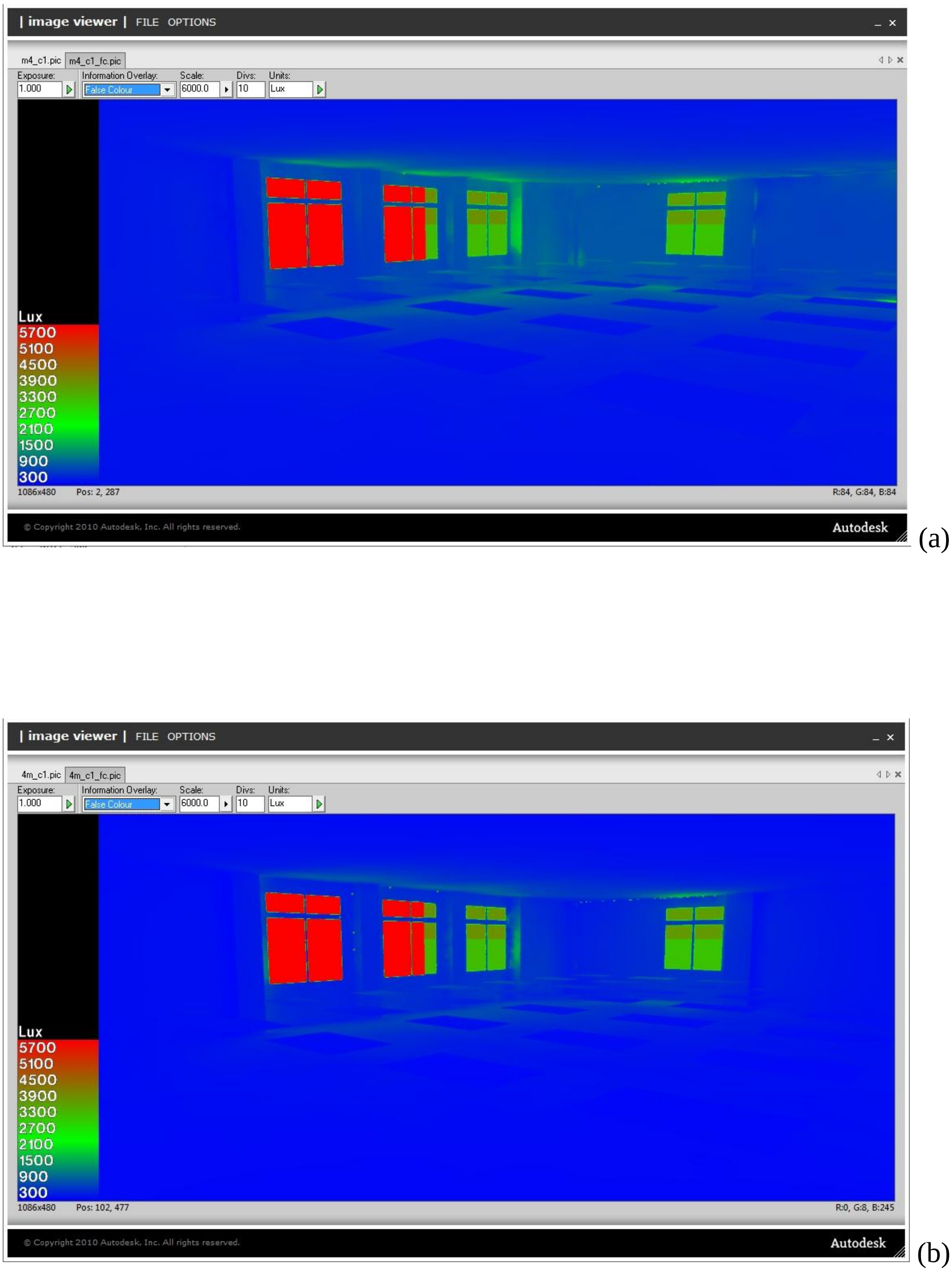
(a)



Exposure: 1.000
Information Overlay: Contour Lines
Scale: 6000.0
Divs: 10
Units: Lux

(b)

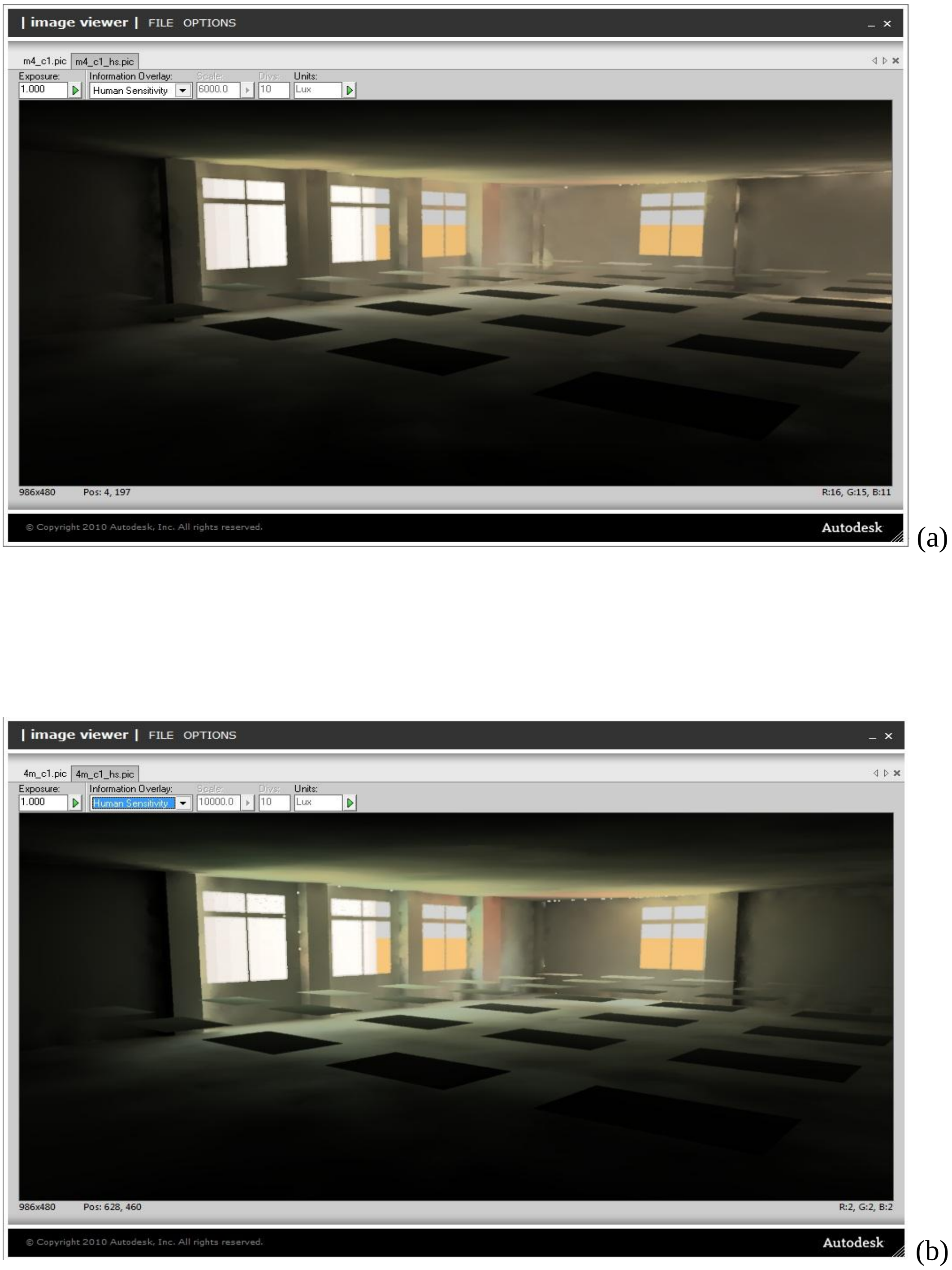
Figure 4.37. Illuminance contour lines showing distribution on May 4th, 10:05 for (a) the current condition and (b) the condition with LCP for studio S04



(a)
Exposure: 1.000
Information Overlay: False Colour
Scale: 6000.0
Divs: 10
Units: Lux
1086x480 Pos: 2, 287 R:84, G:84, B:84

(b)
Exposure: 1.000
Information Overlay: False Colour
Scale: 6000.0
Divs: 10
Units: Lux
1086x480 Pos: 102, 477 R:0, G:8, B:245

Figure 4.38. False colour representations on May 4th, at 10:05 for (a) the current condition and (b) the condition with LCP for studio S04



Exposure: 1.000
Information Overlay: Human Sensitivity
Scale: 6000.0
Divs: 10
Units: Lux

986x480 Pos: 4, 197 R:16, G:15, B:11

Exposure: 1.000
Information Overlay: Human Sensitivity
Scale: 10000.0
Divs: 10
Units: Lux

986x480 Pos: 628, 460 R:2, G:2, B:2

Figure 4.39. Radiance scenes showing human sensitivity on May 4th, at 10:05 for (a) the current condition and (b) the condition with LCP for studio S04

4.3.2. Prismatic Panels

Since the reflective surface angles of the laser cut and prismatic panels differed from each other, they do not have the same light redirecting characteristics. In order to comprehend the effects that the prismatic panels had on the illuminance and uniformity of the four architectural design studios, and to compare their contribution to the daylighting performance of the studios with laser cut panels (and letter with light shelves), daylighting simulations are conducted by using Desktop Radiance. The panels were modeled using Autodesk Ecotect Analysis and the dimensioning and angles of the prismatic surfaces are adjusted regarding an application of Norwegian University of Science and Technology to an office building at Sandvika, Norway (IEA, 2000).

In the model, the panels were placed above eye level like the laser cut panels, 2 meters high from the floor, aiming to prevent glare that might have occurred by the redirection of daylight and not to block the outside view. The reflecting surfaces of the prismatic panels were determined as 45^o. The daylight simulations of the prismatic panel equipped model were conducted for all studios for the two selected days, May 4th and June 21st.

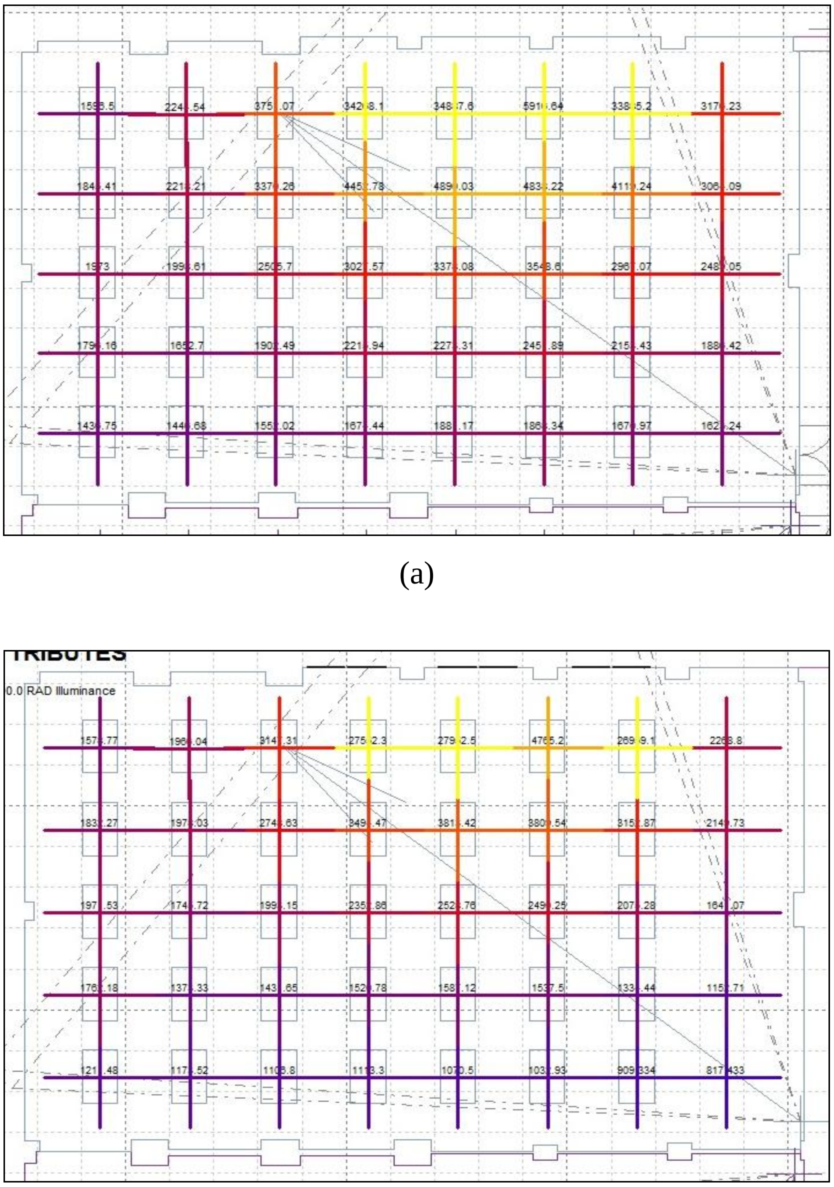
A) Regarding the studio S01, the daylight illuminance distribution showed similar characteristics at May 4th and June 21st according to the simulation results of the prismatic panel equipped model, but the illuminance was lower in June 21st. The illuminance distribution was quietly similar to the current condition at June 21st and thus, the uniformity in the studio did not show remarkable improvement.

The illuminance in the prismatic panel equipped model was lower than the current condition at most of the measurement points on the same day. According to the simulation results of June 21st, the illuminance difference between the current condition and the condition with prismatic panels were greater at the 09:00 simulations. Previous sun patches that were observed in row E were also prevented at 09:00. The illuminance difference between the current condition and the prismatic panel equipped model was remarkably low at 12:30 and 16:10 simulations.

The illuminance distribution of May 4th showed divergences than the current condition, and the uniformity of the studio was even more disturbed than the current condition when the prismatic panels were applied at 12:30 and 16:10. Also at 09:00, the prismatic panels failed to prevent the previous sun patches at the row E.

The uniformity ratio D_{min} / D_{max} was 0.17 at 09:00; 0.18 at 12:30 and 0.15 at 16:10 on May 4th. These were severely lower than the recommended value of 0.67. D_{min} / D_{ave} ratio was closer to the recommended ratio of 0.50. It was 0.41 at 09:00; 0.35 at 12:30; and 0.35 at 16:10.

The simulation outputs of Ecotect/ Radiance model equipped with the prismatic panel are represented in Figures 4.40 – 4.43; at 09:00 on May 4th.

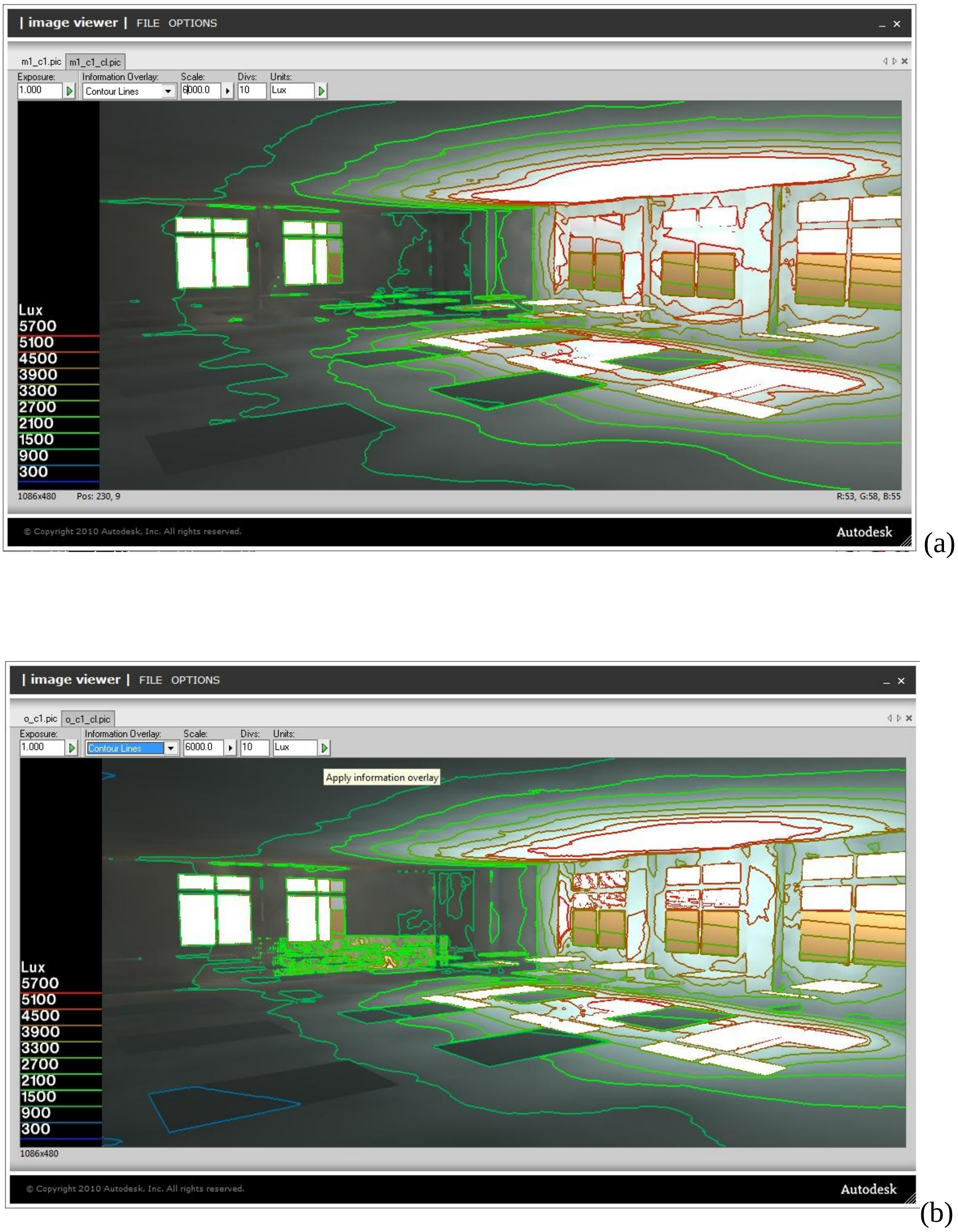


(a)

(b)

Figure 4.40. Simulated illuminance for May 4th, 09:00 for (a) the current condition and (b) the condition with prismatic panel for studio S01

As can be acquired from the illuminance contour lines and false color representations, the illuminance in the studio was lower than the current condition but there was slightly more uniform daylight distribution, when the prismatic panels were applied. Sun patches were still observed, but in a smaller area.



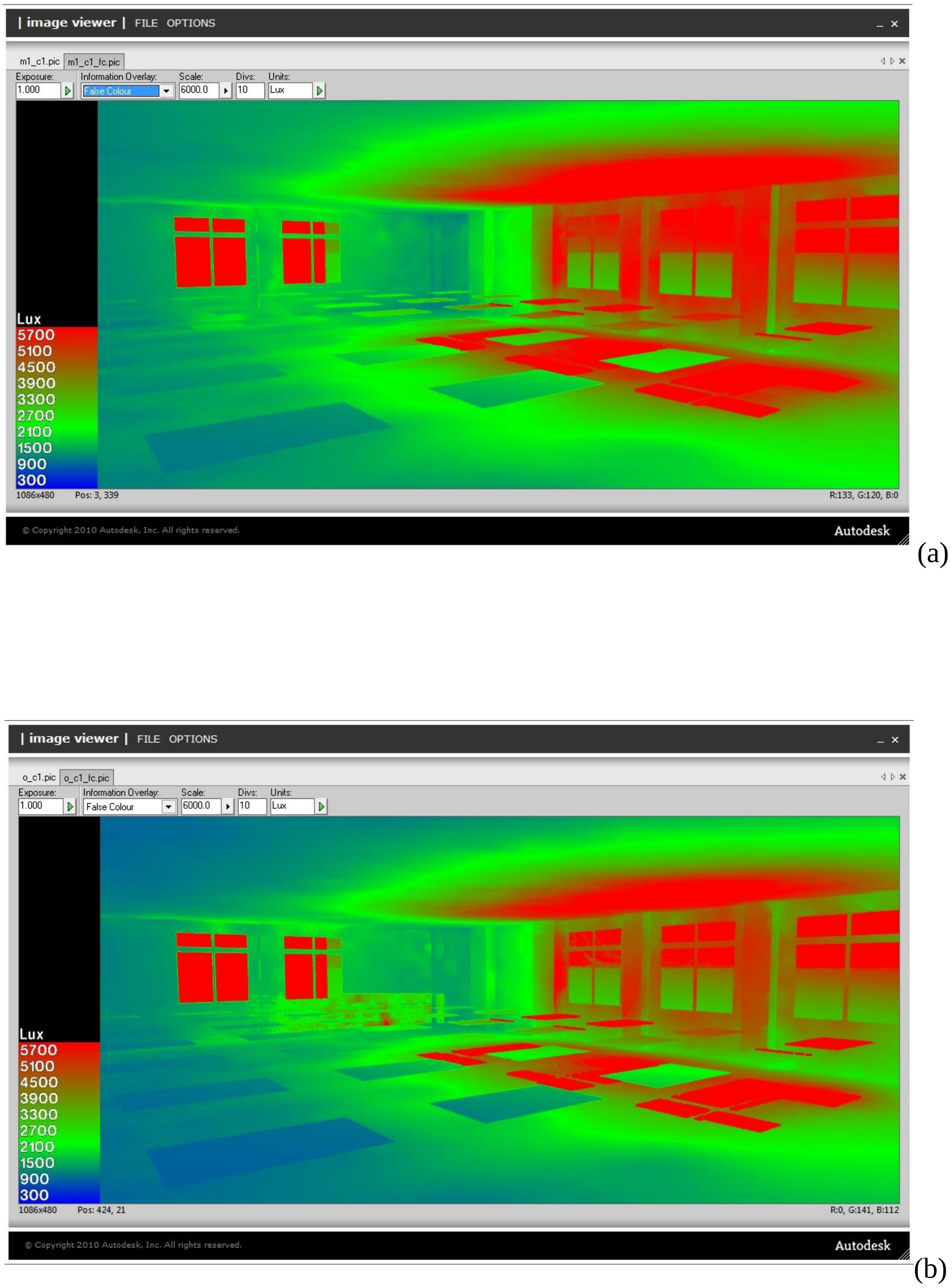
(a) Exposure: 1.000; Information Overlay: Contour Lines; Scale: 6000.0; Divs: 10; Units: Lux

1086x480 Pos: 230, 9 R:53, G:58, B:55

(b) Exposure: 1.000; Information Overlay: Contour Lines; Scale: 6000.0; Divs: 10; Units: Lux

1086x480

Figure 4.41. Illuminance contour lines showing distribution on May 4th, 09:00 for (a) the current condition and (b) the condition with prismatic panel for S01



Exposure: 1.000
Information Overlay: False Colour
Scale: 6000.0
Divs: 10
Units: Lux

1086x480 Pos: 3, 339 R:133, G:120, B:0

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(a)

Exposure: 1.000
Information Overlay: False Colour
Scale: 6000.0
Divs: 10
Units: Lux

1086x480 Pos: 424, 21 R:0, G:141, B:112

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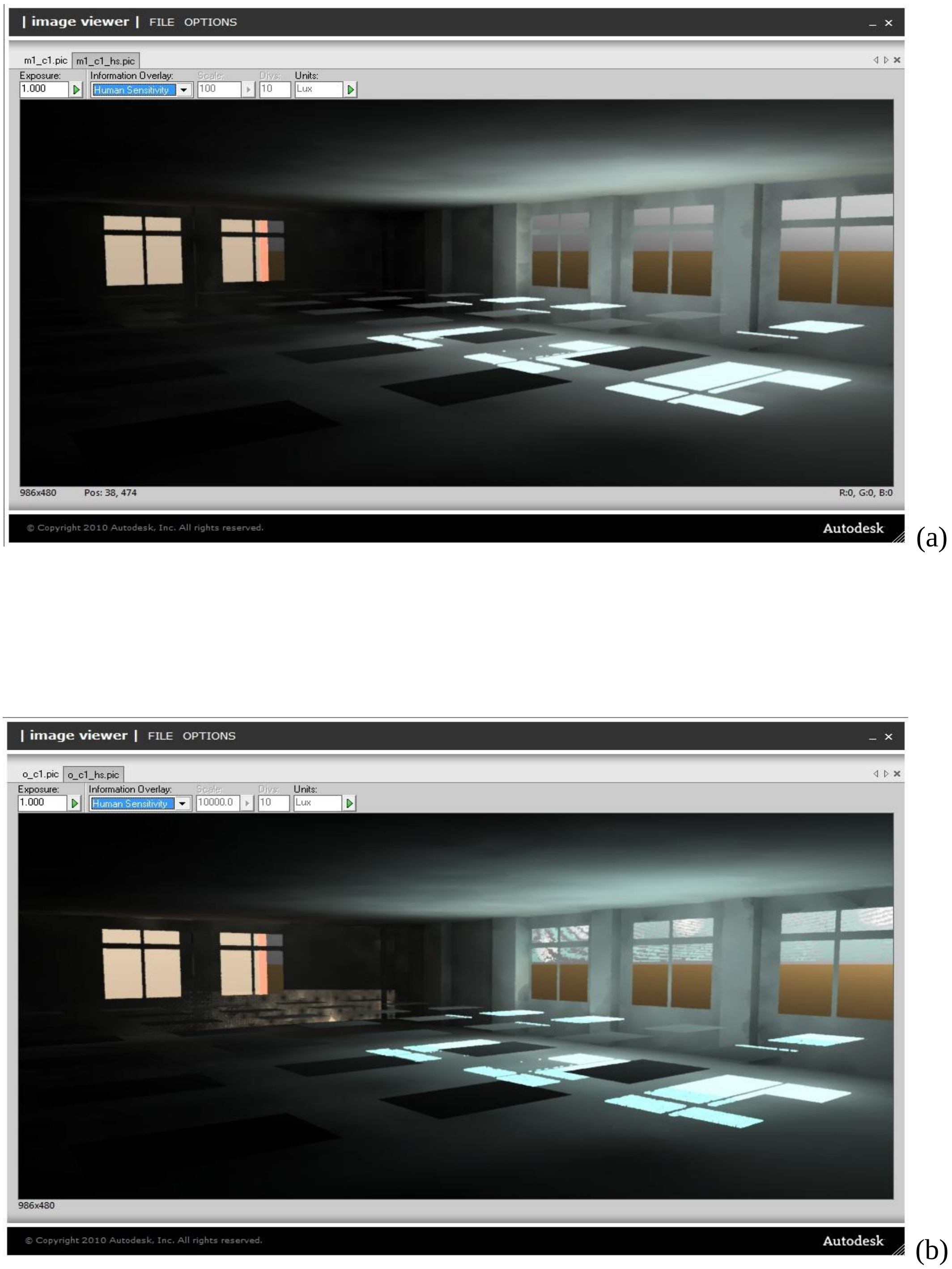
(b)

Figure 4.42. False colour representations for May 4th, 09:00 for (a) the current condition and (b) the condition with prismatic panel for studio S01

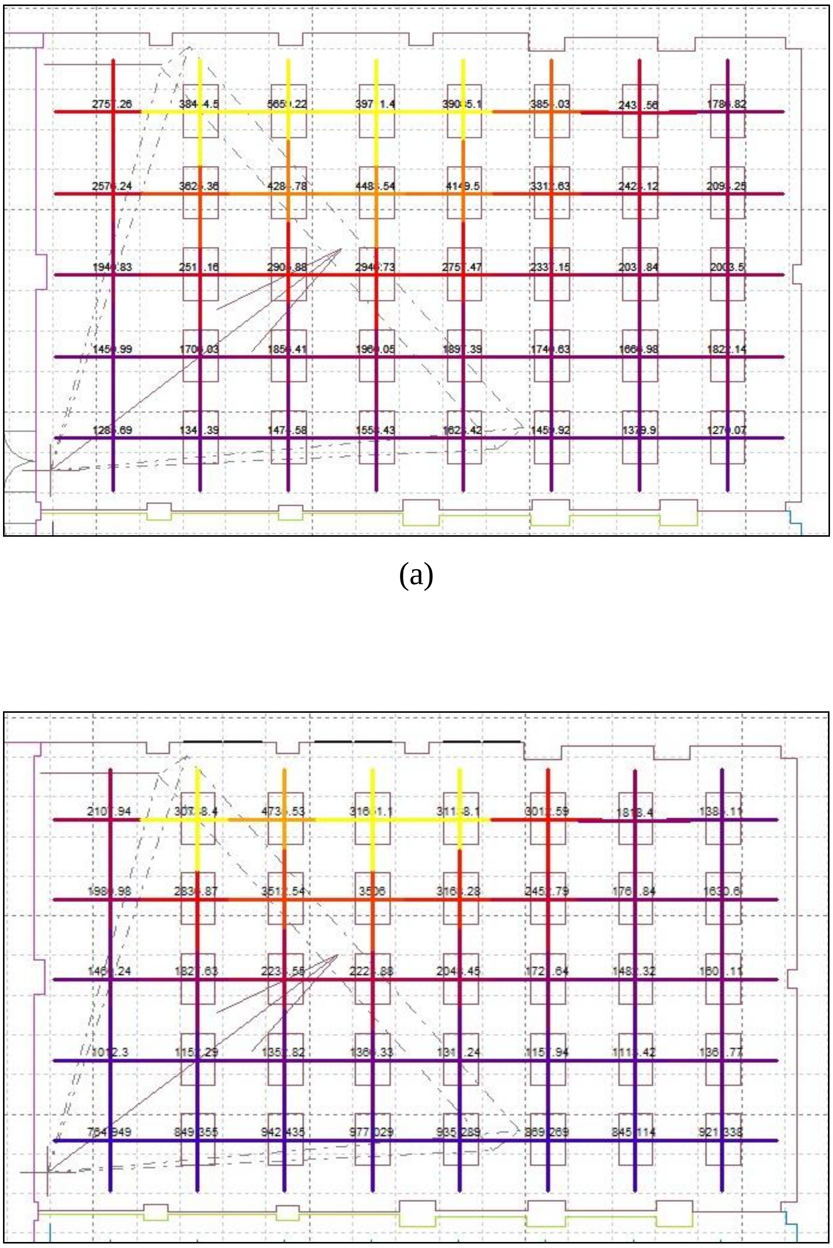


(a)
Exposure: 1.000
Information Overlay: Human Sensitivity
Scale: 100
Divs: 10
Units: Lux
986x480 Pos: 38, 474 R:0, G:0, B:0

(b)
Exposure: 1.000
Information Overlay: Human Sensitivity
Scale: 10000.0
Divs: 10
Units: Lux
986x480

Figure 4.43. Radiance scenes showing human sensitivity on May 4th, at 09:00 for (a) the current condition and (b) the condition with prismatic panel for studio S01

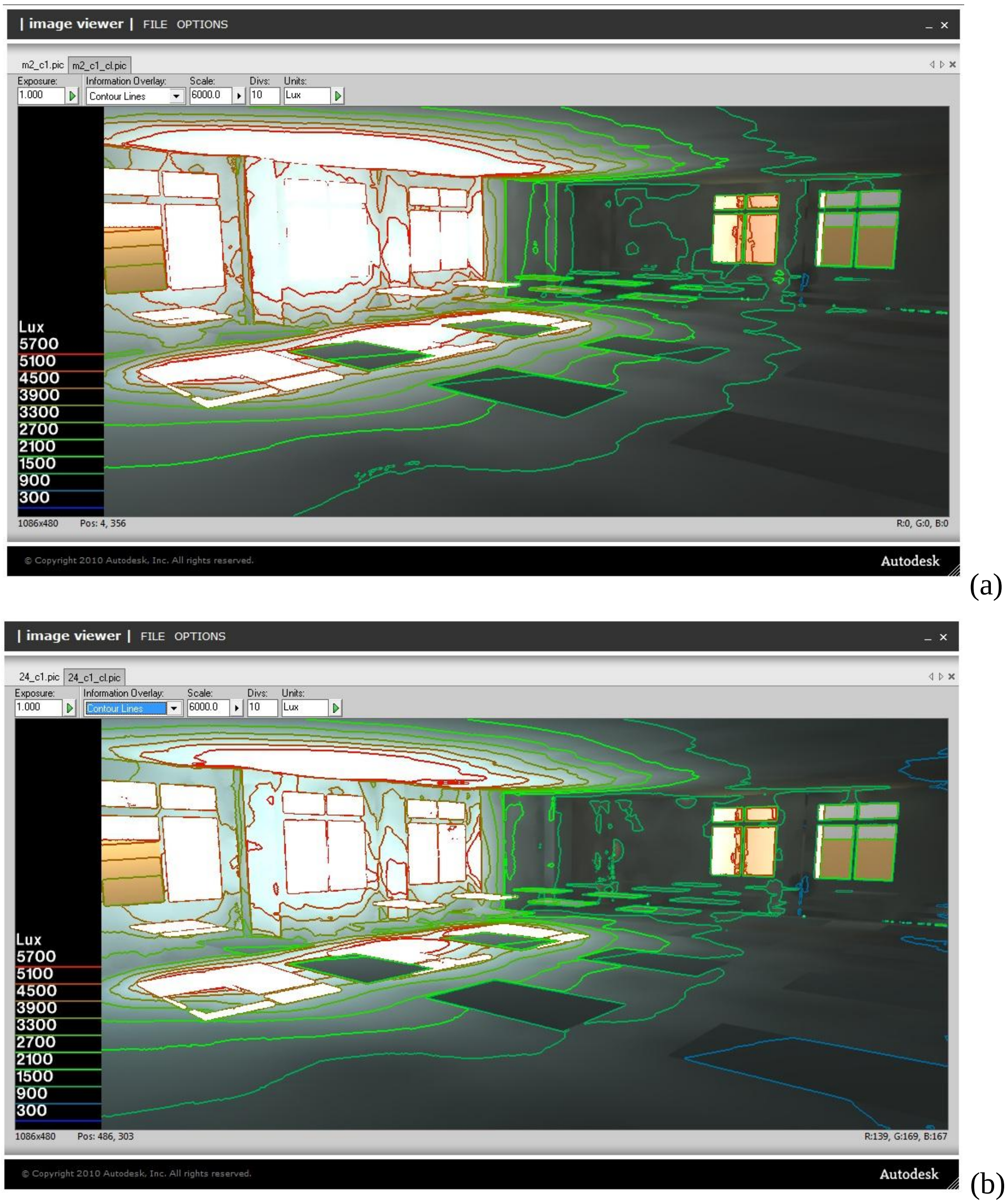
B) Regarding the studio S02, the daylight illuminance distribution did not change remarkably after the application of prismatic panels, according to the simulations. The illuminance of the model with the prismatic panel was lower at the most of the measurement points than the illuminance in all other conducted simulations on May 4th and June 21st.


(a)

(b)

Figure 4.44. Simulated illuminance for May 4th, 09:25 for (a) the current condition and (b) the condition with prismatic panel for studio S02

The uniformity of the studios became more irregular in simulations conducted at 12:30 and 16:10. D_{min}/D_{max} was 0.16 at 09:25, 0.09 at 13:00 and 0.09 at 16:25 on May 4th, pointing out the high differences within the studio between the peak and low points. D_{min} / D_{ave} ratio was 0.43, 0.27, 0.27 at 09:25, 13:00 and 16:25 respectively. Sun patches on Row E at 09:00 previously were prevented in the simulations with prismatic panels on June 21st. However, they were still observed on May 4th.



(a) Exposure: 1.000 Information Overlay: Contour Lines Scale: 6000.0 Divs: 10 Units: Lux

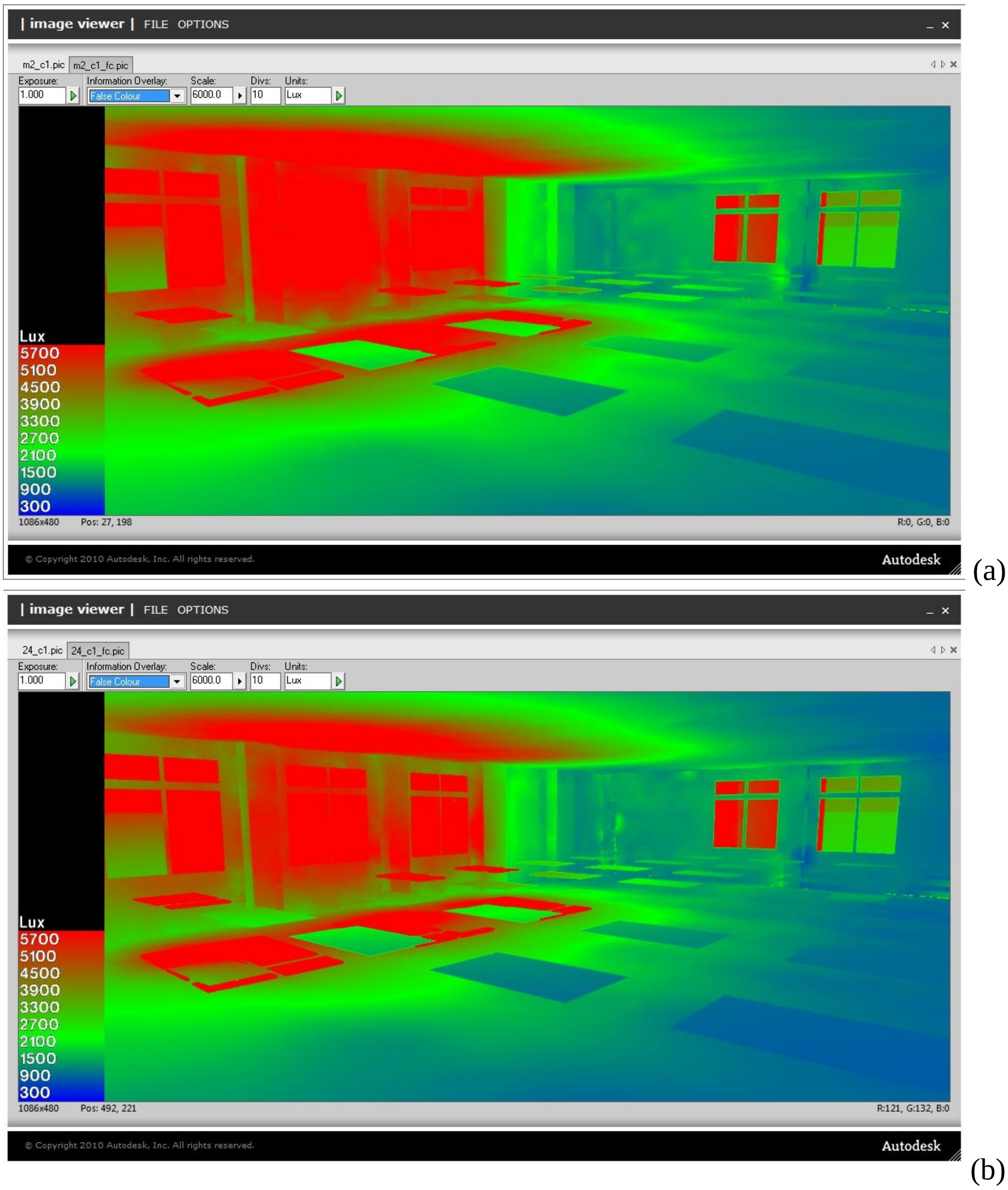
1086x480 Pos: 4, 356 R:0, G:0, B:0

(b) Exposure: 1.000 Information Overlay: Contour Lines Scale: 6000.0 Divs: 10 Units: Lux

1086x480 Pos: 486, 303 R:139, G:169, B:167

Figure 4.45. Illuminance contour lines showing distribution on May 4th, 09:25 for (a) the current condition and (b) the condition with prismatic panel for S02

The findings of the simulations including prismatic panels carried out on May 4th, at 09:25 the simulations representing the current condition of the studio are presented in Figure 4.44 – 4.47. Regarding these, it can be observed that the daylight distribution of the studio was severely non uniform at both conditions. Application of prismatic panels lowered the daylight illuminance within the studio, as can be observed at the illuminance contour lines and false color representations.



m2_c1.pic | m2_c1_fc.pic

Exposure: 1.000
Information Overlay: False Colour
Scale: 6000.0
Divs: 10
Units: Lux

1086x480 Pos: 27, 198 R:0, G:0, B:0

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(a)

24_c1.pic | 24_c1_fc.pic

Exposure: 1.000
Information Overlay: False Colour
Scale: 6000.0
Divs: 10
Units: Lux

1086x480 Pos: 492, 221 R:121, G:132, B:0

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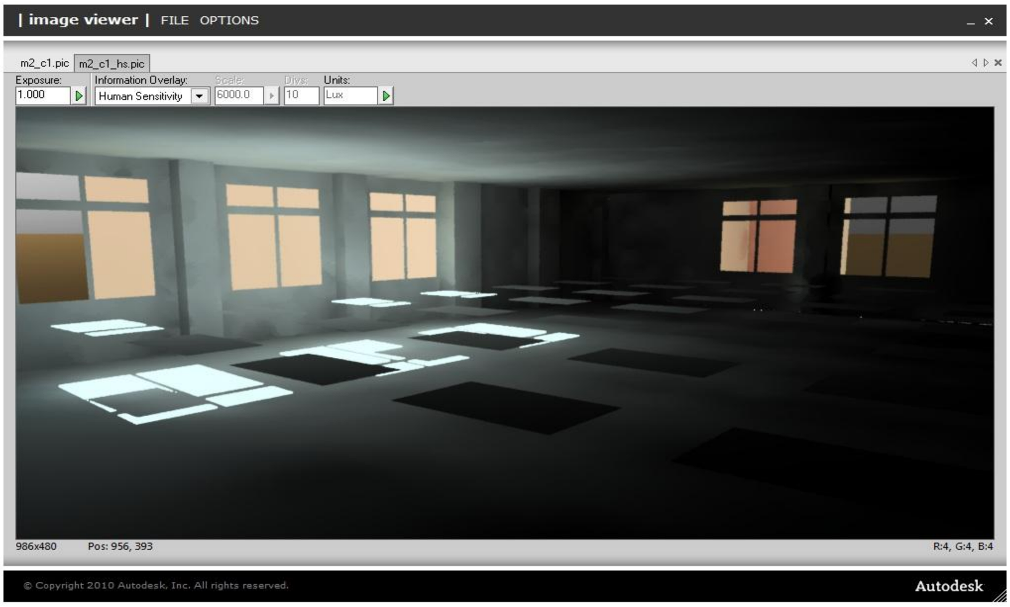
(b)

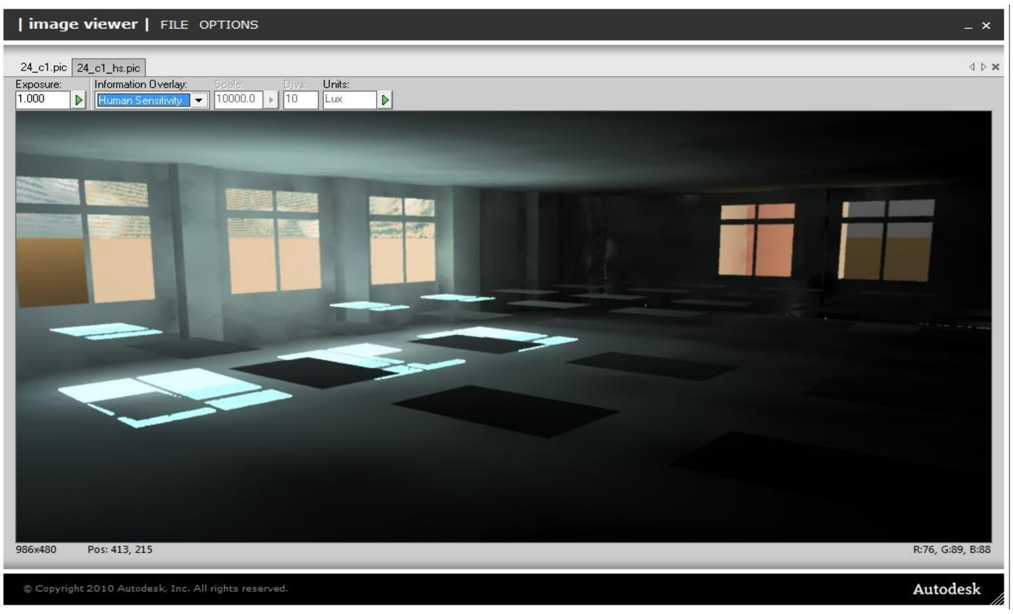
Figure 4.46. False colour representations for May 4th, 09:25 for (a) the current condition and (b) the condition with prismatic panel for studio S02

Sun patches were present in both conditions, but the panels had decreased the sun patch area. As the prismatic panels are located above the eye level, they were not successful to block the direct sunlight totally and diffuse all direct light intensity which reached to the window surface. This reminded another solution which includes the application of light shelves.



Exposure: 1.000
Information Overlay: Human Sensitivity
Scale: 6000.0
Divs: 10
Units: Lux
986x480 Pos: 956, 393 R:4, G:4, B:4

(a)

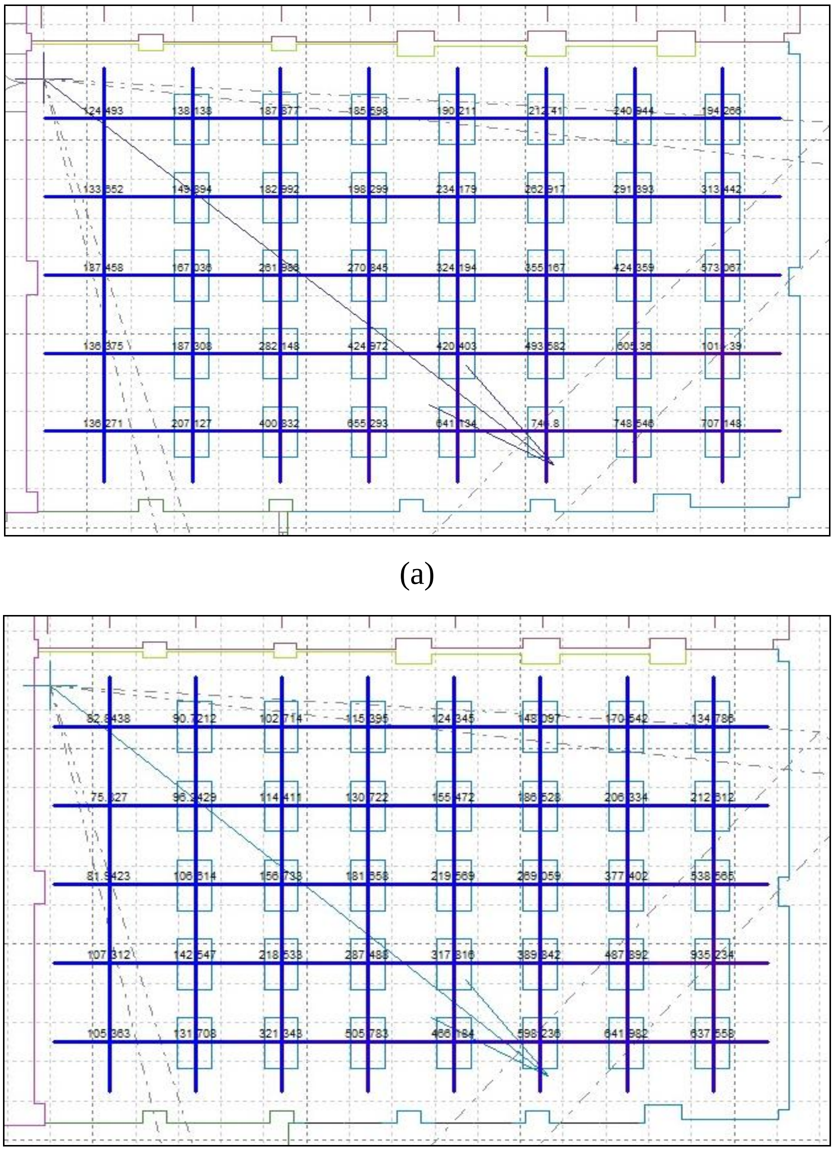


Exposure: 1.000
Information Overlay: Human Sensitivity
Scale: 10000.0
Divs: 10
Units: Lux
986x480 Pos: 413, 215 R:76, G:89, B:88

(b)

Figure 4.47. Radiance scenes showing human sensitivity on May 4th, at 09:25 for (a) the current condition and (b) the condition with prismatic panel for studio S02

C) Regarding the studio S03, the daylighting illuminance distribution of the simulated model with prismatic panels was quietly similar to the current condition; but the illuminance was lower at the majority of the measurement points with the prismatic panel equipped model (Figures 4.16 – 4.19). Sun patches that were observed in the simulations conducted at 16:45 for the current condition were still observed on the prismatic panel applied model at June 21st. The panels could prevent the sun patches on the simulations conducted for May 4th.

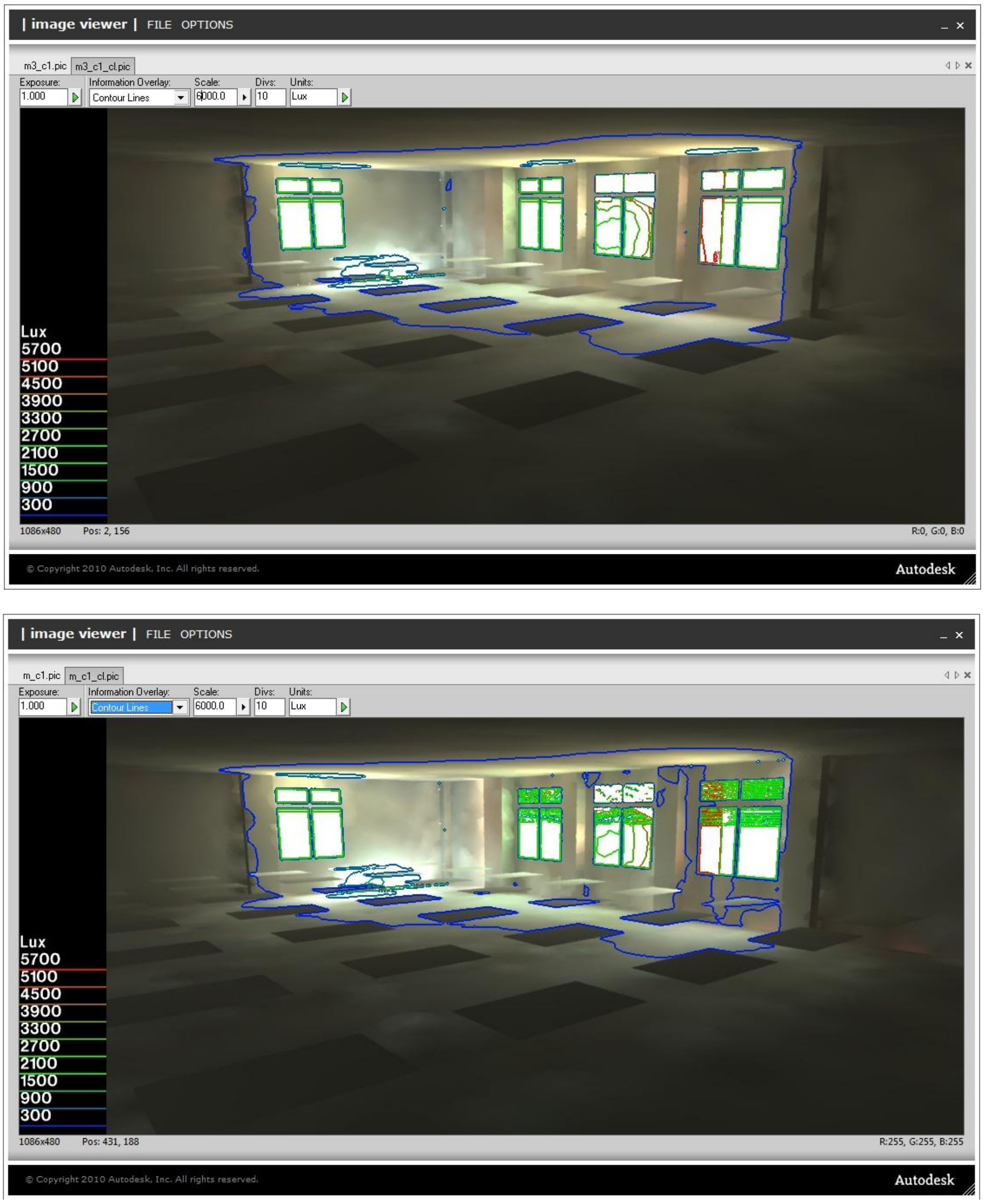


(a)

(b)

Figure 4.48. Simulated illuminance for May 4th, 09:45 for (a) the current condition and (b) the condition with prismatic panel for studio S03

The illuminance in the current condition of the studio was severely lower than the recommended ratio on 09:45 and 13:20. The panels had even lowered more the illuminance in the studio, unlike the predictions. The uniformity ratio D_{min}/D_{max} of the studio S03 was severely under the recommended ratio of 0.67 with 0.08 at 09:45, 0.06 at 13:20 and 0.09 at 16:45; according to the simulations conducted for May 4th with prismatic panel equipped model.



Exposure: 1.000
Information Overlay: Contour Lines
Scale: 6000.0
Divs: 10
Units: Lux

(a)

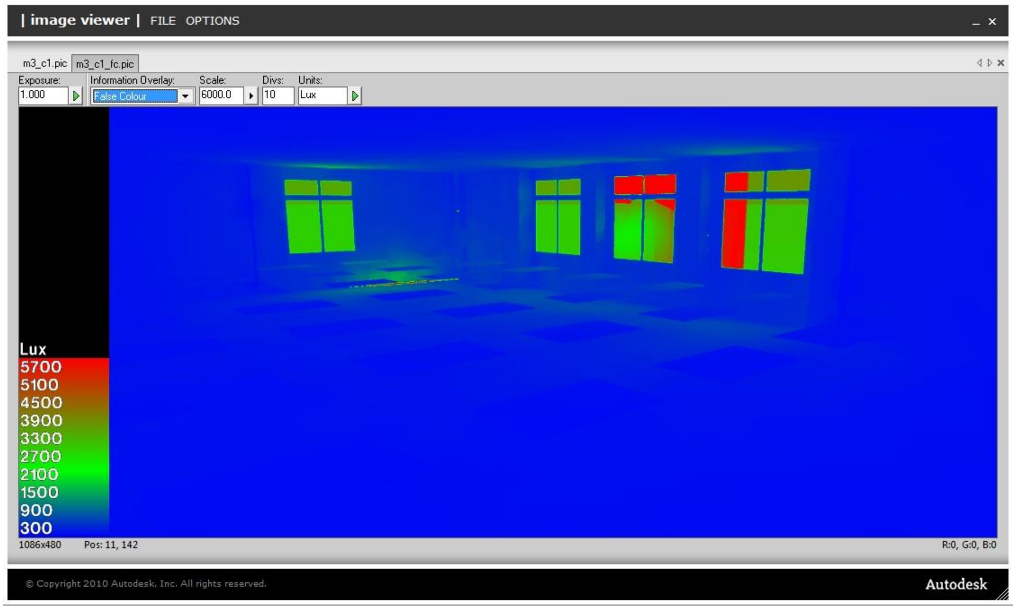
Exposure: 1.000
Information Overlay: Contour Lines
Scale: 6000.0
Divs: 10
Units: Lux

(b)

Figure 4.49. Illuminance contour lines showing distribution on May 4th, 09:45 for (a) the current condition and (b) the condition with prismatic panel for S03

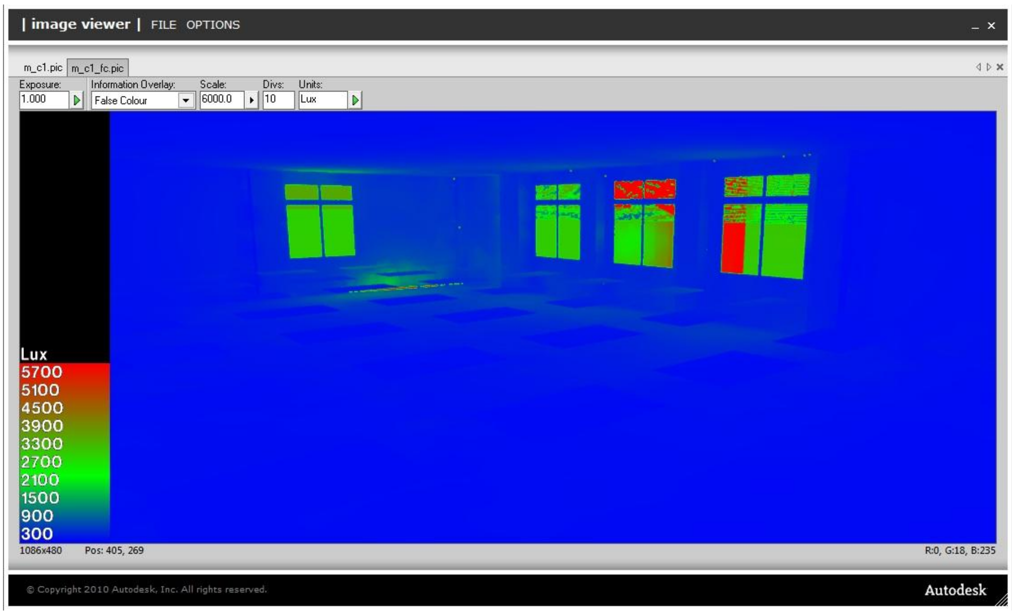
The other uniformity ratio D_{min}/D_{ave} for the same day was 0.29 for 09:45, 0.25 for 13:20 and 0.25 for 16:45, severely lower than the recommended ratio of 0.50.

The simulation outputs of Desktop Radiance conducted on May 4th, at 09:45 for studio S03 with the prismatic panel applied model and the model representing the current condition of the studio are presented in Figure 4.48 – 4.51.



Exposure: 1.000
Information Overlay: False Colour
Scale: 6000.0
Divs: 10
Units: Lux
1086x480 Pos: 11, 142 R:0, G:0, B:0

(a)

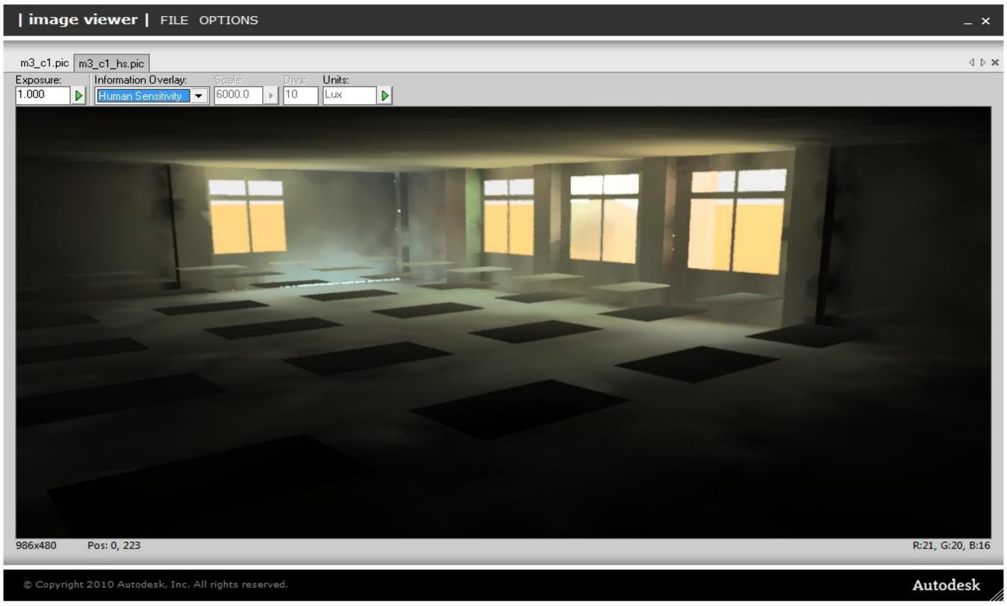


Exposure: 1.000
Information Overlay: False Colour
Scale: 6000.0
Divs: 10
Units: Lux
1086x480 Pos: 405, 269 R:0, G:18, B:235

(b)

Figure 4.50. False colour representations for May 4th, 09:45 for (a) the current condition and (b) the condition with prismatic panel for studio S03

As can be derived from these figures, the illuminance in the Studio S03 was lower than the Studio S01 and S02 according to the simulations conducted in the morning. As the Figure 4.48 illustrates, applying prismatic panels had lowered the illuminance more on most of the measurement points.



Exposure: 1.000
Information Overlay: Human Sensitivity
Scale: 6000.0
Divs: 10
Units: Lux

986x480 Pos: 0, 223 R:21, G:20, B:16

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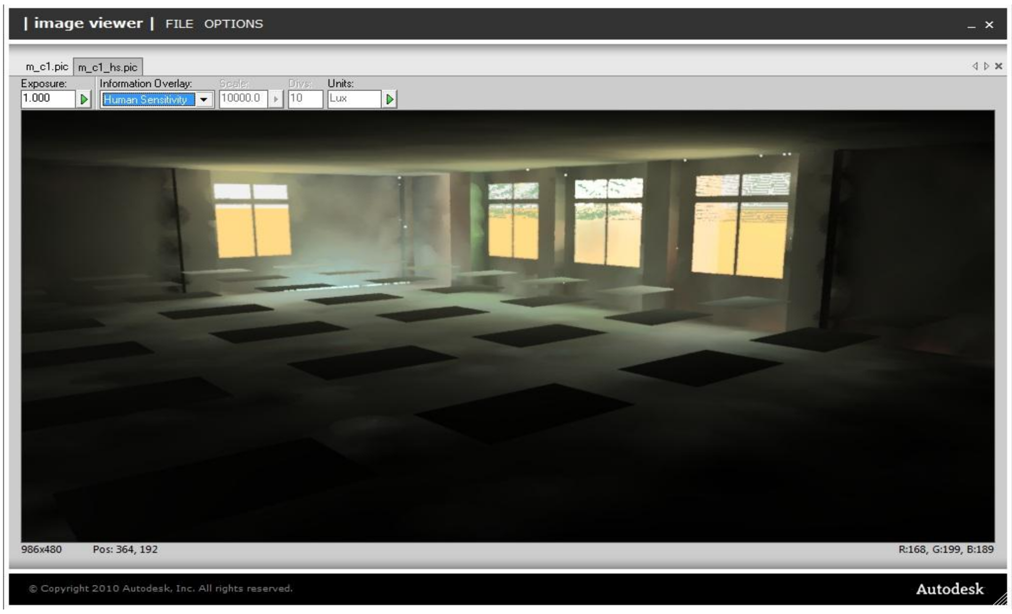
(a)



Exposure: 1.000
Information Overlay: Human Sensitivity
Scale: 10000.0
Divs: 10
Units: Lux

986x480 Pos: 364, 192 R:168, G:199, B:189

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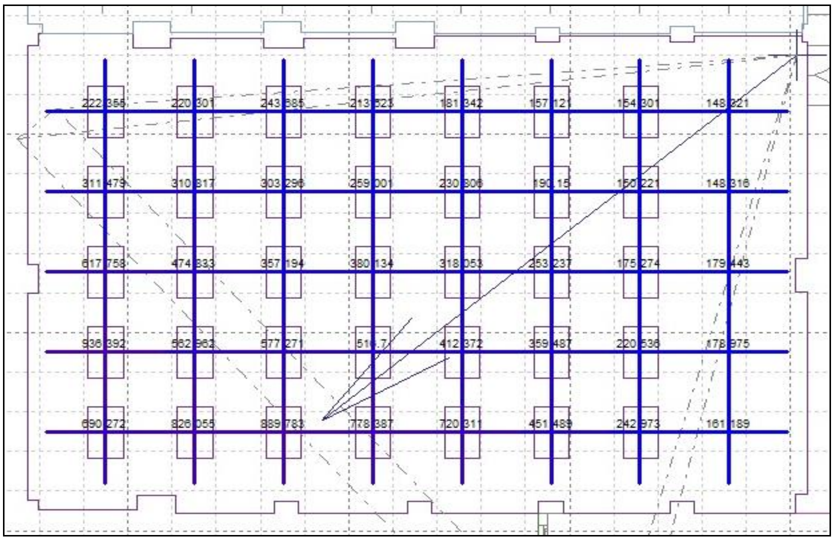
(b)

Figure 4.51. Radiance scenes showing human sensitivity on May 4th, at 09:45 for (a) the current condition and (b) the condition with prismatic panel for studio S03

D) Regarding studio S04, the daylight illuminance distribution of the simulation results of the model with prismatic panels was similar with the current condition except for simulations conducted on May 4th at 10:05 and 13:45. The uniformity of the studio had not improved remarkably by applying prismatic panels. The previous sun patches that were observed in the 17:00 were still present for both days.

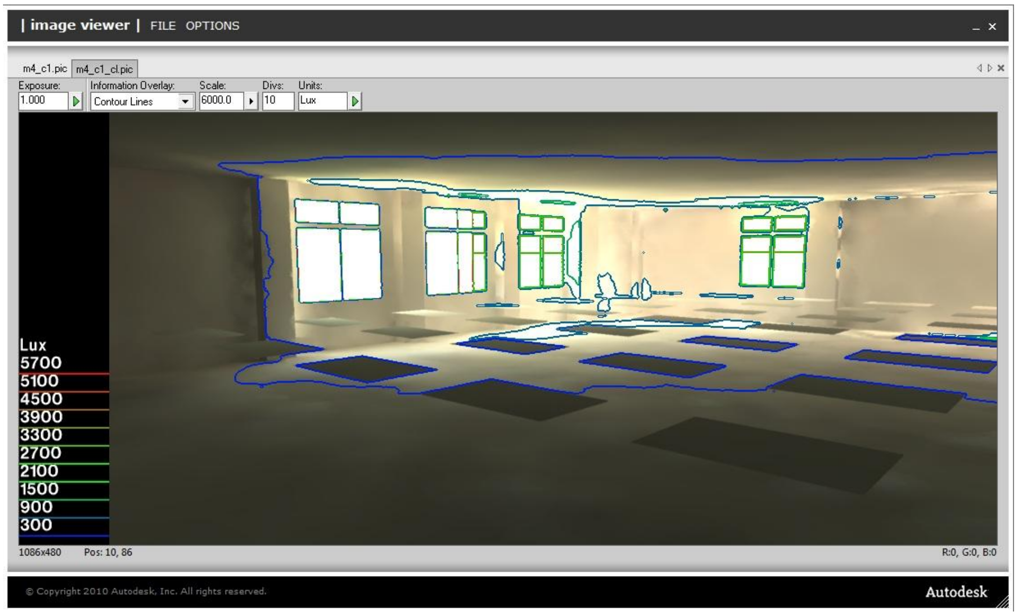


(a)

(b)

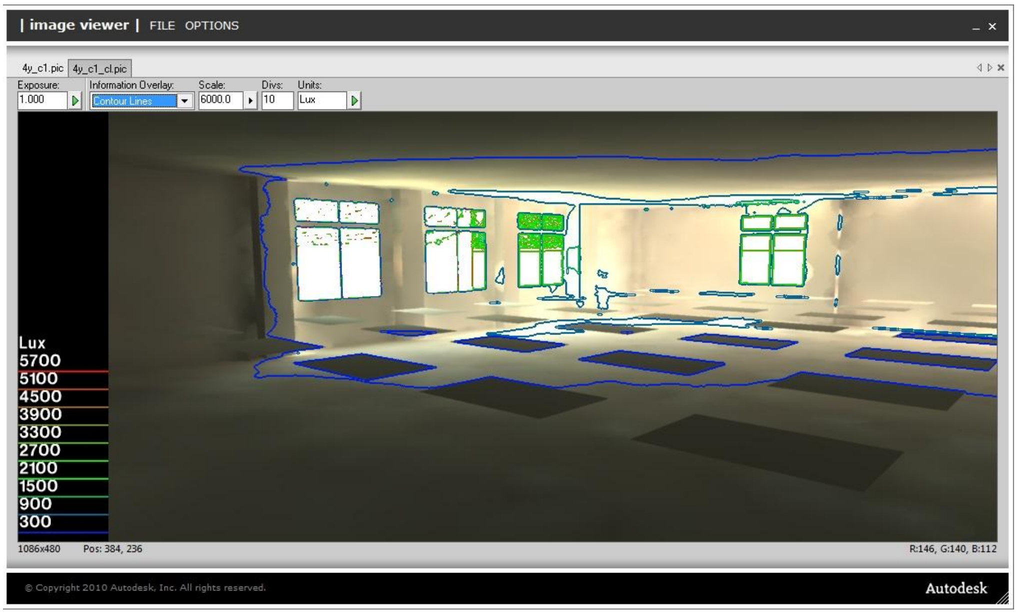
Figure 4.52. Simulated illuminance for May 4th, 10:05 for (a) the current condition and (b) the condition with prismatic panel for studio S04

The uniformity ratio D_{min} / D_{max} for studio S04 calculated for the simulations conducted with prismatic panel applied model for May 4th was 0.1 for 10:05, 0.12 for 13:45 and 0.09 for 17:00; pointing out the high variations in the illuminance levels within the studio. The other uniformity ratio D_{min} / D_{ave} was 0.27 for 10:05, 0.29 for 13:45 and 0.26 for 17:00, almost half of the recommended ratio of 0.50.



Exposure: 1.000
Information Overlay: Contour Lines
Scale: 6000.0
Divs: 10
Units: Lux

(a)

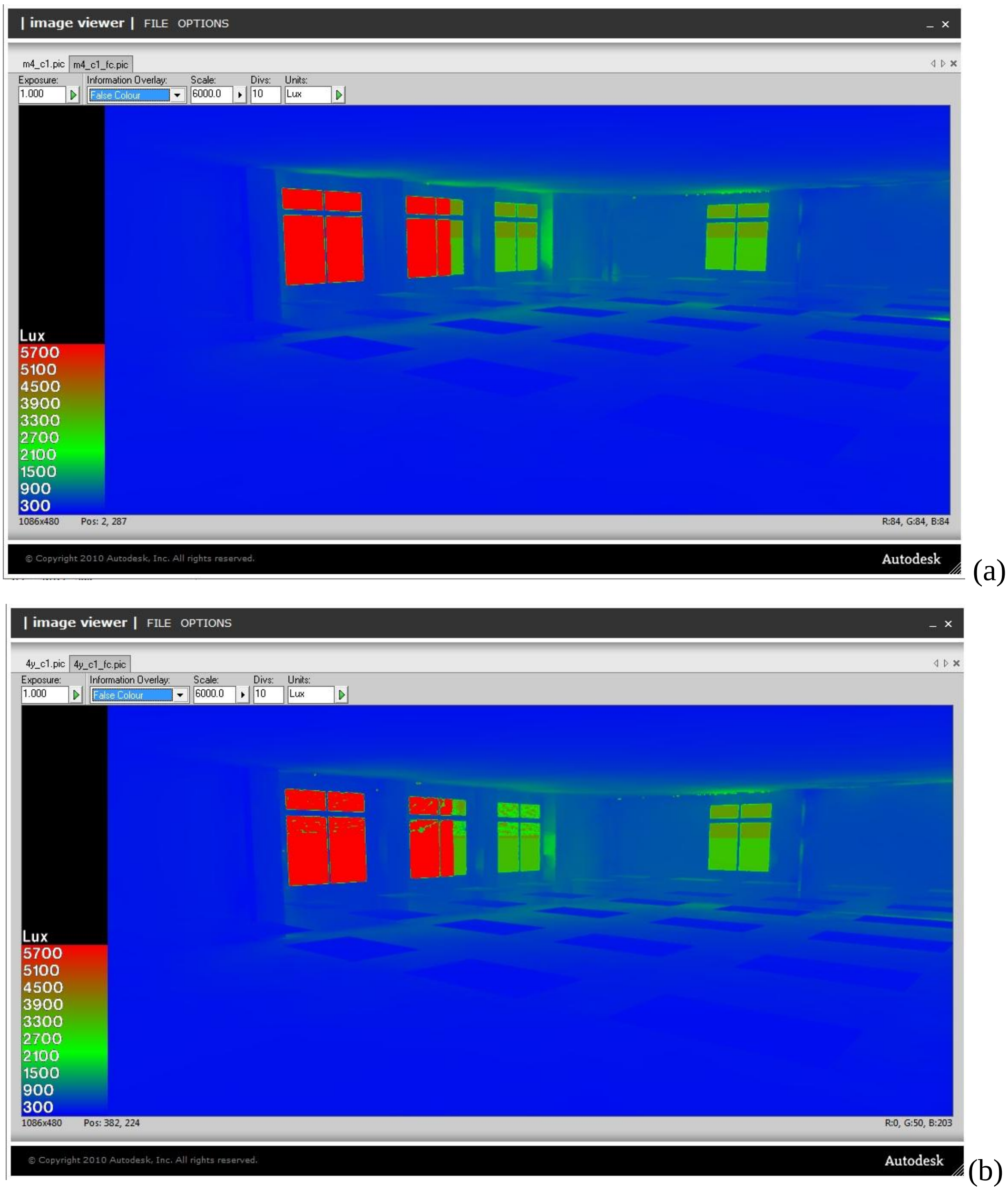


Exposure: 1.000
Information Overlay: Contour Lines
Scale: 6000.0
Divs: 10
Units: Lux

(b)

Figure 4.53. Illuminance contour lines showing distribution on May 4th, 10:05 for (a) the current condition and (b) the condition with prismatic panel for S04

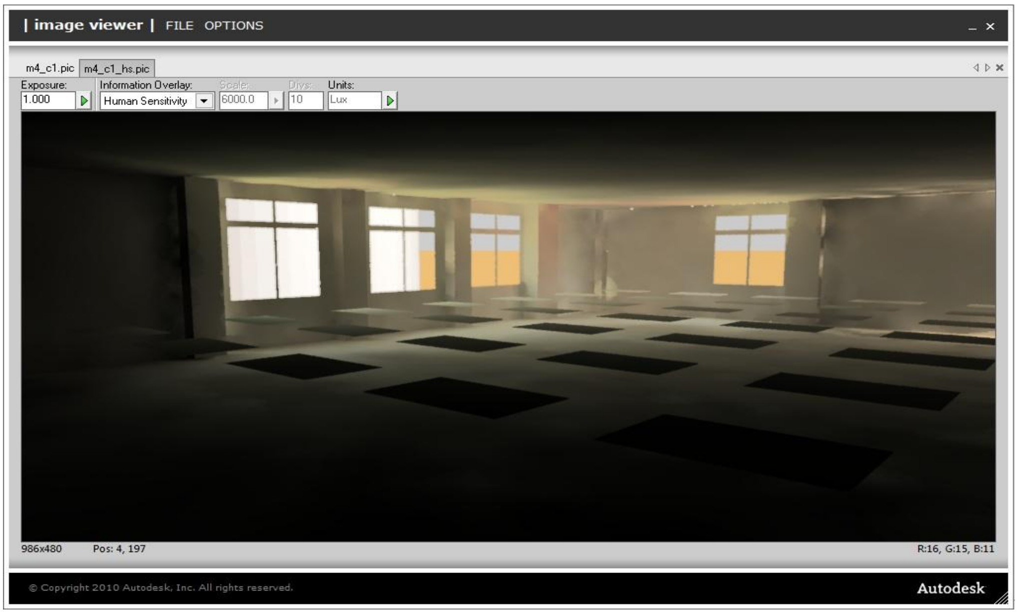
From the false color representations and simulated illuminance analysis, it can be acquired that the application of panels increased the illuminance in the middle and back area of the studio, columns 4,5,6,7 and 8 at each row. The illuminance became closer to the desired levels after the panels were applied, but still was not adequate. In spite of this increase in the illuminance levels, the uniformity became more irregular after the panels were applied (Figures 4.52 – 4.55).



(a) Exposure: 1.000 Information Overlay: False Colour Scale: 6000.0 Divs: 10 Units: Lux
1086x480 Pos: 2, 287 R:84, G:84, B:84

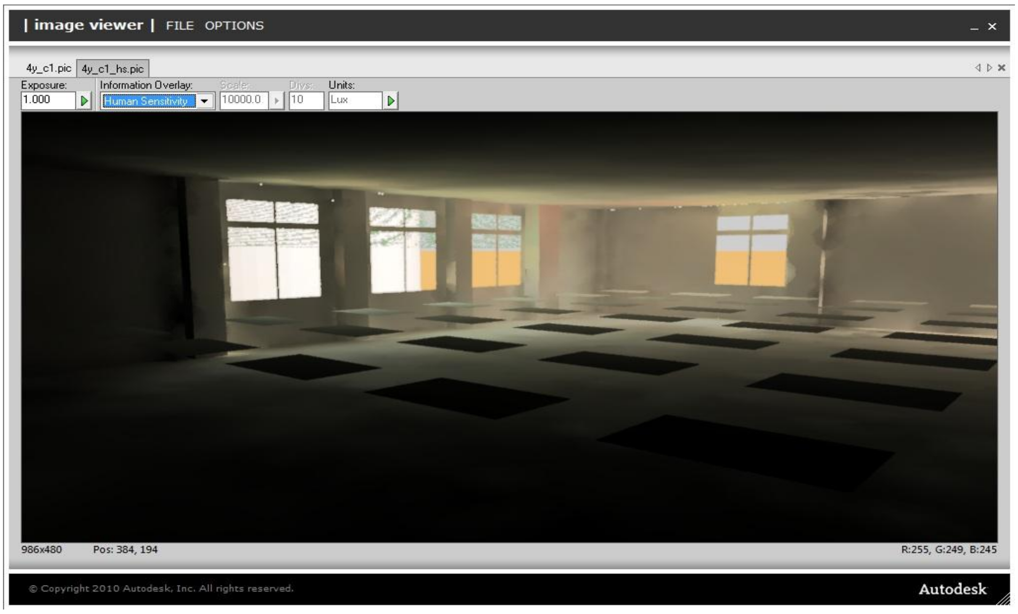
(b) Exposure: 1.000 Information Overlay: False Colour Scale: 6000.0 Divs: 10 Units: Lux
1086x480 Pos: 382, 224 R:0, G:50, B:203

Figure 4.54. False colour representations for May 4th, 10:05 for (a) the current condition and (b) the condition with prismatic panel for studio S04



Exposure: 1.000
Information Overlay: Human Sensitivity
Scale: 6000.0
Divs: 10
Units: Lux
986x480 Pos: 4, 197 R:16, G:15, B:11

(a)



Exposure: 1.000
Information Overlay: Human Sensitivity
Scale: 10000.0
Divs: 10
Units: Lux
986x480 Pos: 384, 194 R:255, G:249, B:245

(b)

Figure 4.55. Radiance scenes showing human sensitivity on May 4th, at 10:05 for (a) the current condition and (b) the condition with prismatic panel for studio S04

4.3.3. Light Shelves

Since the light redirecting capabilities of the applied laser cut and prismatic panels were not adequate for improving the illuminance and uniformity of the four selected design studios, light shelves were selected to comprehend and compare how much effect they would make to improve these conditions.

Since the distance between the window wall and the rear wall of the studios were quite deep, which was 11.25m; it was considered that the reflective surfaces of the panels were not wide enough to reflect the sunlight into an adequate distance inside. Thus, light shelves were selected for daylight simulations, because of their wider reflective surfaces.

The light shelves were modeled in Autodesk Ecotect Analysis and their dimensioning was adjusted as 80cm wide, regarding an application of the Danish Building Research Institute in Denmark (IEA, 2000). But unlike the “flight wing” shape that was used in that application in Denmark, the shape of the light shelves was selected as rectangular.

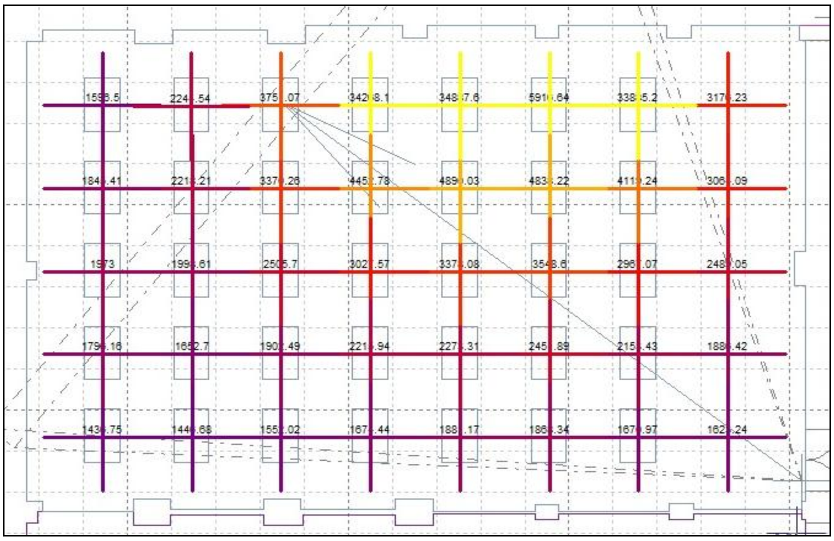
A) Regarding the studio S01, the distribution of daylight illuminance in the studio was largely similar with the current condition except the simulations conducted at12:30 on May 4th; according to the simulation results of the light shelf equipped model on May 4th and June 21st.

The simulations conducted at 09:00 showed an improvement in uniformity at the rows A and B, and the illuminance was also closer to 750 lux. The remaining area of the studio showed almost the same illuminance distribution with lower illuminance levels. Also, the previous sun patches that were observed on 09:00 in the current condition were prevented totally by the application of light shelves for both days.

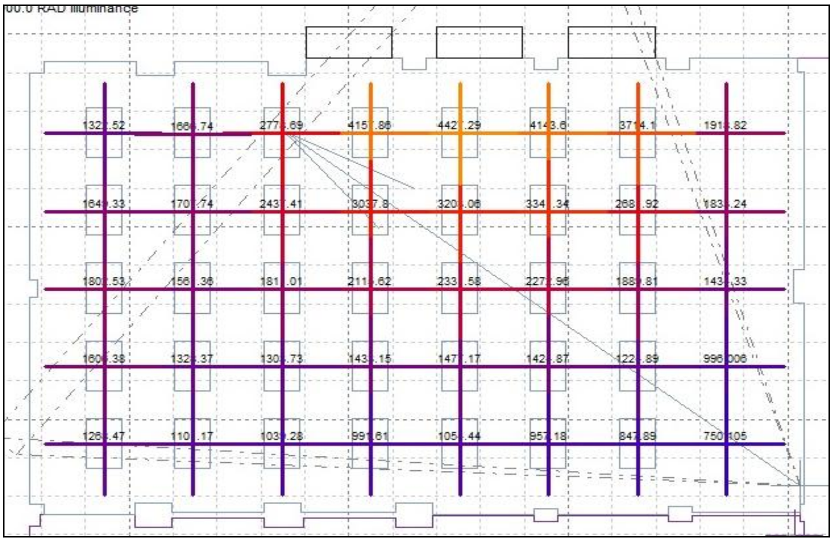
The simulation results conducted at 12:30 and 16:10 on June 21st were almost identical to the current condition in terms of illuminance and uniformity. The reason why light shelves had almost no effect on the daylighting condition of the studio might be because of the application of the light shelves only on one façade of the studio, which was the east wall with the largest glazing area.

The simulations conducted on May 4th at 12:30 were, on the other hand, severely irregular in terms of distribution and did not showed remarkable similarities with the current condition which might be due to the variations in the sky condition on May 4th.

The uniformity ratio D_{min} / D_{max} for studio S01 on May 4th calculated from the simulation results of light shelf equipped model was 0.18 at 09:00, 0.18 at 12:30 and 0.18 at 16:10. The other uniformity ratio D_{min} / D_{ave} for the same day was calculated as 0.42 at 09:00, 0.34 at 12:30 and 0.39 at 16:10.



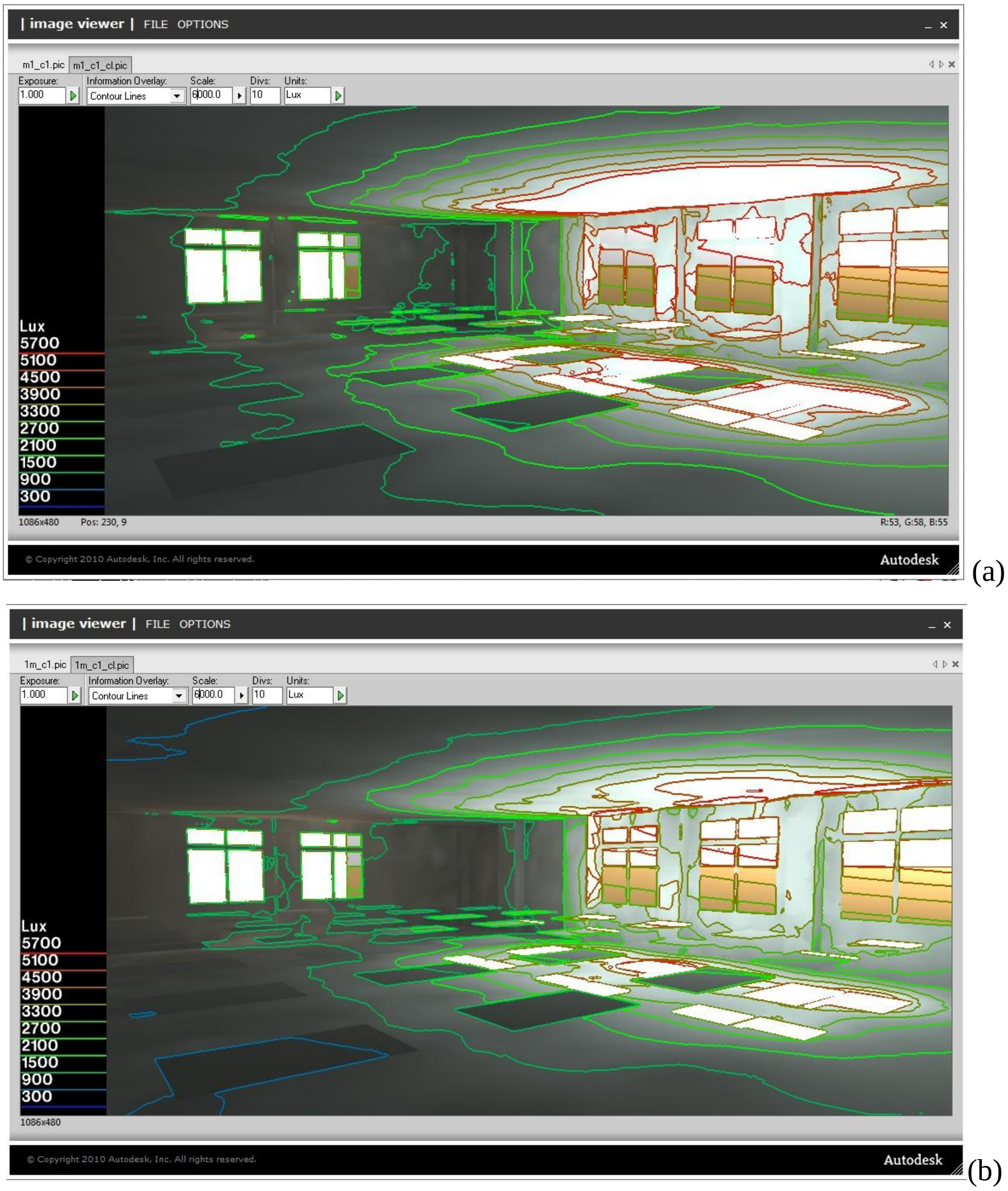
(a)



(b)

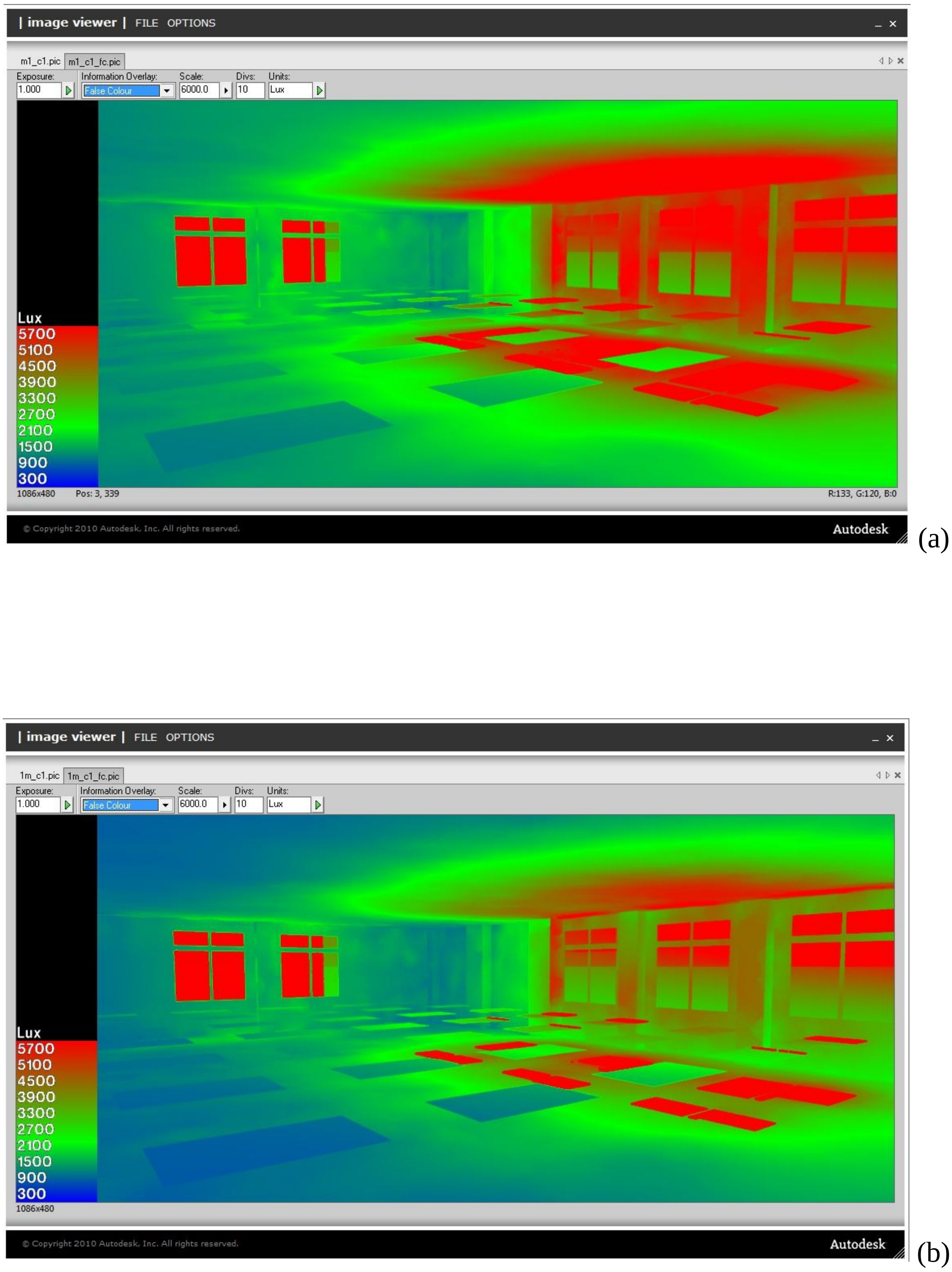
Figure 4.56. Simulated illuminance for May 4th, 09:00 for (a) the current condition and (b) the condition with light shelf for the studio S01

The simulation outputs of Desktop Radiance are presented for the current condition and for the model equipped with light shelves. Regarding these figures, it can be acquired that the overall illuminance in the studio decreased by the application of the light shelves (Figure 4.56 – 4.59). Sun patches previously occurred on the measurement points were prevented, although on the work plane level they were still observed in a small area near the east facing window wall (Figure 4.57 – 4.58).



Exposure: 1.000
Information Overlay: Contour Lines
Scale: 6000.0
Divs: 10
Units: Lux

Figure 4.57. Illuminance contour lines showing distribution on May 4th, 09:00 for (a) the current condition and (b) the condition with light shelf for S01



(a) Exposure: 1.000 Information Overlay: False Colour Scale: 6000.0 Divs: 10 Units: Lux
1086x480 Pos: 3, 339 R:133, G:120, B:0

(b) Exposure: 1.000 Information Overlay: False Colour Scale: 6000.0 Divs: 10 Units: Lux
1086x480

Figure 4.58. False colour representations for May 4th, 09:00 for (a) the current condition and (b) the condition with light shelf for the studio S01

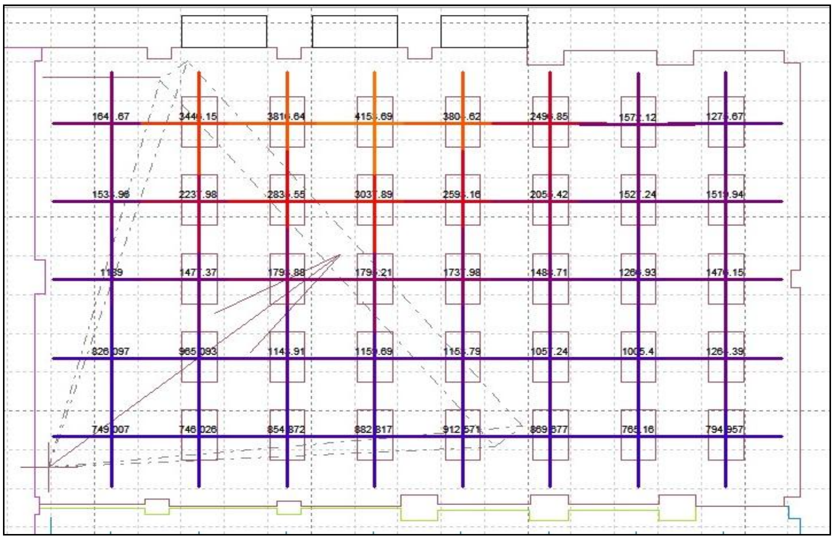
(a) Exposure: 1.000 Information Overlay: Human Sensitivity Scale: 100 Divs: 10 Units: Lux

(b) Exposure: 1.000 Information Overlay: Human Sensitivity Scale: 10000.0 Divs: 10 Units: Lux

Figure 4.59. Radiance scenes showing human sensitivity on May 4th, at 09:00 for (a) the current condition and (b) the condition with light shelf for the studio S01

B) Regarding the studio S02, the daylight distribution of the simulated model with light shelves was quietly similar with the current condition for May 4th and June 21st. The illuminance was lower at 09:25 on both days, but at 13:00 and 16:25, the values were very close to the current condition, pointing out the light shelves did not have remarkable effects on the daylight condition of the studio. Sun patches observed at the measurement points on both days were prevented by the application of light shelves.

(a)

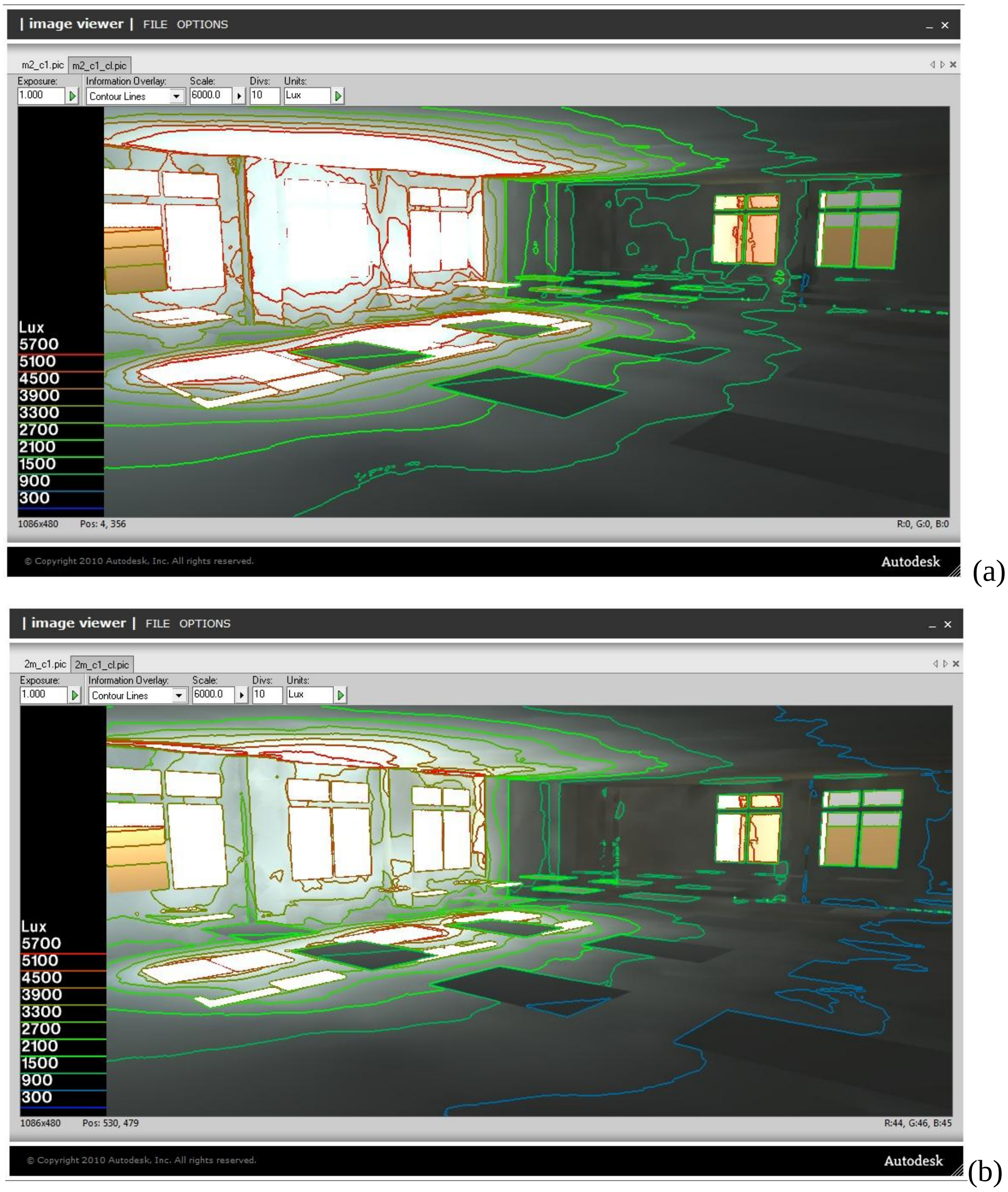


(b)

Figure 4.60. Simulated illuminance for May 4th, 09:25 for (a) the current condition and (b) the condition with light shelf for the studio S02

The uniformity ratio D_{min} /D_{max} calculated from the simulation results of the light shelf equipped model for May 4th was 0.20 for 09:25, 0.1 for 13:00 and 0.09 for 16:25. The uniformity ratio D_{min} / D_{ave} on the other hand, was calculated as 0.50, 0.29 and 0.26 for 09:25, 13:00 and 16:25; respectively.

The simulation outputs of Desktop Radiance for the model equipped with light shelves and the model of the current condition are presented in Figures 4.60 – 4.63.



m2_c1.pic m2_c1_cl.pic
Exposure: 1.000
Information Overlay: Contour Lines
Scale: 6000.0
Divs: 10
Units: Lux
1086x480 Pos: 4, 356 R:0, G:0, B:0
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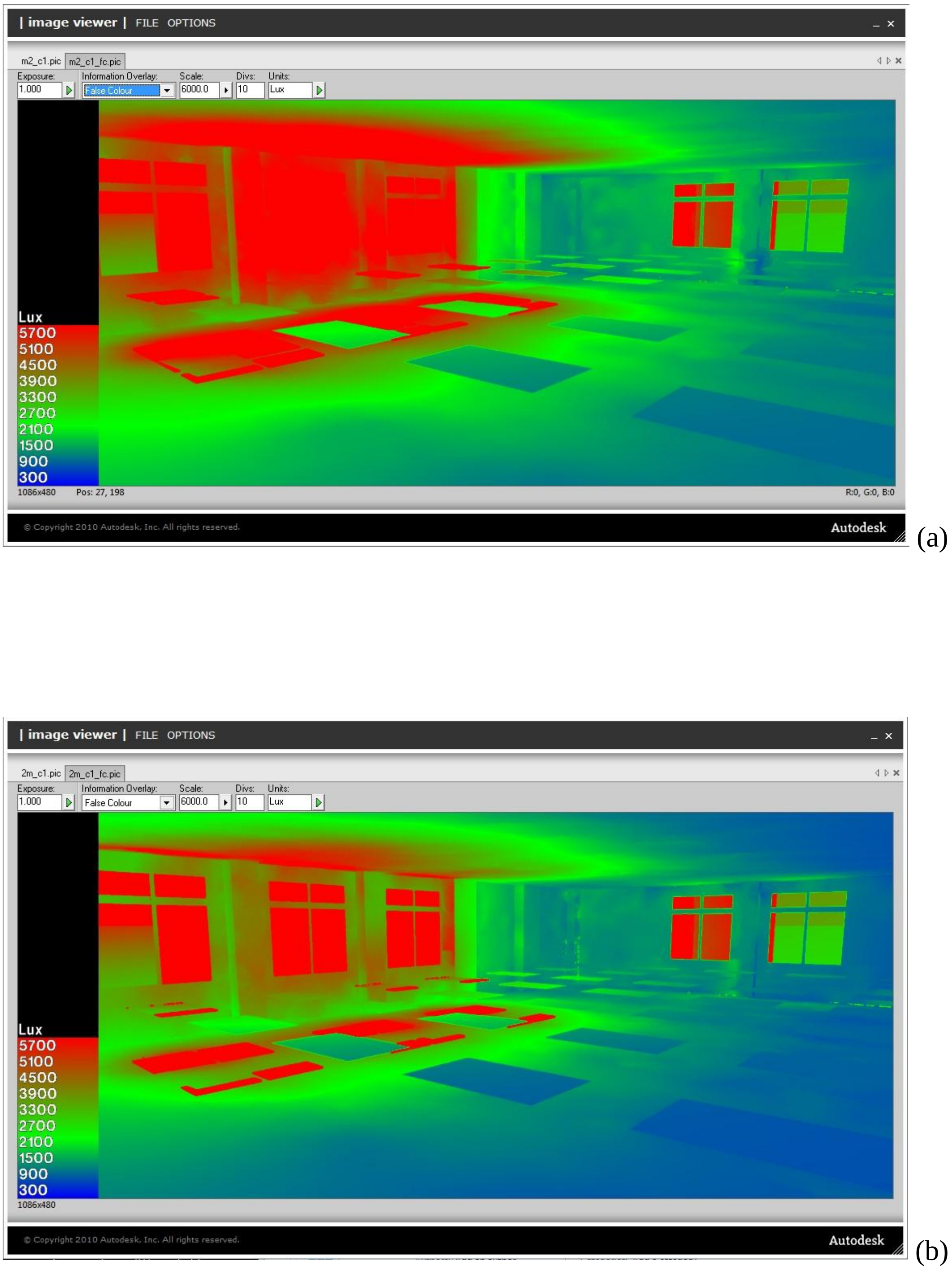
(a)

2m_c1.pic 2m_c1_cl.pic
Exposure: 1.000
Information Overlay: Contour Lines
Scale: 6000.0
Divs: 10
Units: Lux
1086x480 Pos: 530, 479 R:44, G:46, B:45
© Copyright 2010 Autodesk, Inc. All rights reserved.

(b)

Figure 4.61. Illuminance contour lines showing distribution on May 4th, 09:25 for (a) the current condition and (b) the condition with light shelf for S02



m2_c1.pic | m2_c1_fc.pic

Exposure: 1.000
Information Overlay: False Colour
Scale: 6000.0
Divs: 10
Units: Lux

1086x480 Pos: 27, 198 R:0, G:0, B:0

(a)

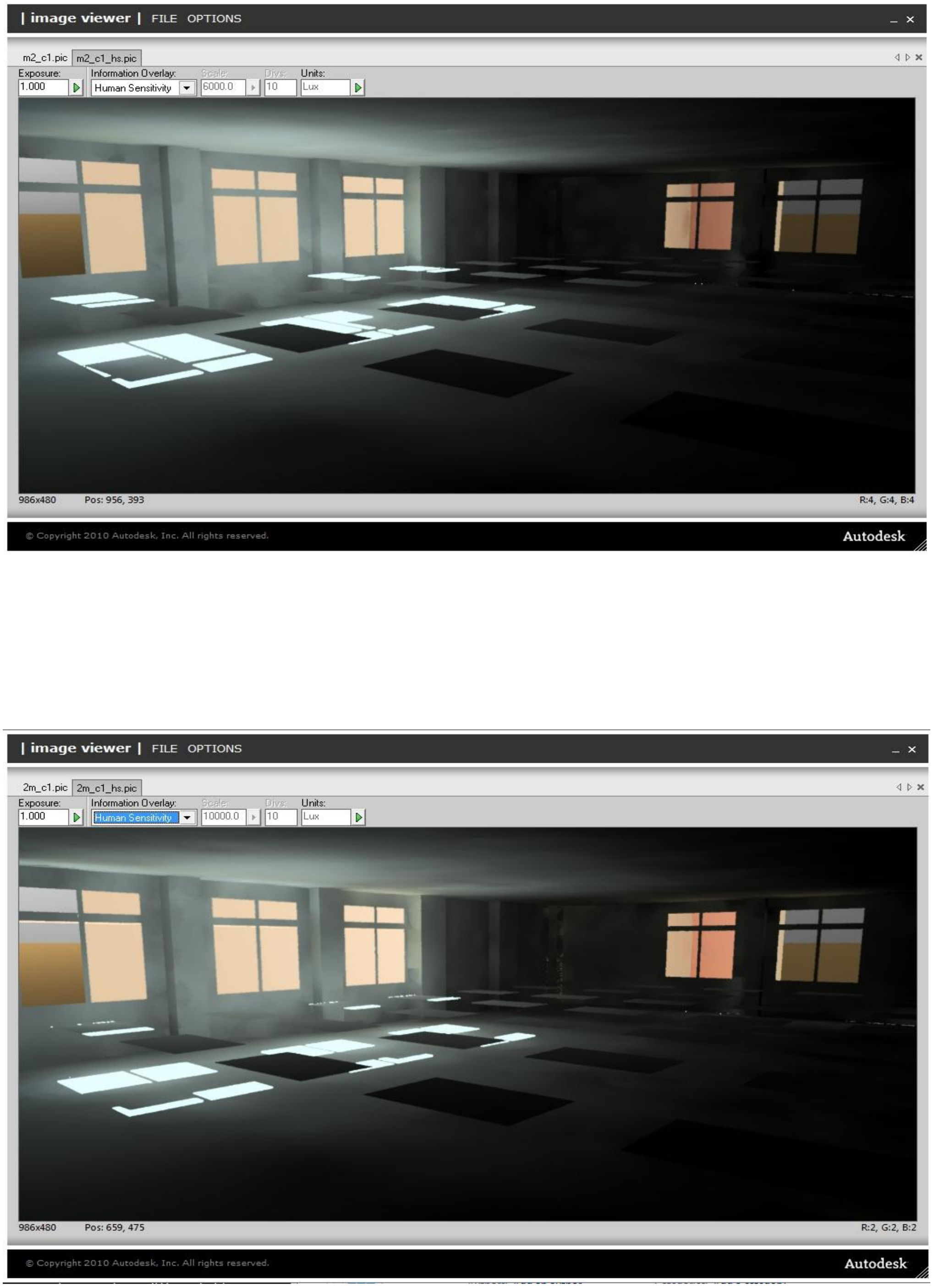
2m_c1.pic | 2m_c1_fc.pic

Exposure: 1.000
Information Overlay: False Colour
Scale: 6000.0
Divs: 10
Units: Lux

1086x480

(b)

Figure 4.62. False colour representations for May 4th, 09:25 for (a) the current condition and (b) the condition with light shelf for the studio S02



Exposure: 1.000
Information Overlay: Human Sensitivity
Scale: 6000.0
Divs: 10
Units: Lux

986x480 Pos: 956, 393 R:4, G:4, B:4

(a)

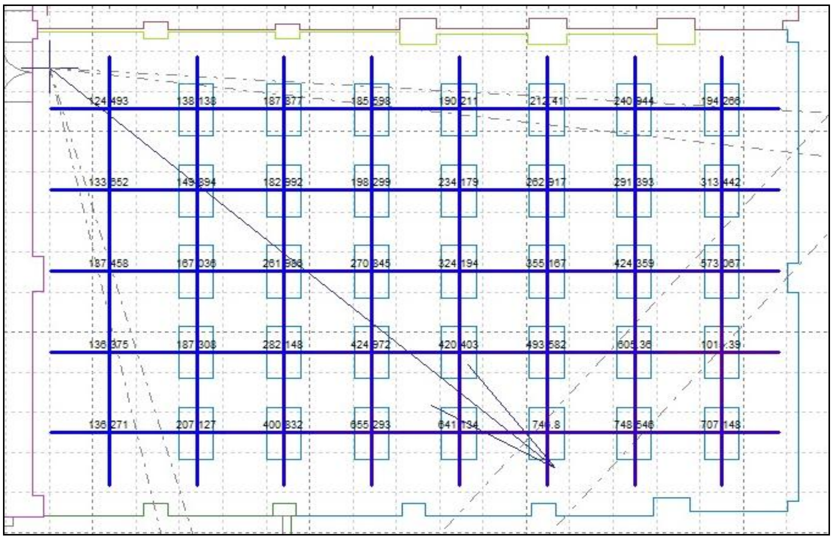
Exposure: 1.000
Information Overlay: Human Sensitivity
Scale: 10000.0
Divs: 10
Units: Lux

986x480 Pos: 659, 475 R:2, G:2, B:2

(b)

Figure 4.63. Radiance scenes showing human sensitivity on May 4th, at 09:25 for (a) the current condition and (b) the condition with light shelf for the studio S02

C) Regarding studio S03, the light shelves did not improve illuminance and uniformity noticeably either, according to the simulation results of Desktop Radiance with the light shelf equipped model. The illuminance distribution was very close with the current condition, and the illuminance in the light shelf equipped model was slightly lower than the current condition at most of the measurement points. Sun patches that were observed on row E at 16:45 was still observed on June 21st.

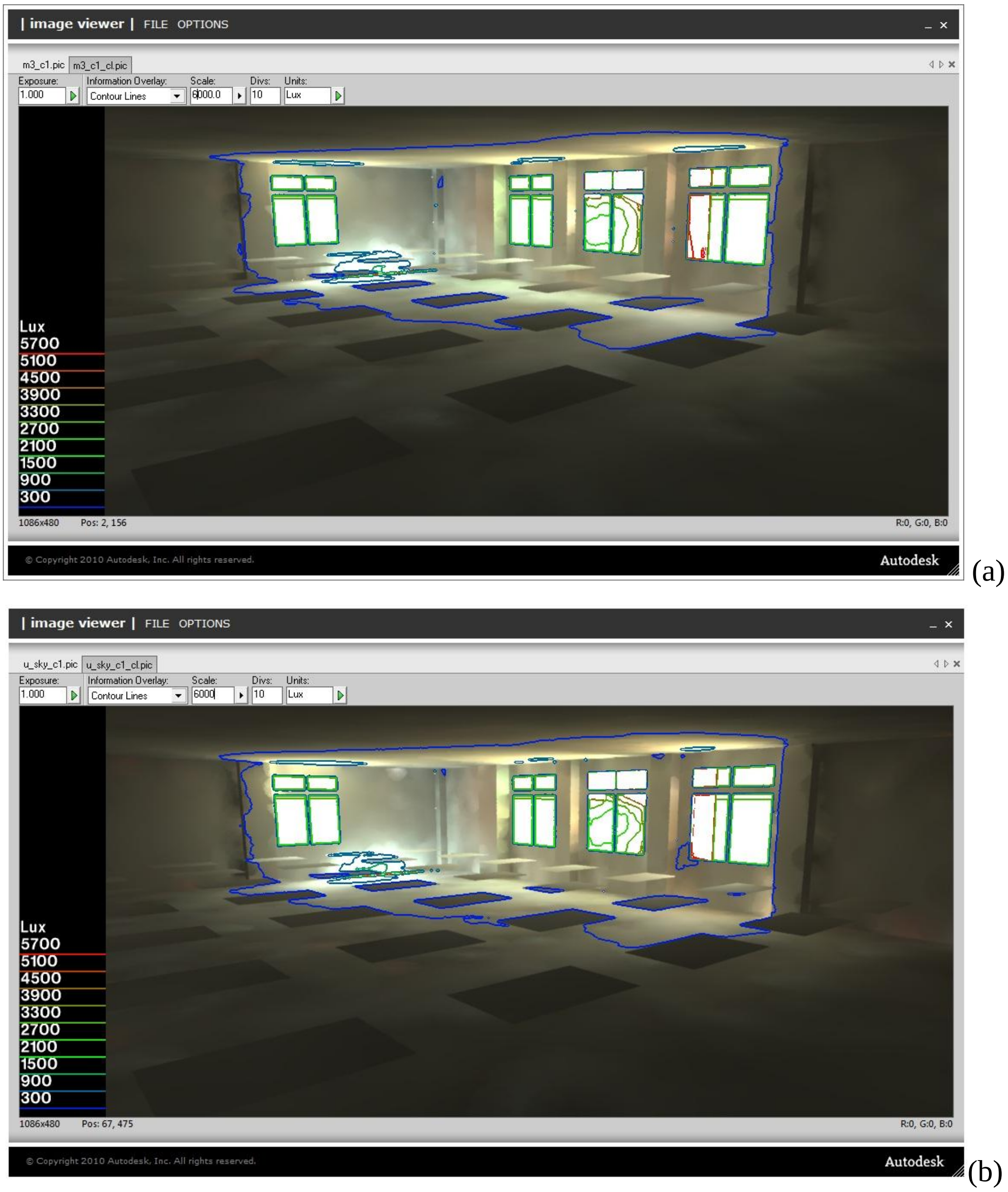


(a)

(b)

Figure 4.64. Simulated illuminance for May 4th, 09:45 for (a) the current condition and (b) the condition with light shelf for studio S03

The uniformity ratio D_{min} /D_{max} calculated from the simulation results of the light shelf equipped model for May 4th was 0.10 for 09:45, 0.09 for 13:20 and 0.09 for 16:45. The uniformity ratio D_{min} / D_{ave} on the other hand, was calculated as 0.32, 0.33 and 0.26 for 09:45, 13:20 and 16:45; respectively. In the figures 4.64 – 4.67 are presented the Radiance outputs of the simulation results for the current condition and the condition with light shelf equipped panel for May 4th at 09:45.



m3_c1.pic m3_c1_cl.pic

Exposure: 1.000 Information Overlay: Contour Lines Scale: 6000.0 Divs: 10 Units: Lux

1086x480 Pos: 2, 156 R:0, G:0, B:0

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(a)

u_sky_c1.pic u_sky_c1_cl.pic

Exposure: 1.000 Information Overlay: Contour Lines Scale: 6000 Divs: 10 Units: Lux

1086x480 Pos: 67, 475 R:0, G:0, B:0

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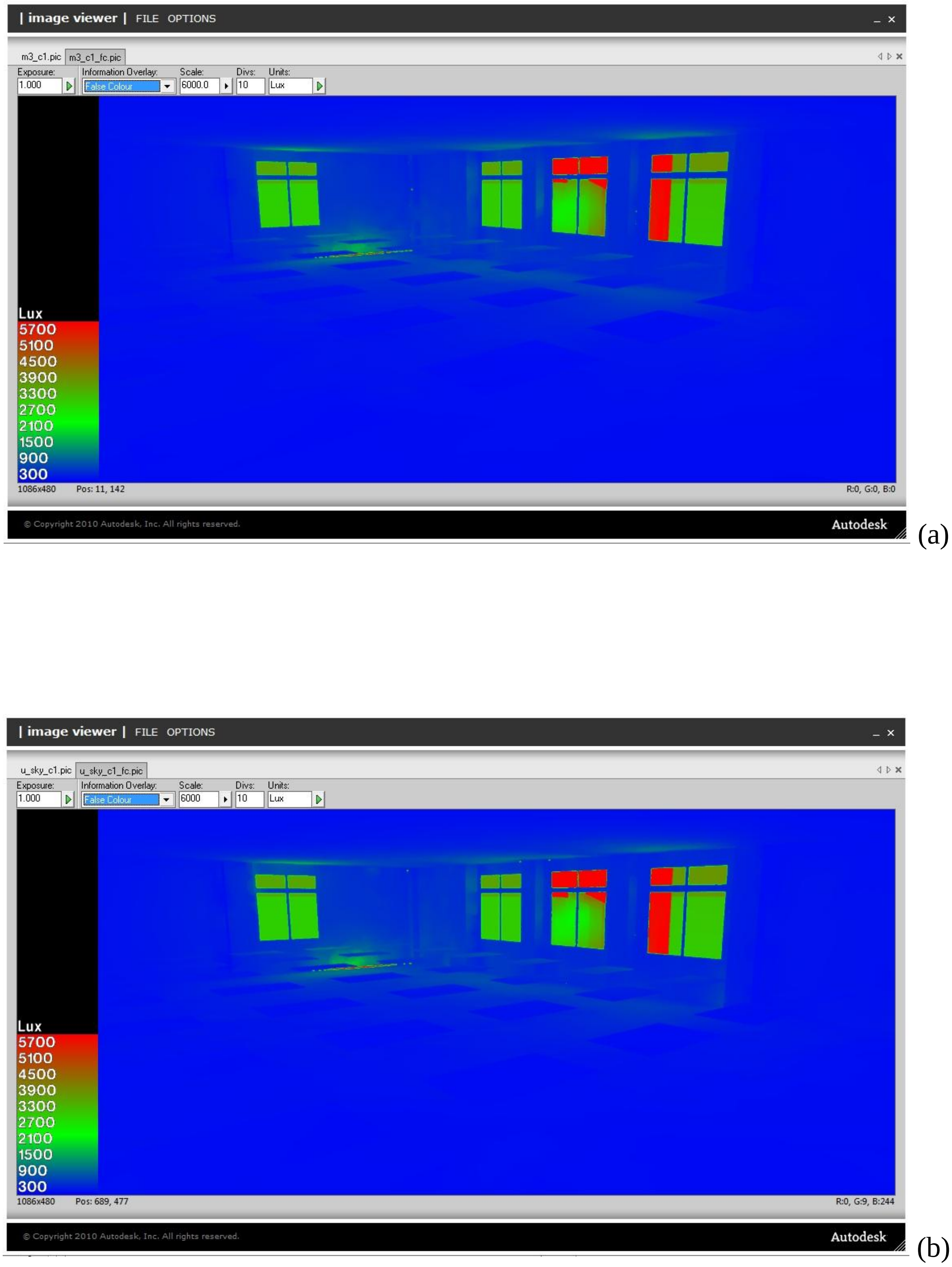
(b)

Figure 4.65. Illuminance contour lines showing distribution on May 4th, 09:45 for (a) the current condition and (b) the condition with light shelf for S03



(a)

| image viewer | FILE OPTIONS

m3_c1.pic m3_c1_fc.pic

Exposure: 1.000

Information Overlay: False Colour

Scale: 6000.0

Divs: 10

Units: Lux

1086x480 Pos: 11, 142 R:0, G:0, B:0

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(b)

| image viewer | FILE OPTIONS

u_sky_c1.pic u_sky_c1_fc.pic

Exposure: 1.000

Information Overlay: False Colour

Scale: 6000

Divs: 10

Units: Lux

1086x480 Pos: 689, 477 R:0, G:9, B:244

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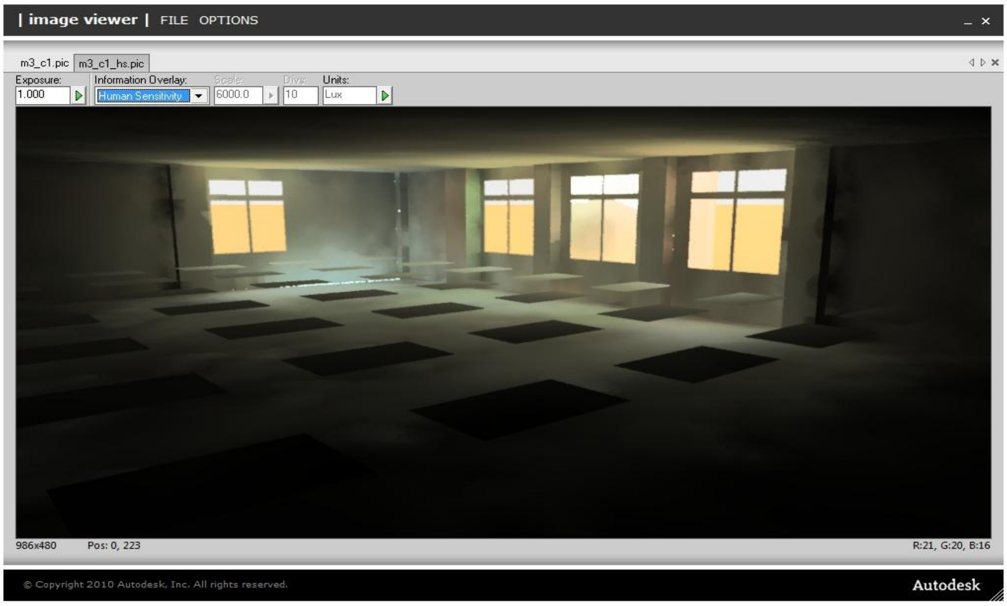
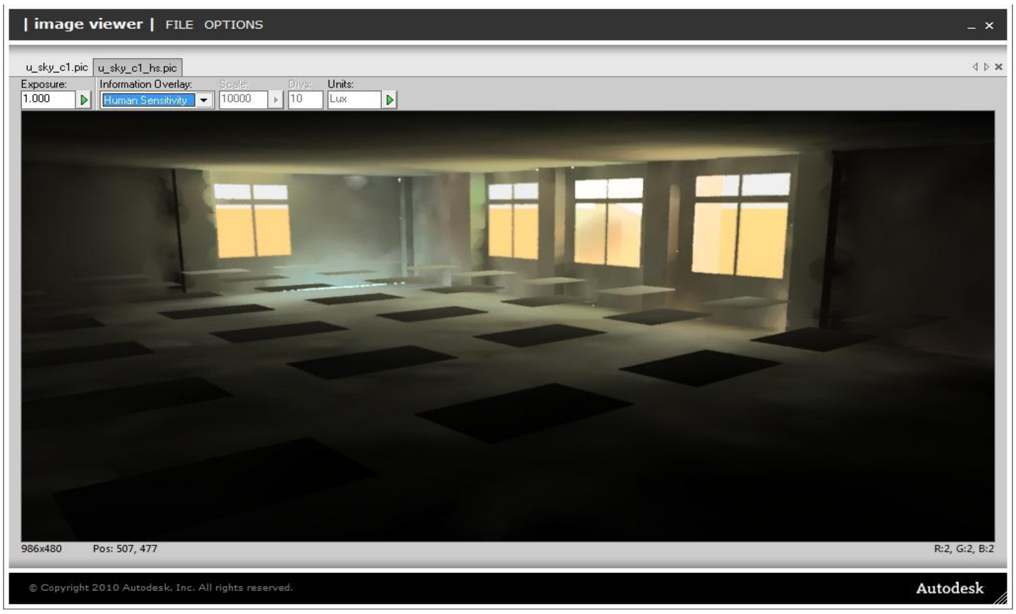
Figure 4.66. False colour representations for May 4th, 09:45 for (a) the current condition and (b) the condition with light shelf for the studio S03



Exposure: 1.000
Information Overlay: Human Sensitivity
Scale: 6000.0
Divs: 10
Units: Lux
986x480
Pos: 0, 223
R:21, G:20, B:16

(a)



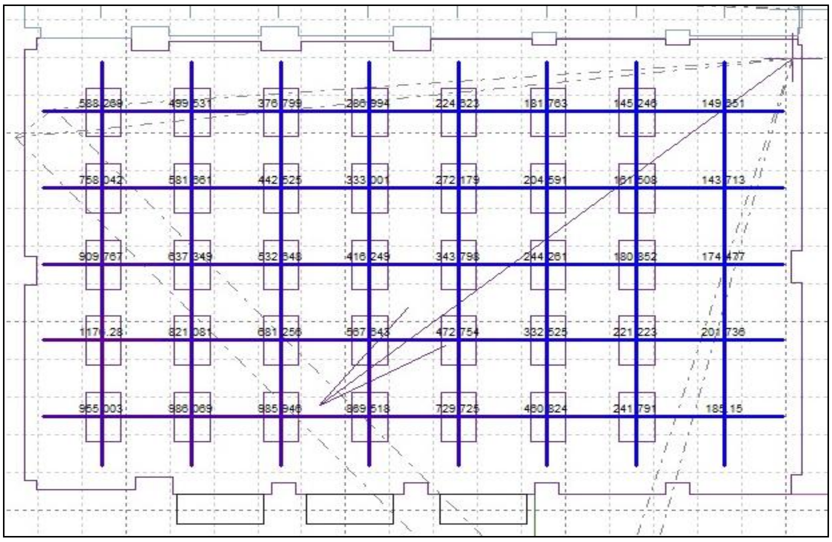
Exposure: 1.000
Information Overlay: Human Sensitivity
Scale: 10000
Divs: 10
Units: Lux
986x480
Pos: 507, 477
R:2, G:2, B:2

(b)

Figure 4.67. Radiance scenes showing human sensitivity on May 4th, at 09:45 for (a) the current condition and (b) the condition with light shelf for the studio S03

D) Regarding studio S04, the daylight illuminance distribution only showed variations on the simulations conducted for May 4th, 10:05 and 13:45. This condition was observed in studio S01, too; which had a north facing window wall, like the studio S04. Otherwise, the distribution obtained from the simulation results of the light shelf equipped model was quietly similar to the current condition, only the illuminance was lower at most of the points.

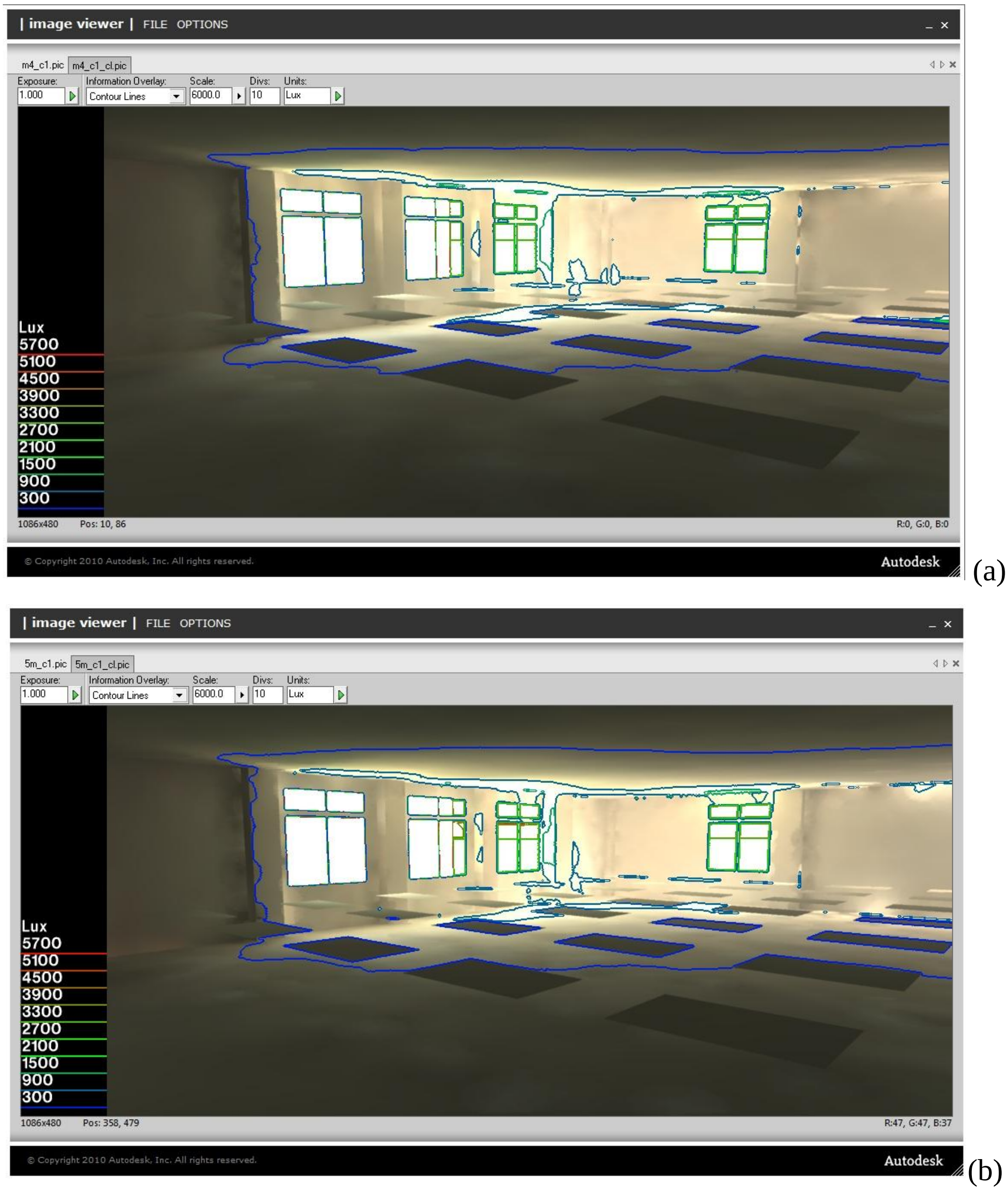
(a)



(b)

Figure 4.68. Simulated illuminance for May 4th, 10:05 for (a) the current condition and (b) the condition with light shelf for the studio S04

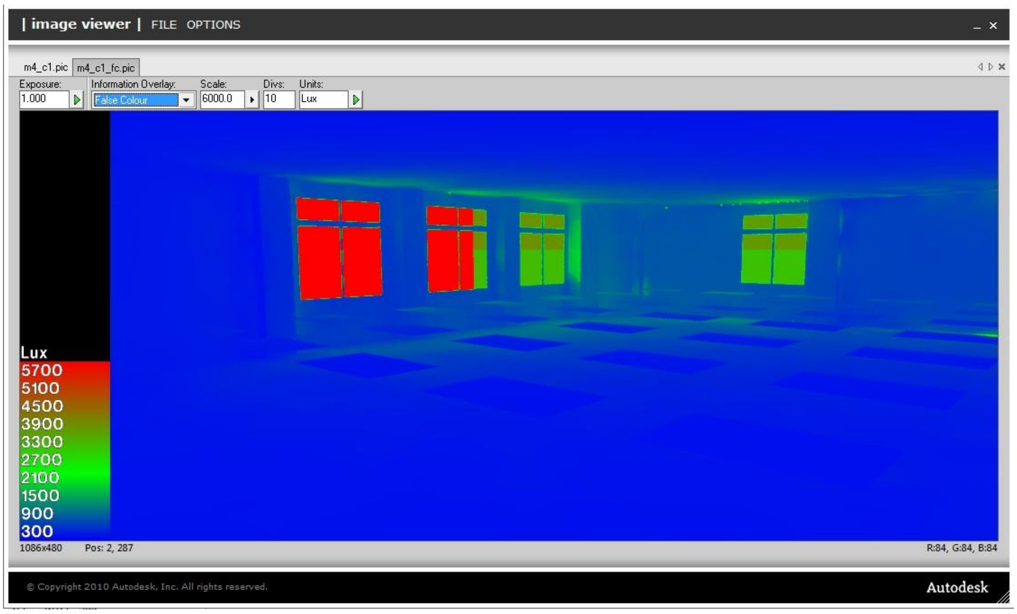
Previous sun patches that were observed on row E at 17:00 in the current condition was still observed on June 21st with the light shelf employed model. On the other hand, sun patches observed on May 4th was prevented. The uniformity ratio D_{min} / D_{max} calculated from the simulation results for May 4th was 0.12 for 10:05, 0.10 for 13:45 and 0.09 for 17:00. The uniformity ratio D_{min} / D_{ave} on the other hand, was calculated as 0.31, 0.27 and 0.26 for 10:05, 13:45 and 17:00; respectively.



Exposure: 1.000
Information Overlay: Contour Lines
Scale: 6000.0
Divs: 10
Units: Lux

Figure 4.69. Illuminance Contour lines showing distribution on May 4th, 10:05 for (a) the current condition and (b) the condition with light shelf for S04

In the figures 4.68 – 4.71 are presented the Radiance outputs of the simulation results for May 4th at 10:05 for the current condition of the studio and the condition with the light shelves.



Exposure: 1.000
Information Overlay: False Colour
Scale: 6000.0
Divs: 10
Units: Lux

1086x480 Pos: 2, 287 R:84, G:84, B:84

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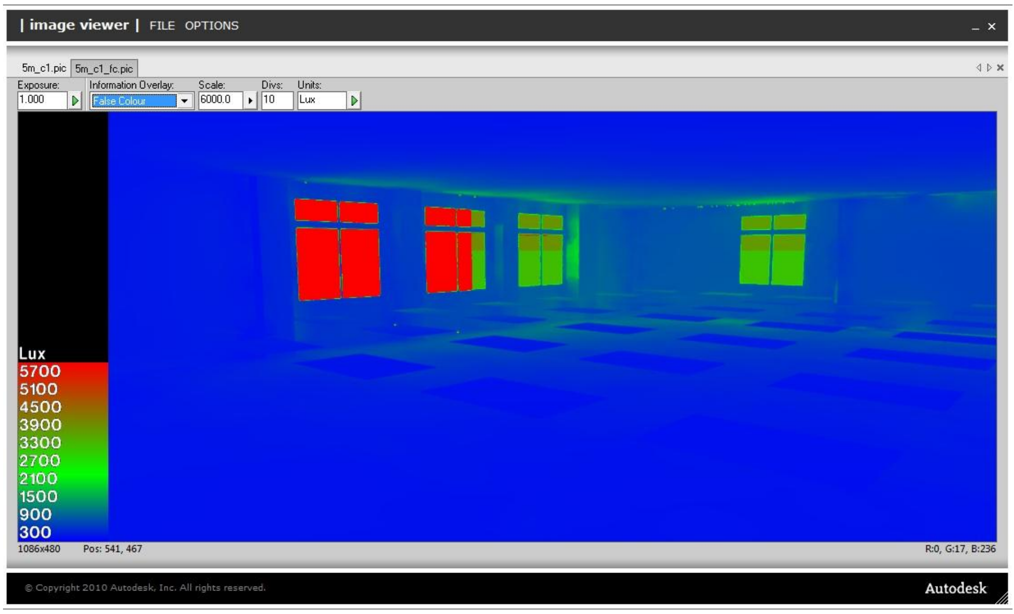
(a)



Exposure: 1.000
Information Overlay: False Colour
Scale: 6000.0
Divs: 10
Units: Lux

1086x480 Pos: 541, 467 R:0, G:17, B:236

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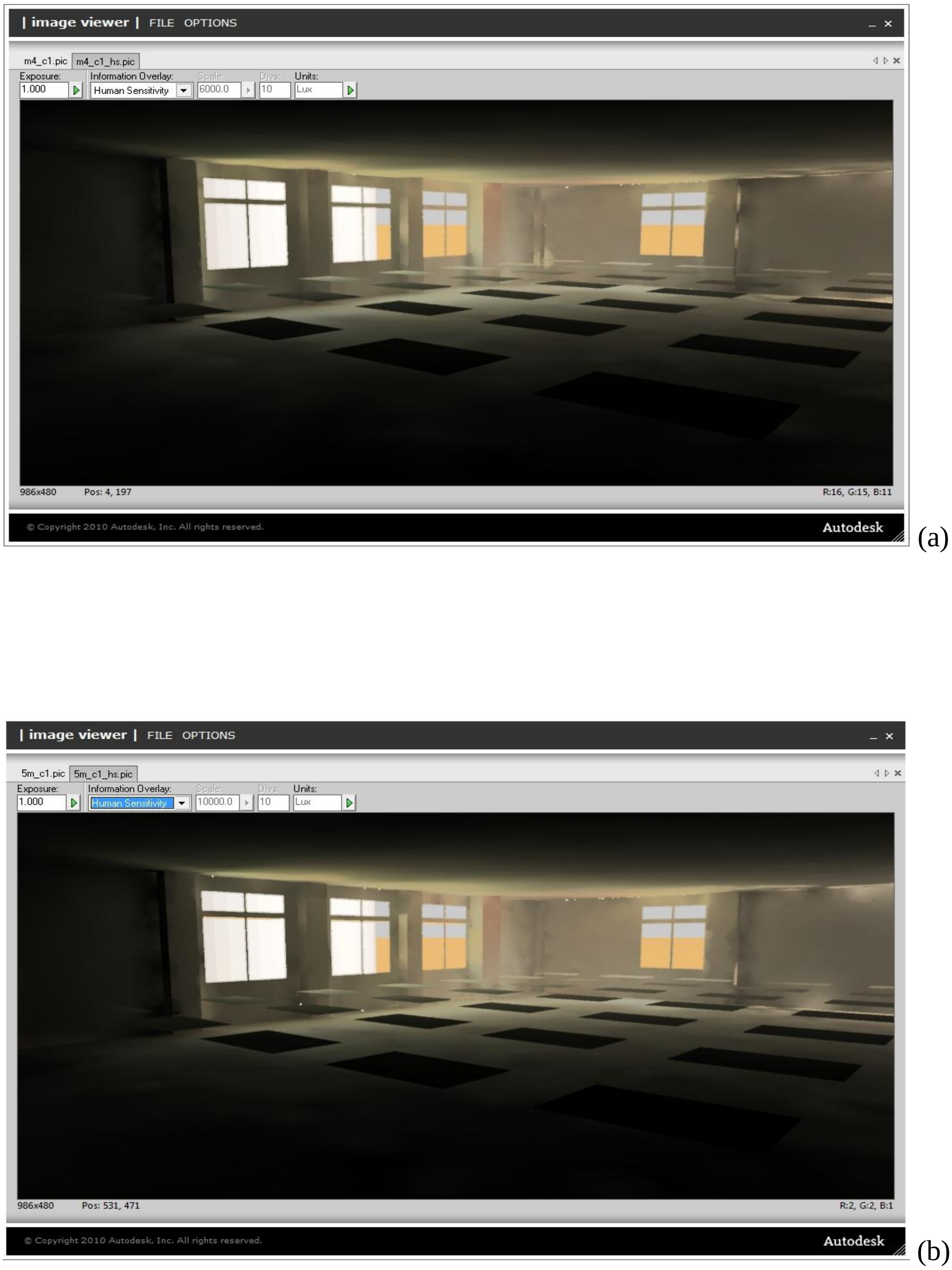
(b)

Figure 4.70. False colour representations for May 4th, 10:05 for (a) the current condition and (b) the condition light shelf for the studio S04



(a)

m4_c1.pic | m4_c1_hs.pic

Exposure: 1.000
Information Overlay: Human Sensitivity
Scale: 6000.0
Divs: 10
Units: Lux

986x480 Pos: 4, 197 R:16, G:15, B:11

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(b)

5m_c1.pic | 5m_c1_hs.pic

Exposure: 1.000
Information Overlay: Human Sensitivity
Scale: 10000.0
Divs: 10
Units: Lux

986x480 Pos: 531, 471 R:2, G:2, B:1

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Figure 4.71. Radiance scenes showing human sensitivity on May 4th, at 10:05 for (a) the current condition and (b) the condition with light shelf for the studio S04

4.3.4. Overview

Aiming to make a comparison between the simulation findings of the simulation findings of the four architectural design studios in IYTE for the current daylighting conditions and the daylighting conditions with the proposed daylighting systems, namely, laser cut panels, prismatic panels and light shelves; below are presented the uniformity ratios calculated from the simulation results (Table 4.1) and an overview of the results of the conducted simulations (Tables 4.2 – 4.5).

Table 4.1. Calculated uniformity ratios D_{min} / D_{max} and D_{min} / D_{ave} for (a) S01, (b) S02, (c) S03 and (d) S04

S01	**Dmin / Dmax**	**Simulation**	**Laser Cut Panel**	**Prismatic Panel**	**Light Shelf**
	09:00	0.24	0.17	0.17	0.18
	12:30	0.24	0.17	0.18	0.18
	16:10	0.24	0.15	0.15	0.18
	Dmin / Dave	**Simulation**	**Laser Cut Panel**	**Prismatic Panel**	**Light Shelf**
	09:00	0.55	0.46	0.41	0.42
	12:30	0.49	0.37	0.35	0.34
	16:10	0.46	0.36	0.35	0.39

(a)

S02	**Dmin / Dmax**	**Simulation**	**Laser Cut Panel**	**Prismatic Panel**	**Light Shelf**
	09:25	0.22	0.17	0.16	0.20
	13:00	0.13	0.1	0.09	0.1
	16:25	0.13	0.07	0.09	0.09
	Dmin / Dave	**Simulation**	**Laser Cut Panel**	**Prismatic Panel**	**Light Shelf**
	09:25	0.53	0.48	0.43	0.50
	13:00	0.32	0.30	0.27	0.29
	16:25	0.33	0.24	0.27	0.26

(b)

(cont. on next page)

Table 4.1. (cont.)

	Dmin / Dmax	Simulation	Laser Cut Panel	Prismatic Panel	Light Shelf
S03	**09:45**	0.12	0.08	0.08	0.1
	13:20	0.1	0.06	0.06	0.09
	17:00	0.12	0.07	0.09	0.09
	Dmin / Dave	**Simulation**	**Laser Cut Panel**	**Prismatic Panel**	**Light Shelf**
	09:45	0.37	0.31	0.29	0.32
	13:20	0.32	0.28	0.25	0.33
	17:00	0.33	0.23	0.25	0.26

(c)

	Dmin / Dmax	Simulation	Laser Cut Panel	Prismatic Panel	Light Shelf
S04	**10:05**	0.16	0.08	0.1	0.12
	13:45	0.14	0.08	0.12	0.1
	16:10	0.12	0.07	0.09	0.09
	Dmin / Dave	**Simulation**	**Laser Cut Panel**	**Prismatic Panel**	**Light Shelf**
	10:05	0.40	0.26	0.27	0.31
	13:45	0.36	0.23	0.29	0.27
	16:10	0.32	0.23	0.26	0.26

(d)

Table 4.2. Overview of the simulation results of the four architectural studios for the current condition on May 4th

May 4th	Illuminance (lux)	Floor Area Ratios (%)			Assessments
		Simulation			
		Morning	Noon	Afternoon	
S01	< 500	0	0	40	Excessive illuminance levels during morning.
	500 - 1000	0	50	50	Half of the floor area is overly illuminated at noon.
	> 1000	100	50	10	Severely unstable illuminance distribution in the afternoon.
S02	< 500	0	7.5	25	Similar illuminance distribution with S01.
	500 - 1000	0	35	35	Lesser floor area meets the desired illuminance levels at noon and in the afternoon.
	> 1000	100	57.5	40	
S03	< 500	80	45	2.5	Severely insufficient illuminance during morning at more than 3/4 of the floor area. In the afternoon, half of the measurement points are overly illuminated. Unstable illuminance distribution on hourly basis.
	500 - 1000	17.5	30	47.5	
	> 1000	2.5	25	50	
S04	< 500	75	62.5	0	Extreme changes in illuminance on hourly basis.
	500 - 1000	25	25	15	75% of the floor area is low illuminated in the morning, 85% of the floor area is overly illuminated in the afternoon.
	> 1000	0	12.5	85	

Table 4.3. Overview of the simulation results of the four architectural studios for the condition with LCP on May 4th

May 4th	Illuminance (lux)	Floor Area Ratios (%)			Assessments
		Laser Cut Panel			
		Morning	Noon	Afternoon	
S01	< 500	0	35	55	In the morning, 27,5% of the floor area reached the desired illuminance. At noon and in the afternoon, overly illuminated areas decreased while there has been a remarkable increase in the low illuminated areas.
	500 - 1000	27.5	45	40	
	> 1000	72.5	20	5	
S02	< 500	0	32.5	45	Again, similar distribution with S01. While the overly illuminated areas decreased, the illuminance levels fell below the required norms at noon and in the afternoon.
	500 - 1000	27.5	27.5	40	
	> 1000	72.5	40	15	
S03	< 500	87.5	65	37.5	While there has been a decrease in overly illuminated areas after the panels were applied, also the low illuminated floor area increased, causing a severe deficiency in the daylighting conditions.
	500 - 1000	12.5	22.5	30	
	> 1000	0	12.5	32.5	
S04	< 500	82.5	77.5	27.5	Similar distribution with S03. The panels acted as a shading device and lowered the illuminance throughout the studio.
	500 - 1000	17.5	22.5	30	
	> 1000	0	0	42.5	

Table 4.4. Overview of the simulation results of the four architectural studios for the condition with prismatic panels on May 4th

May 4th	Illuminance (lux)	Floor Area Ratios (%)			Assessments
		Prismatic Panel			
		Morning	Noon	Afternoon	
S01	< 500	0	12.5	42.5	Prismatic panels did not cause remarkable changes in illuminance distribution in the morning and in the afternoon. At noon, the panels worsened the daylighting conditions remarkably.
	500 - 1000	5	35	47.5	
	> 1000	95	52.5	10	
S02	< 500	0	27.5	45	In the morning, the panels provided adequate illumination to 20% of the floor area, while at noon and in the afternoon caused an increase in the low illuminated areas.
	500 - 1000	20	32.5	37.5	
	> 1000	80	40	17.5	
S03	< 500	85	60	17.5	The panels increased the amount of low illuminated areas while did not provide much improvement in the areas exposed to high levels of illumination.
	500 - 1000	15	25	32.5	
	> 1000	0	15	50	
S04	< 500	62.5	55	7.5	The panels increased the amount of floor area that meet the desired illuminance during the day, but also increased the low illuminated areas at noon and in the afternoon.
	500 - 1000	35	32.5	30	
	> 1000	2.5	12.5	62.5	

Table 4.5. Overview of the simulation results of the four architectural studios for the condition with light shelves on May 4th

May 4th	Illuminance (lux)	Floor Area Ratios (%)			Assessments
		Light Shelf			
		Morning	Noon	Afternoon	
S01	< 500	0	12.5	35	In the morning, provided adequate illumination to 12.5% of the floor area, but the laser cut panels had a better performance. At noon and in the afternoon, worsened the distribution.
	500 - 1000	12.5	37.5	45	
	> 1000	87.5	50	20	
S02	< 500	0	17.5	37.5	In the morning, provided adequate illumination to 1/4 of the floor area, but laser cut panels had a better performance. Distribution was similar with S01.
	500 - 1000	25	32.5	32.5	
	> 1000	75	50	30	
S03	< 500	77.5	55	25	In the morning, light shelves provided the best performance. At noon and in the afternoon, they decreased the uniformity and lowered the illuminance throughout the studio.
	500 - 1000	22.5	22.5	37.5	
	> 1000	0	22.5	37.5	
S04	< 500	62.5	50	15	The light shelves increased the amount of floor area exposed to adequate levels of illumination throughout the day, but also increased the overly illuminated areas in the morning and at noon, while increased the low illuminated areas in the afternoon.
	500 - 1000	35	30	35	
	> 1000	2.5	20	50	

4.4. Discussion

The aim of this thesis was to improve the illuminance and uniformity of the four architectural design studios in İzmir Institute of Technology by applying advanced daylighting systems. Besides, the simulation model was employed in order to estimate and evaluate the daylight illuminance and uniformity. There are several studies which included the advanced daylighting systems selected for this thesis, namely, the light shelves, laser cut panels and prismatic panels. For instance, Bleney and Edmonds (2013) recommended using laser cut panels as light redirection systems only if they were designed with the combination of fixed shading devices, at the end of an analysis of the laser cut panels they conducted in a school in Brisbane, Australia. In another example, Sweitzer (1991) identified the critical impacts of prismatic panels on the reflections and shadows on interior surfaces in perimeter offices. They concluded similarly that these redirecting systems effectively altered the daylighting distribution only if the window aperture was set accordingly.

In view of these studies, since the floor plan depth of the architectural studios selected for this thesis were too deep, 11.25 meters to 17.65 meters, and the illuminance was inadequate in the areas near the rear wall; it was assumed that by using those daylight redirecting elements which were mentioned above, the daylight could reach efficiently through these low illuminated areas. In addition, it would be possible to balance the average illuminance within the studios regardless of time when moving from the rear wall towards the main wall including the largest glazing area. Even, sun patches observed near the window would be prevented. Therefore the illuminance in these areas should have been decreased in order to provide a healthy environment to conduct the tasks of an architectural design studio. In the light of these arguments, it was also thought that the daylighting systems that would be applied on the exterior of the windows should also have sun shading characteristics.

Regarding these considerations, the Desktop Radiance employed the daylighting simulations with the inclusion of three selected advanced daylighting systems which met the needs of sun shading and redirection of daylight; namely, laser cut panels, prismatic panels and light shelves.

Discussions about several noteworthy findings of this study may guide further researchers and lighting designers in two ways, as iterated below.

a. First, Ecotect and Radiance are two simulation tools which may be suggested to be used in daylighting performance studies together.

One noteworthy discussion may base on the physical correctness, usability and applicability of the daylighting simulation tools. They have been the frequently-used and the mostly-reliable tools among the scale models and mathematical calculations in the prediction of illuminance and daylight factor in the field of daylighting design. Their priority depends on being less-time consuming, providing various visual scenes for various physical and sky conditions. It is possible to detect any deficiency in the design phase and provide solutions before its construction. So it is cost-efficient. Here, in this study, the Autodesk Ecotect Analysis and Desktop Radiance tools were used to model the studios and analyze their lighting condition. Majority of the studies reviewed from literature concluded that Radiance is the most accurate tool among other tools and preferred to design and examine some technological components, i.e., laser-cut or prismatic panels in glazing. However, it was also understood that even the most precise tool might display misleading findings by the consideration of the various real sky conditions and a plenty of surface reflectance values. There are also evidences to support this statement in this study; i.e. there were several unbalanced illuminance variation between the measurements and the simulation model during the day, especially observed at the measurement points near the windows.

It is obvious that the advances in simulation technologies would continue with a growing acceleration. However the noteworthy point here is that which tool is the most accurate one at the moment and that its accuracy/or inaccuracy depends on which factors (such as sky model, material, etc.) The answers would allow the improvement in the simulation technology. Designers and researchers also would use such tools with an absolute awareness.

b. Second, the simulation results indicated that none of the applied daylighting systems satisfactorily improved the illuminance and daylight uniformity in the architectural design studios.

Another discussion may be stated here about the impact of daylighting systems on the parameters of daylighting performance, namely, the illuminance and uniformity. The prevented excessive light intensity by laser cut panels reduced the horizontal illuminance. For example, laser cut panels reduced the horizontal illuminance on the working surface near the window from about 39klux to about 3klux. Although they were successful in avoiding sun patches, they were unable to enhance the uniformity ratios up to the recommended values. Thus, the systems only reduced the horizontal illuminance in general. On the other hand, the prismatic panels did not provide adequate sun shading for the areas which were overly illuminated.

The studies about the daylighting performance of laser cut and prismatic panels were mostly included office buildings whose plan depths were 5 – 6 m. However, the horizontal depth of the architectural studios which were subjected in this thesis was 11.25 m. Each studio was approximately 200m^2. There were windows only on the two façades, and the total glazing ratio was almost 10%. The glazing ratio, as well as the number of glazed facades was inadequate in such a space of this amount of floor area. All of these considerations might be the cause of the inadequacy of the selected daylighting systems. Also, all of these conditions were the results of unsolved design problems at the preliminary stages of the architectural design of the studios.

CHAPTER 5

CONCLUSION

This study aimed to obtain the best daylighting illuminance and uniformity in an architectural design studio. The measurements were taken to evaluate the real case lighting conditions and to validate the simulation model which was employed by Autodesk Ecotect Analysis. Then, simulated lighting analyses were carried out to construct trial models in Desktop Radiance by applying advanced daylighting systems(laser cut panels, prismatic panels and light shelves with different size and material combinations in May and June. It was predicted that the applied daylighting systems would illuminate the areas near the rear wall with their light guiding characteristics, balance the average illuminance regardless of time within the studios when moving from the rear wall to the window wall with the largest glazing area, and prevent the previous sun patches with their sun shading characteristics.

But the simulation results indicated that, all three of the systems failed to increase the illuminance near the rear wall, the systems did not improved the uniformity of the studios and all three of the systems showed sun shading characteristics rather than acting as light guiding elements.

Findings showed that the 20% of the floor area did not receive enough daylight in the morning period; and almost 60% of the floor area was gloomy at noon (daytime) for the studios facing east. The existing daylighting conditions did not satisfy the uniformity rates. By applying laser-cut panels, prismatic panels and light shelves, trial simulation models displayed that uniformity values wouldn’t be improved, although illuminance near the windows decreased sharply. One reason might be the depth of the studio was far away from the range of daylighting system’s effectiveness. In literature (Greenup, Edmonds, &Compagnon, 2000; Thanachareonkit, & Scartezzini, 2006) such systems were applied in smaller spaces, such as offices or classrooms. Similarly, the systems were very effective on the floor area close to the windows and decreased the horizontal illuminance in that overall space while they improved the uniformity. Another reason might be the rate of window area to the floor area was not enough to admit sufficient amount of daylight inside. It is almost one third of the values proposed in standards. It is considered that retrofitting efforts after the construction would be inadequate due to daylighting, unless complying with the standards during the design process. In other words, designers and professionals should pay attention to apply requirements mentioned in the standards/or norms about daylighting in the design stage.

Another finding was that Ecotect/Radiance modeling was a suitable tool to evaluate and retrofit an existing building's daylighting performance. It was believed that further retrofitting/repairing applications such as opening additional windows and considering their design together with laser-cut panels and light shelves would help to find better daylighting conditions.

In the light of these, the findings of this study can be summarized as;

- Autodesk Ecotect Analysis and Desktop Radiance are two powerful simulation tools which may be suggested to be used in daylighting performance studies together,
- None of the applied daylighting systems satisfactorily improved the illuminance and uniformity in the selected design studios due to the previously mentioned reasons; and
- Daylighting decisions should be integrated with the building design in the preliminary design stages, since the main design decisions like glazing ratio, the number and positioning of the daylight apertures have remarkable effects on the daylighting performance of the buildings.

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APPENDIX A

THE COEFFICIENT OF DETERMINATION (R^2) VALUES DISPLAYED ON DISTRIBUTION CHARTS OF MEASURED AND MODELED ILLUMINANCE

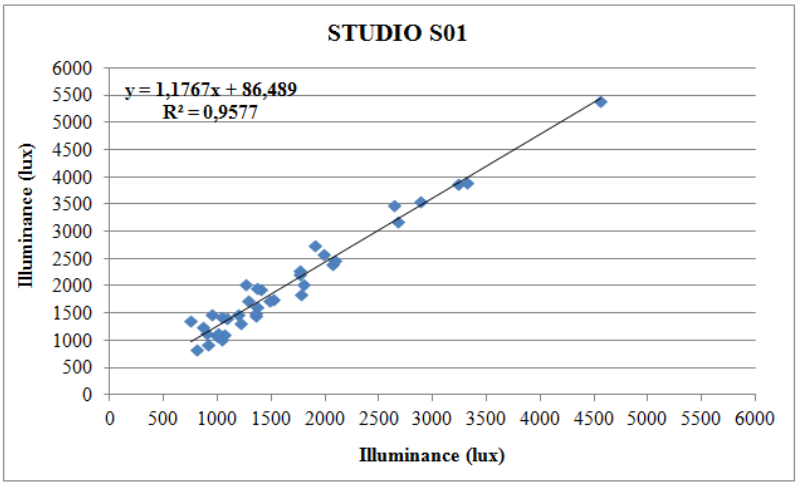


Figure A.1. Distribution of daylight illuminance for S01 in the morning on June 21st.

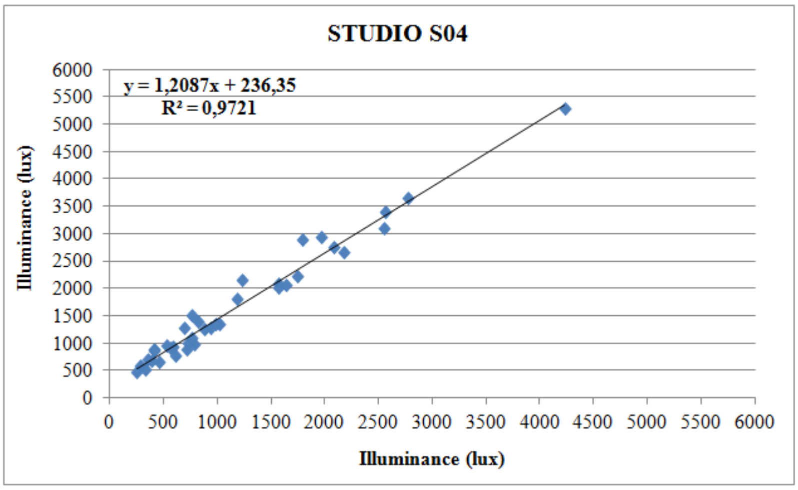
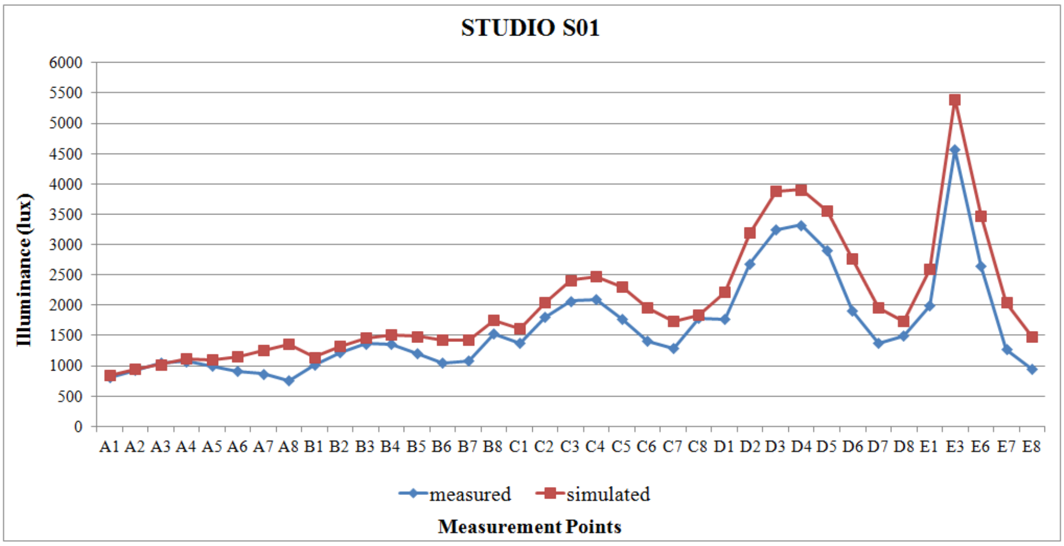


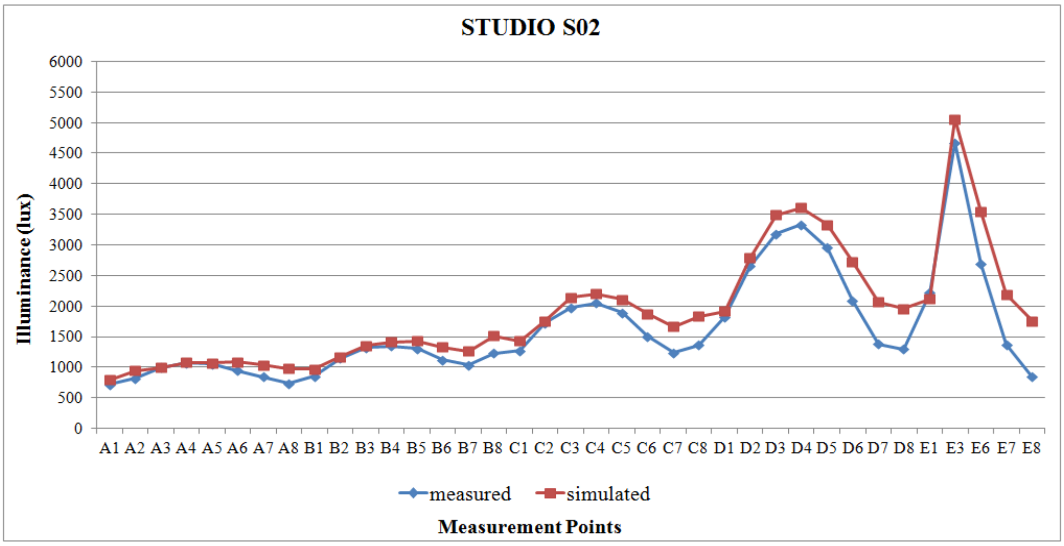
Figure A.2. Distribution of daylight illuminance for S04 in the afternoon on June 21st.

APPENDIX B

DISTRIBUTION OF MEASURED AND MODELED DAYLIGHT ILLUMINANCE REGARDING MEASUREMENT POINTS



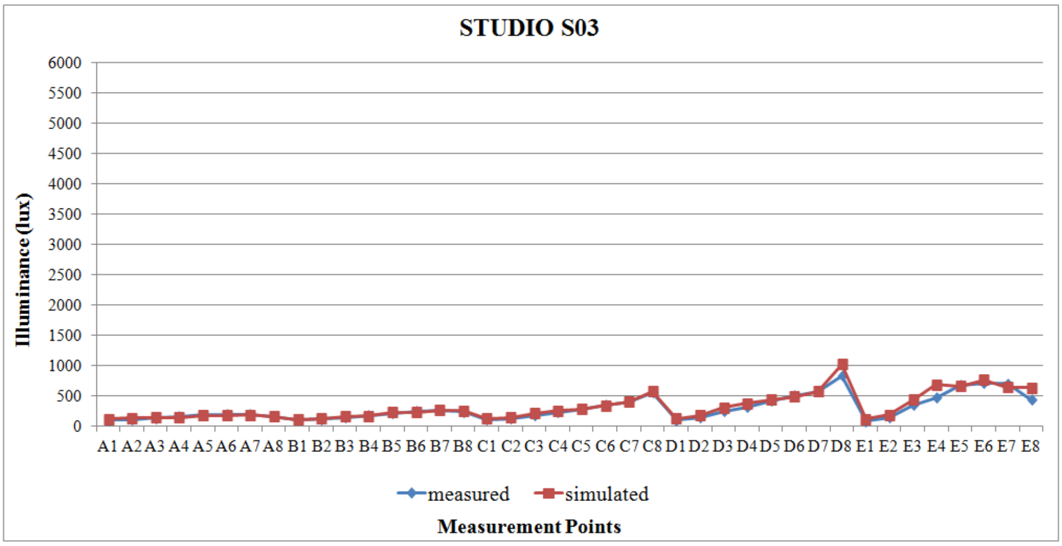
(a)



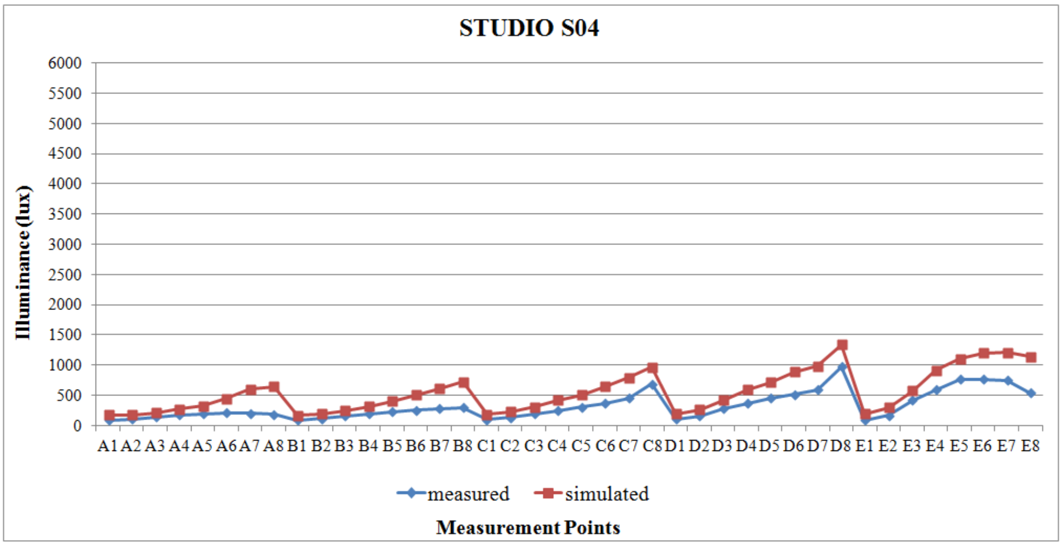
(b)

Figure B.1. Distribution of measured and modeled daylight illuminance for (a) S01; (b) S02; (c) S03; (d) S04; in the morning on June 21st

(cont. on next page)

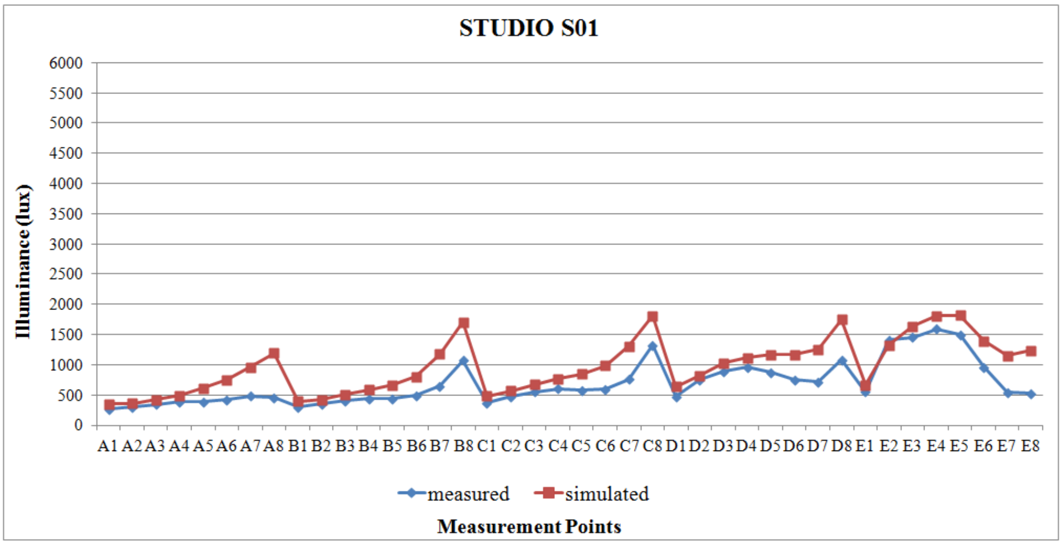


(c)

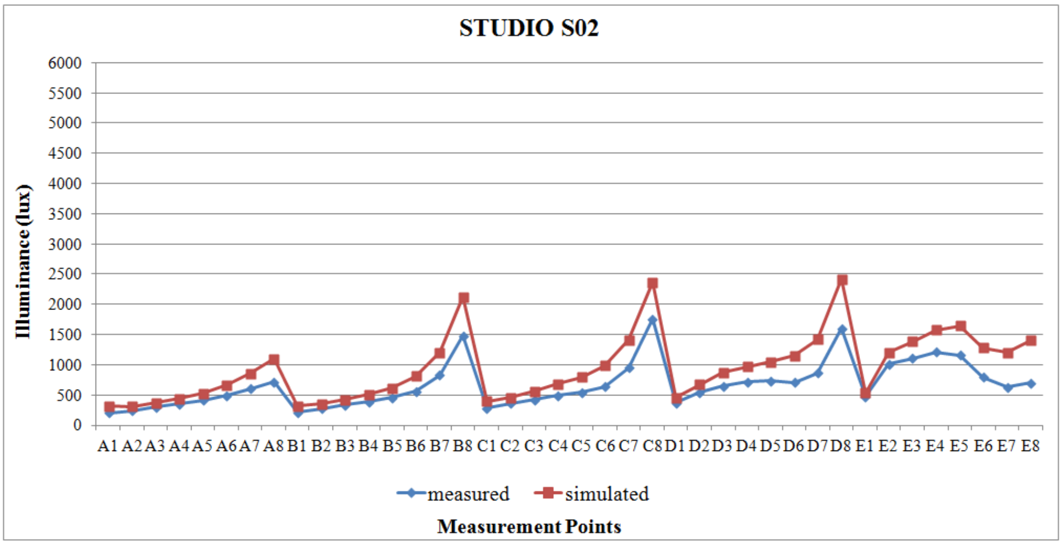


(d)

Figure B.1. (cont.)



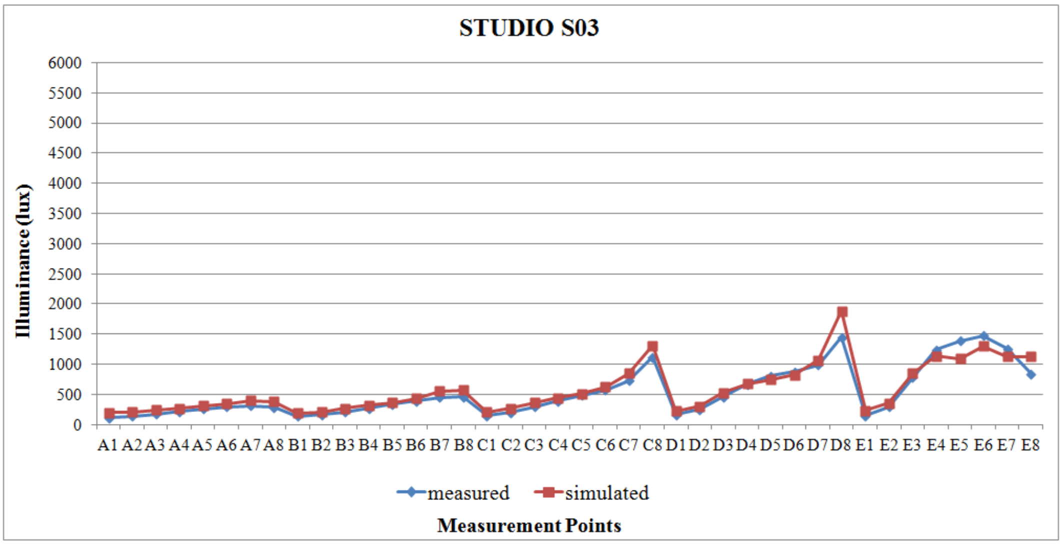
(a)



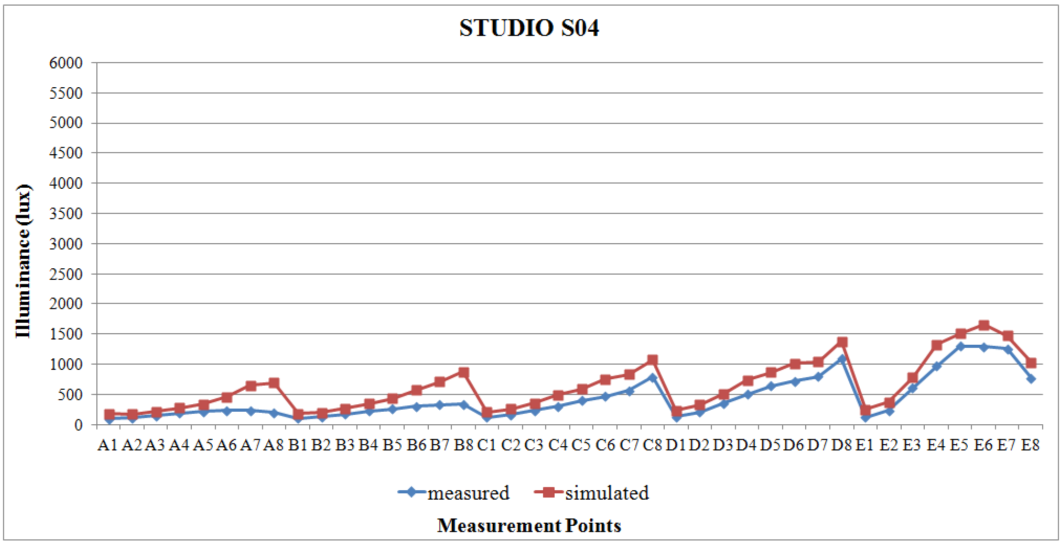
(b)

Figure B.2. Distribution of measured and modeled daylight illuminance for (a) S01; (b) S02; (c) S03; (d) S04; at noon on June 21st

(cont. on next page)

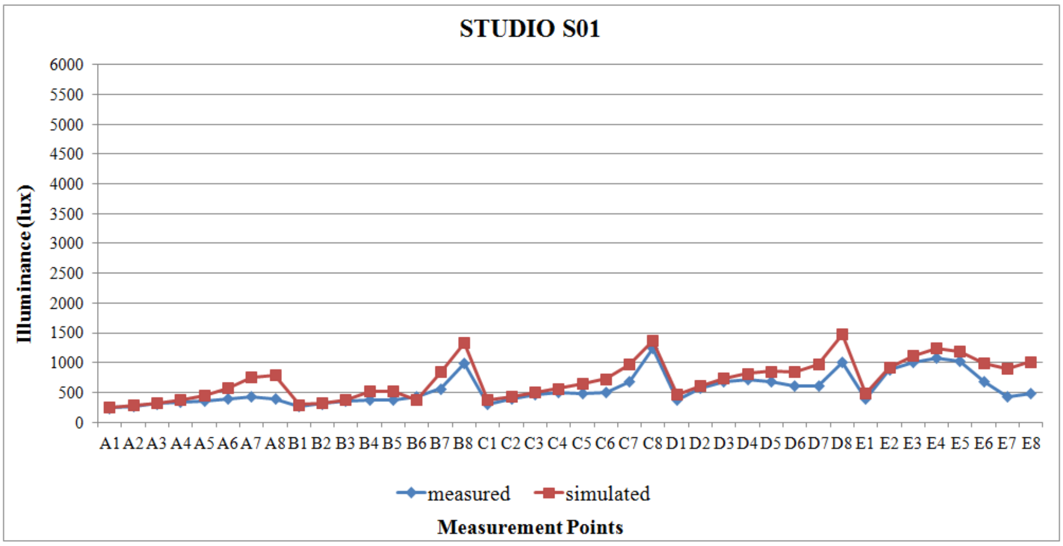


(c)

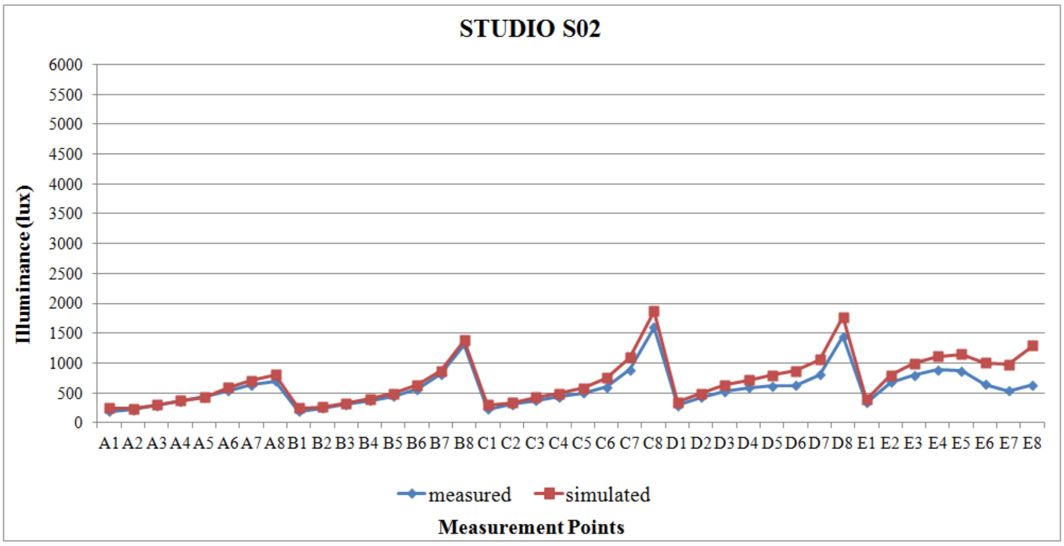


(d)

Figure B.2. (cont.)



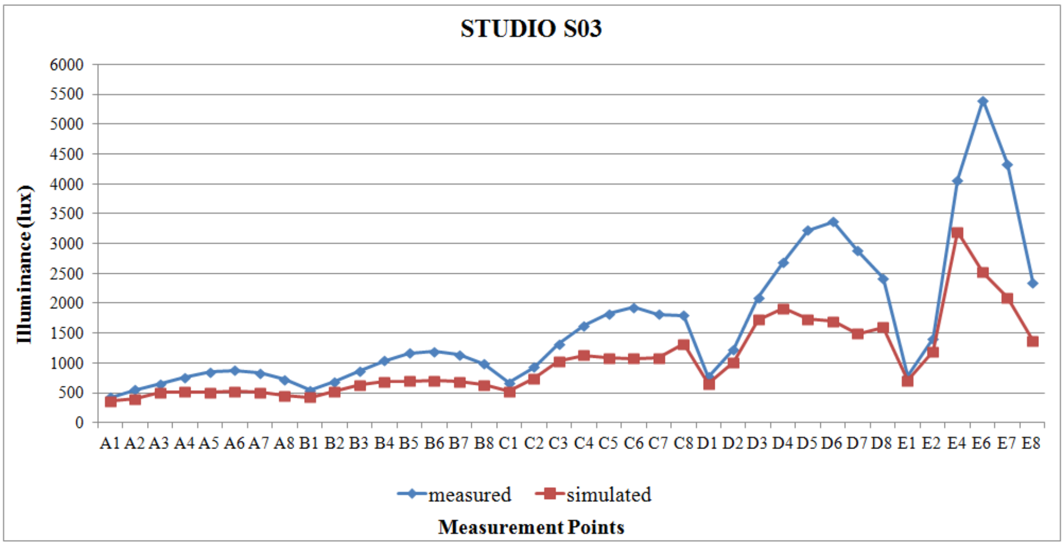
(a)



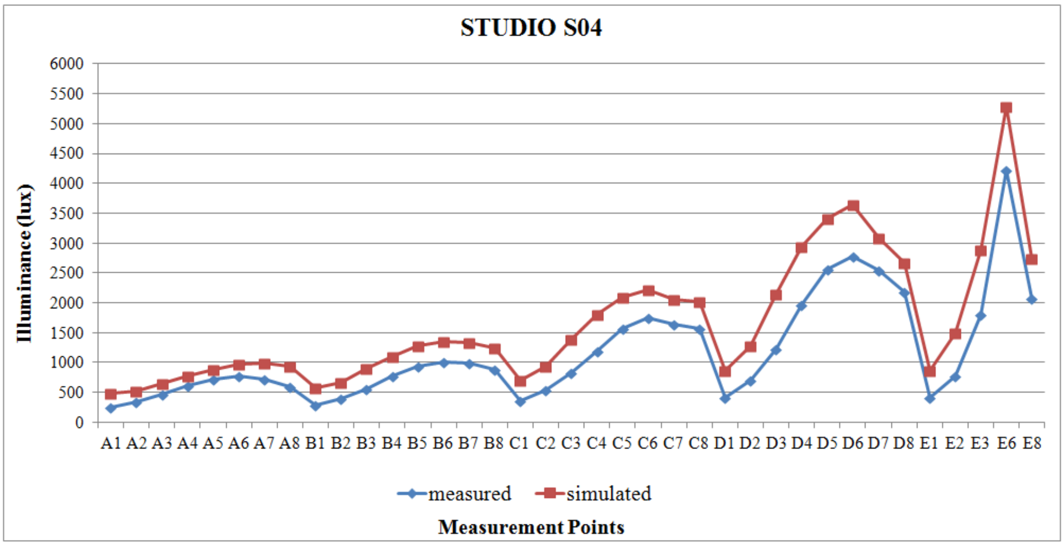
(b)

Figure B.3. Distribution of measured and modeled daylight illuminance for (a) S01; (b) S02; (c) S03; (d) S04; in the afternoon on June 21st

(cont. on next page)



(c)

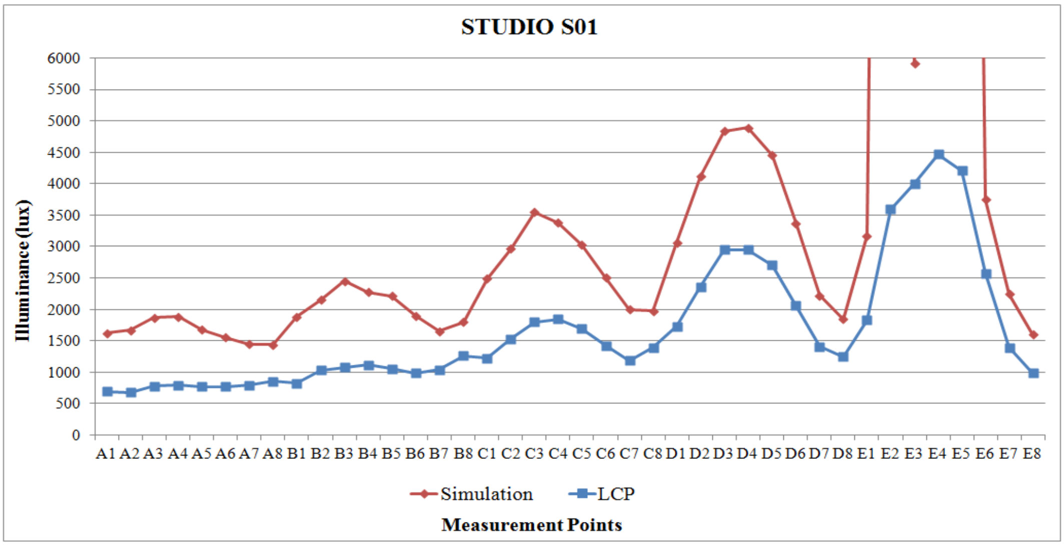


(d)

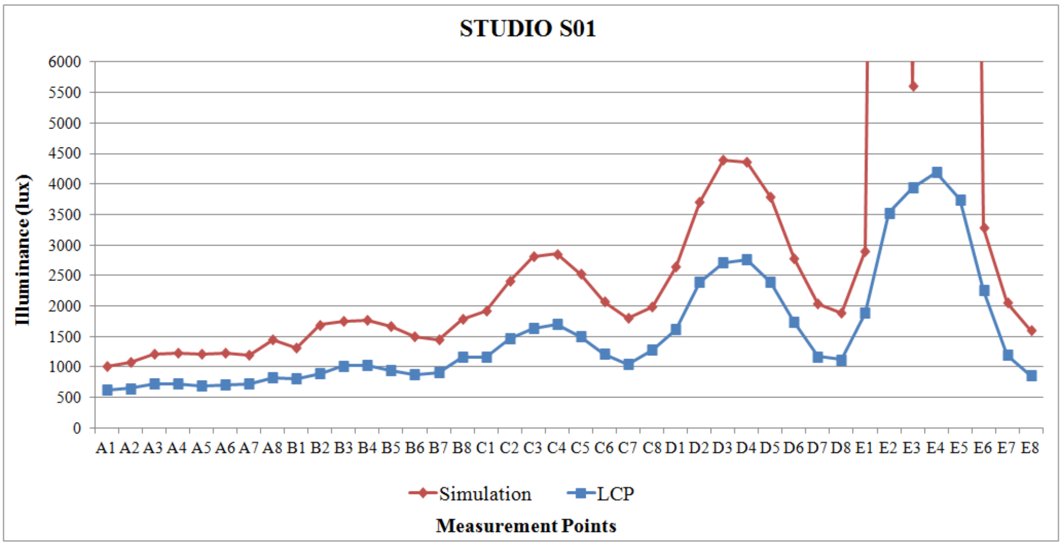
Figure B.3. (cont.)

APPENDIX C

DISTRIBUTION OF DAYLIGHT ILLUMINANCE AFTER THE LASER CUT PANELS WERE APPLIED

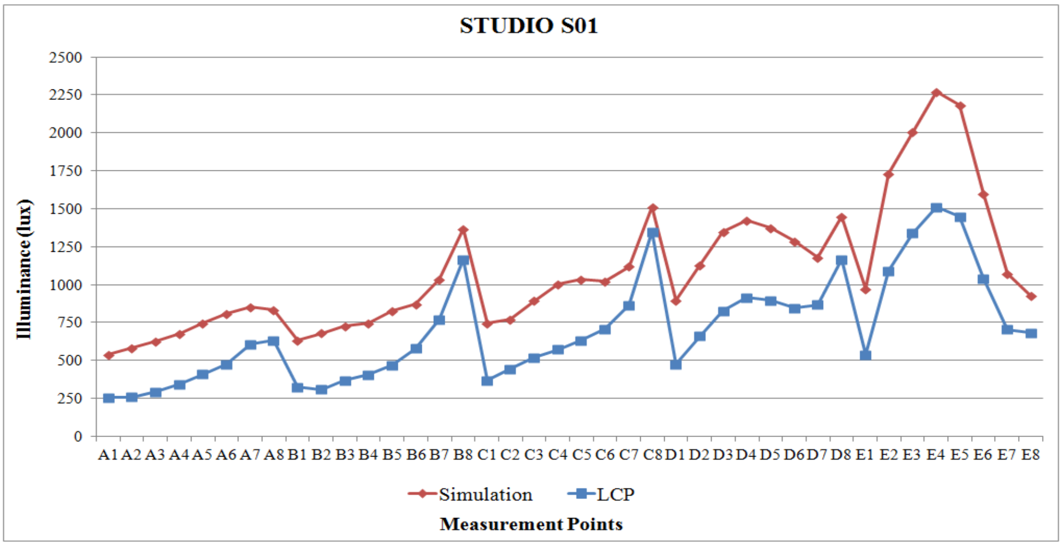


(a)

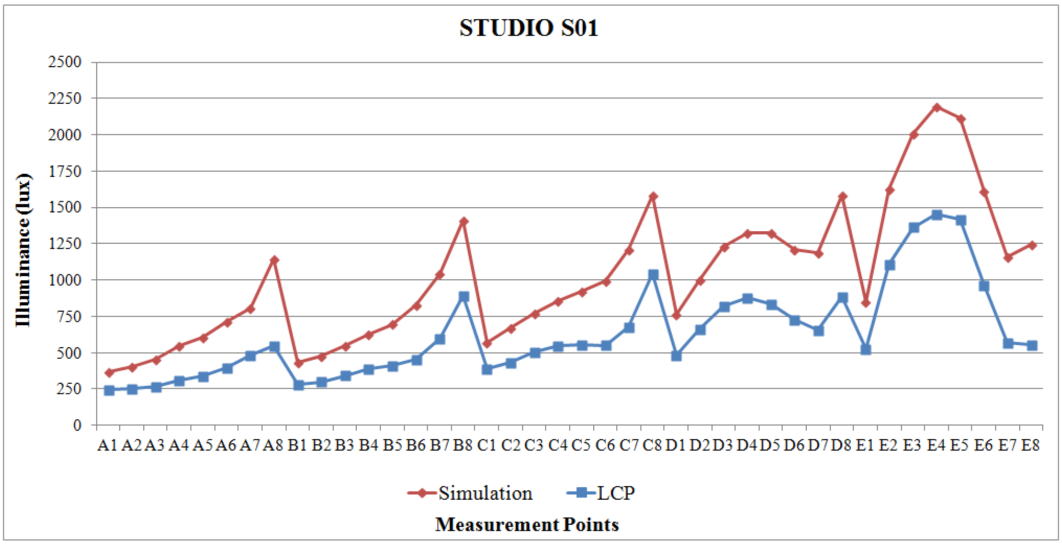


(b)

Figure C.1. Distribution of daylight illuminance for S01 with LCP on (a) May 4th and (b) June 21st at 09:00

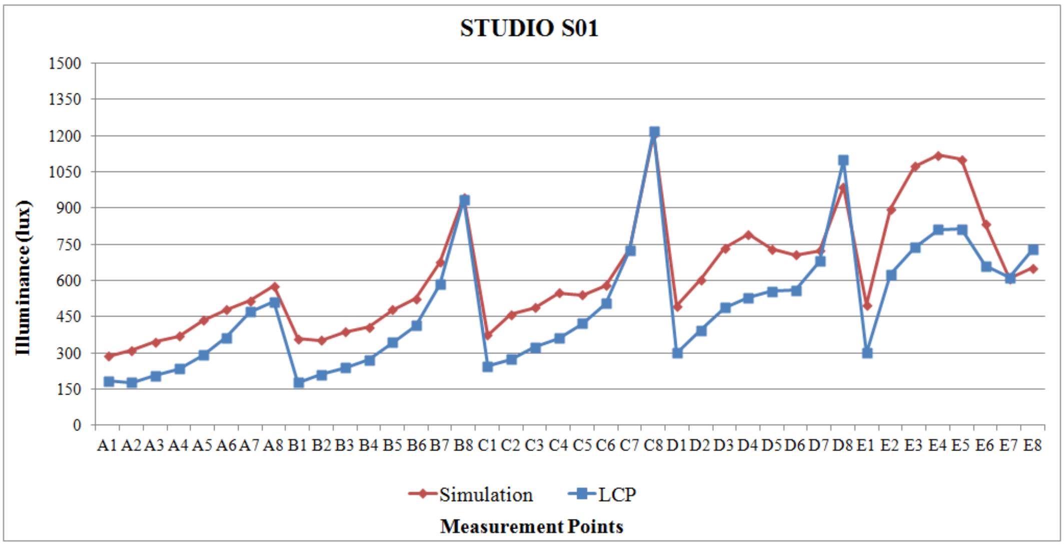


(a)

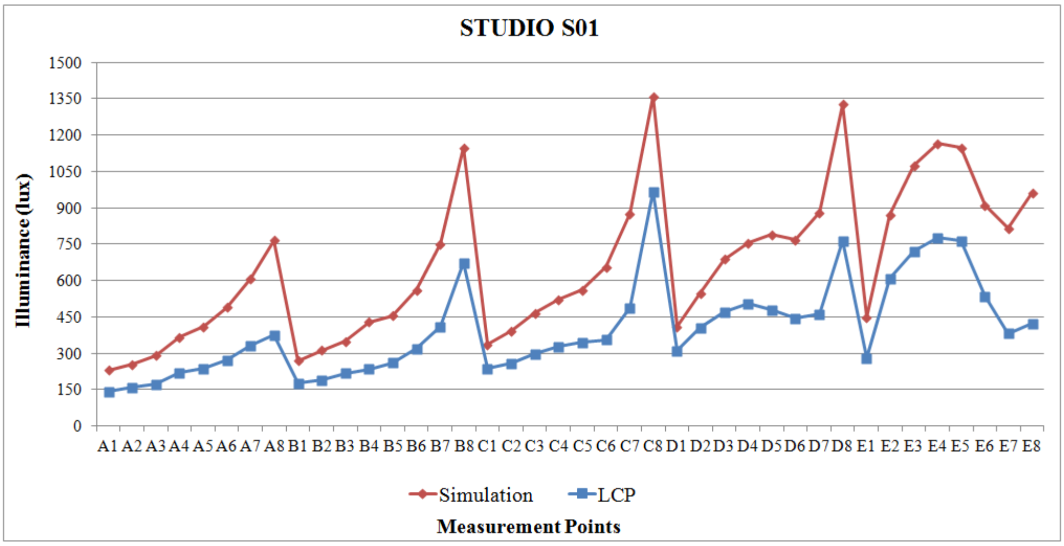


(b)

Figure C.2. Distribution of daylight illuminance for S01 with LCP on (a) May 4th and (b) June 21st at 12:30

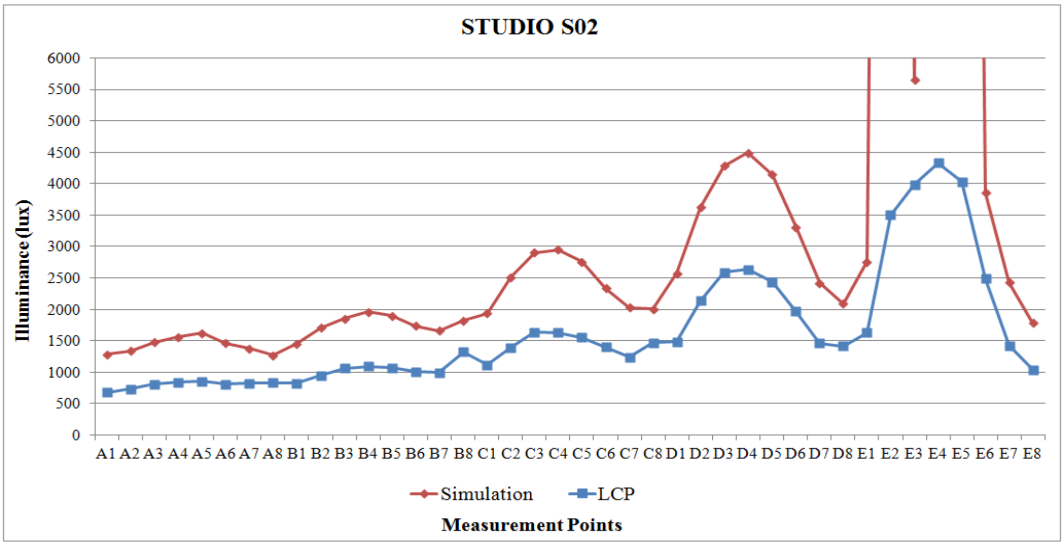


(a)

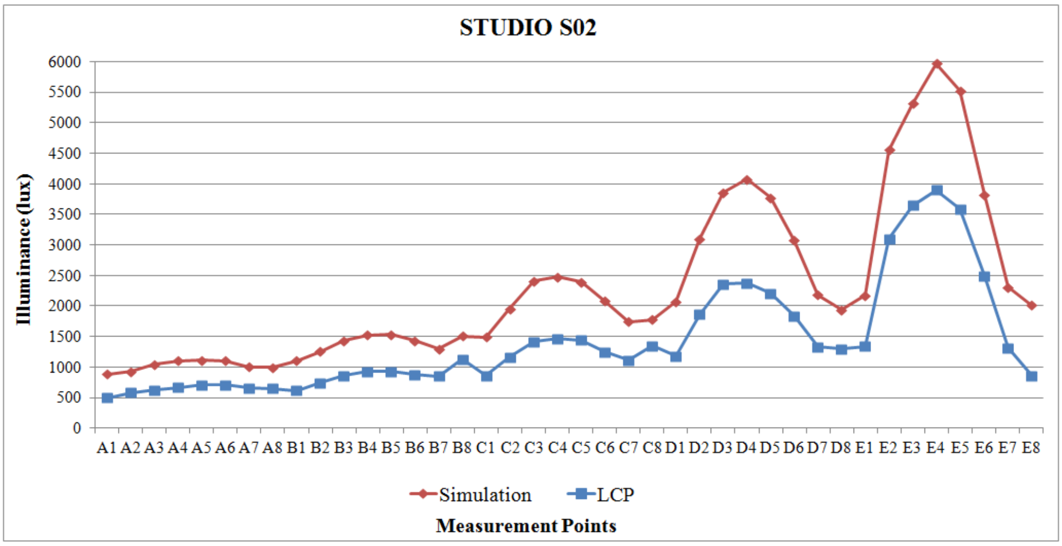


(b)

Figure C.3. Distribution of daylight illuminance for S01 with LCP on (a) May 4th and (b) June 21st at 16:10

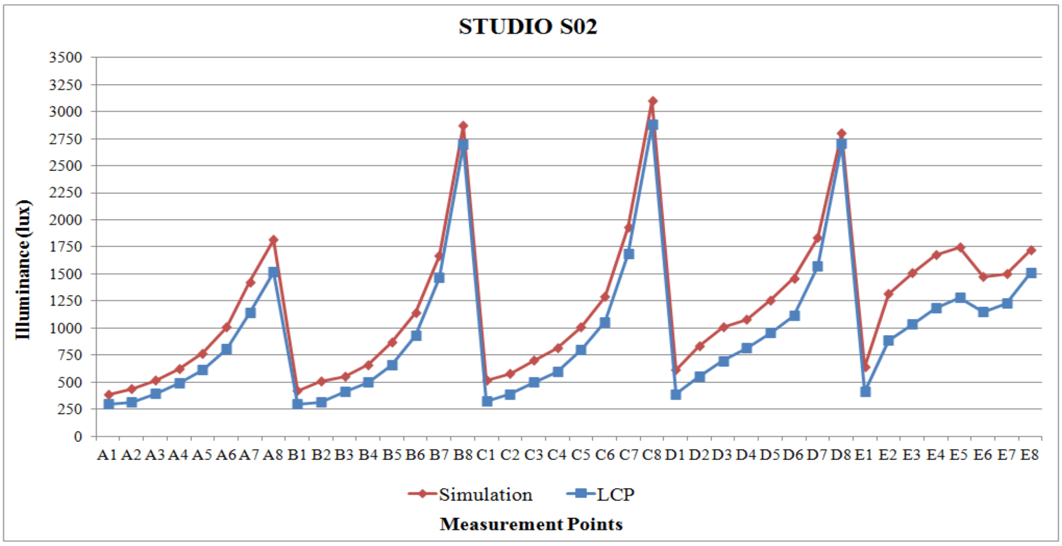


(a)

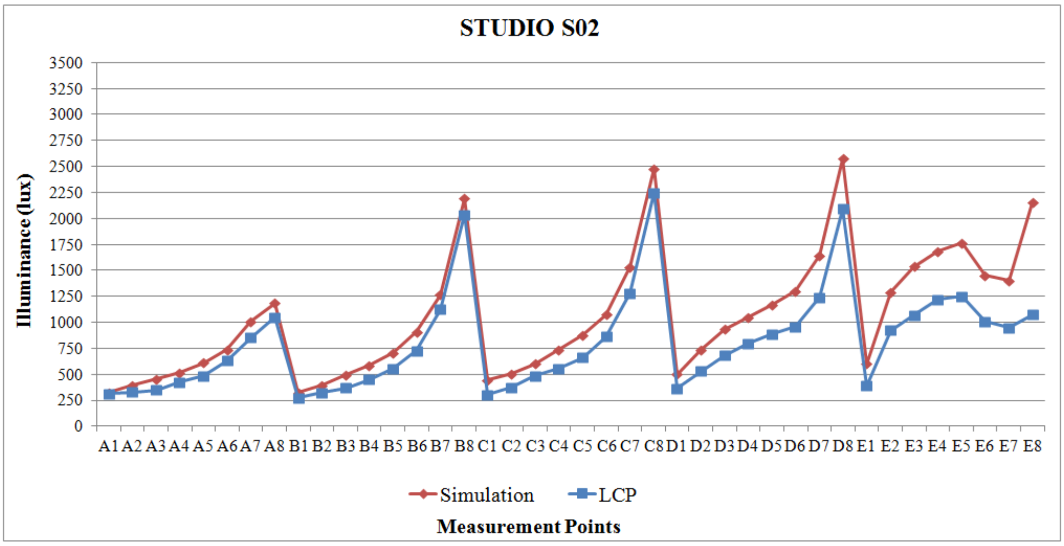


(b)

Figure C.3. Distribution of daylight illuminance for S02 with LCP on (a) May 4th and (b) June 21st at 09.25

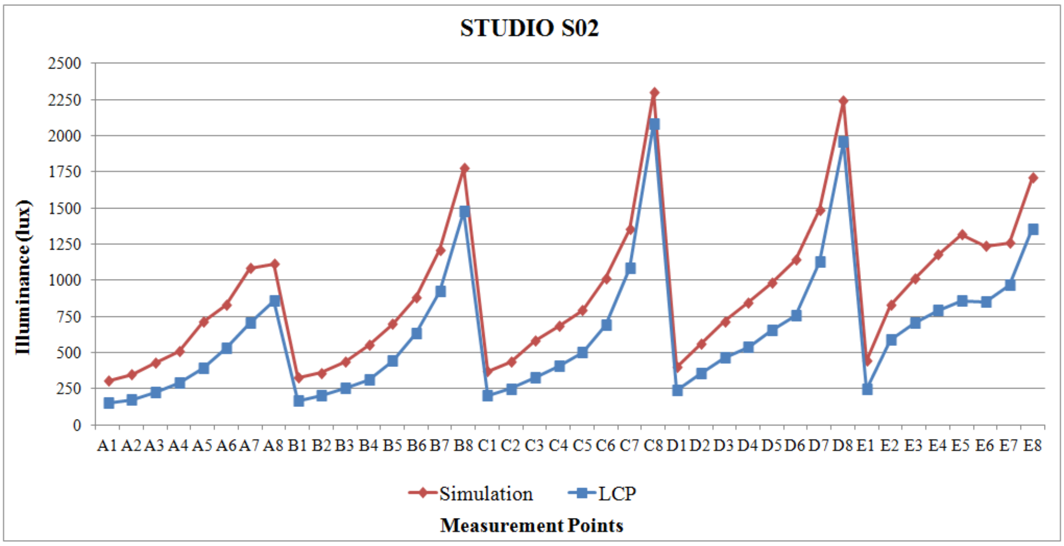


(a)

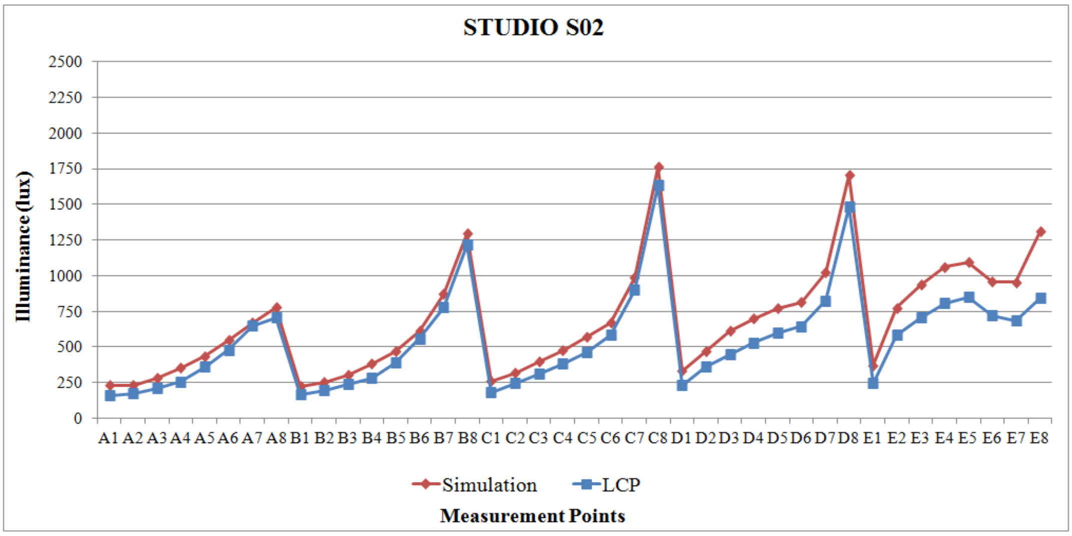


(b)

Figure C.4. Distribution of daylight illuminance for S02 with LCP on (a) May 4th and (b) June 21st at 13:00

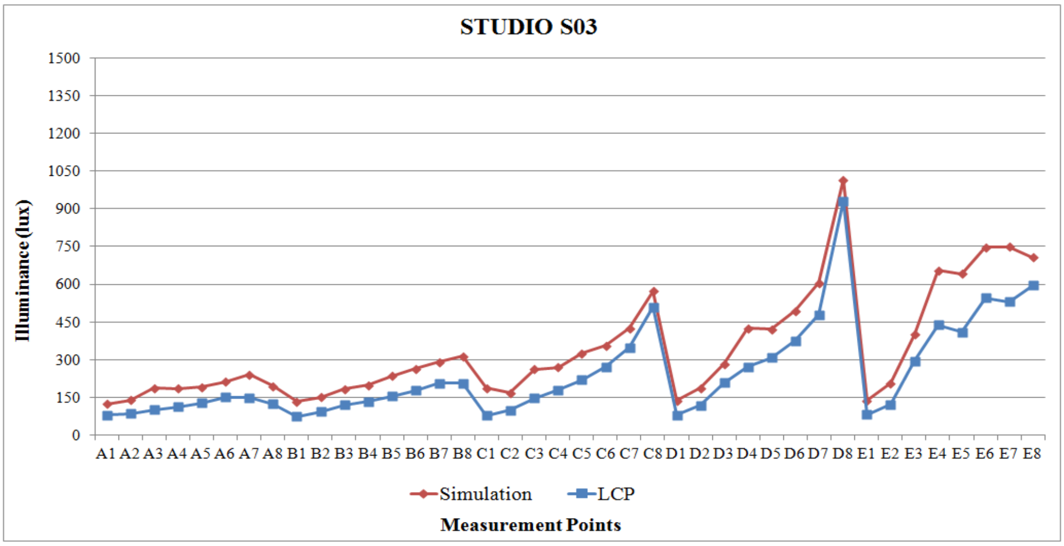


(a)

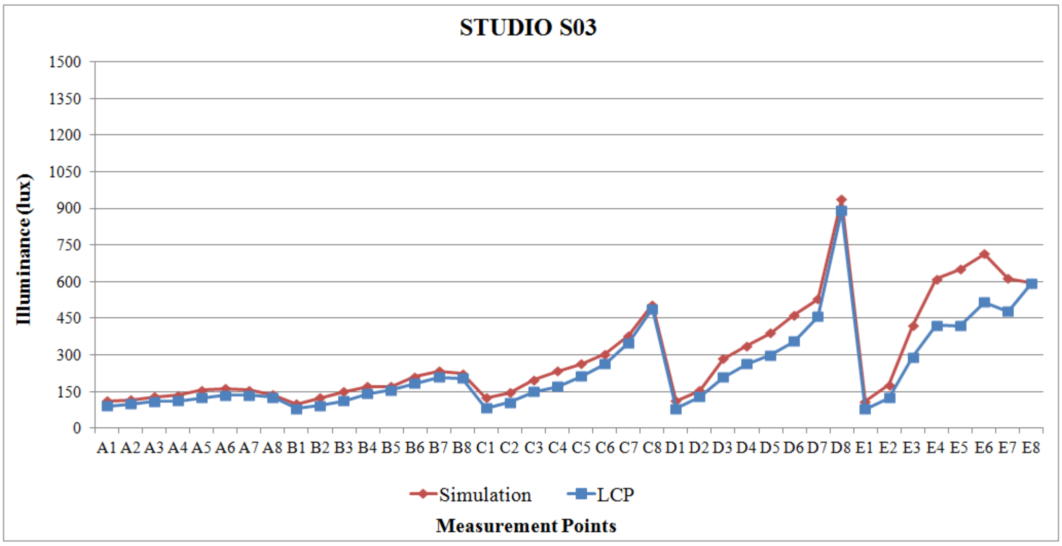


(b)

Figure C.5. Distribution of daylight illuminance for S02 with LCP on (a) May 4th and (b) June 21st at 16:25

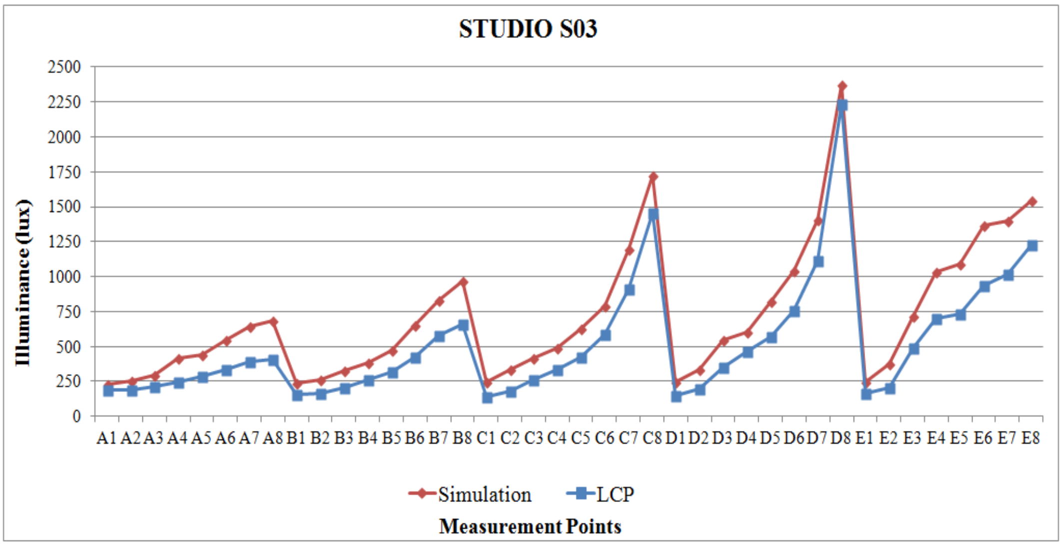


(a)

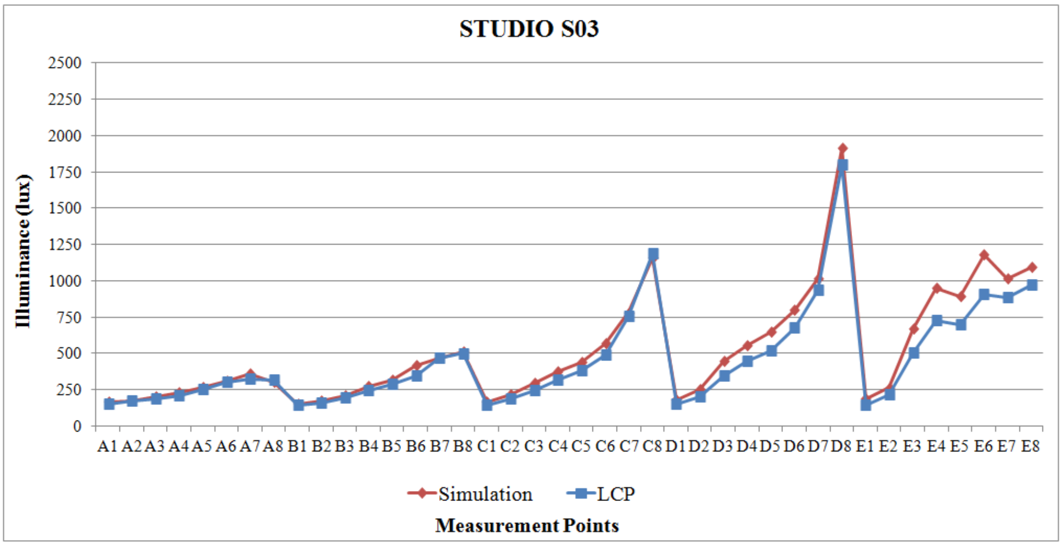


(b)

Figure C.6. Distribution of daylight illuminance for S03 with LCP on (a) May 4th and (b) June 21st at 09:45

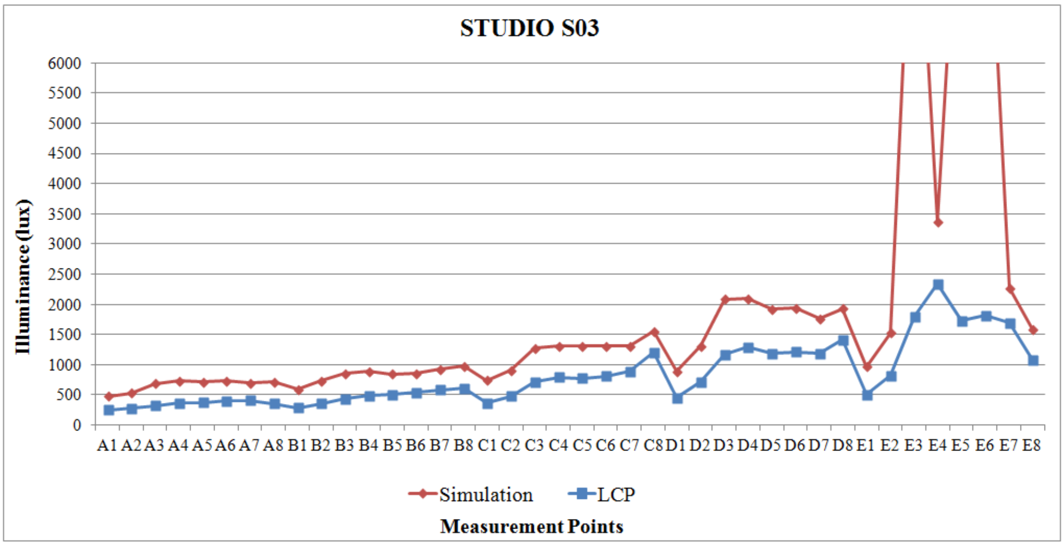


(a)

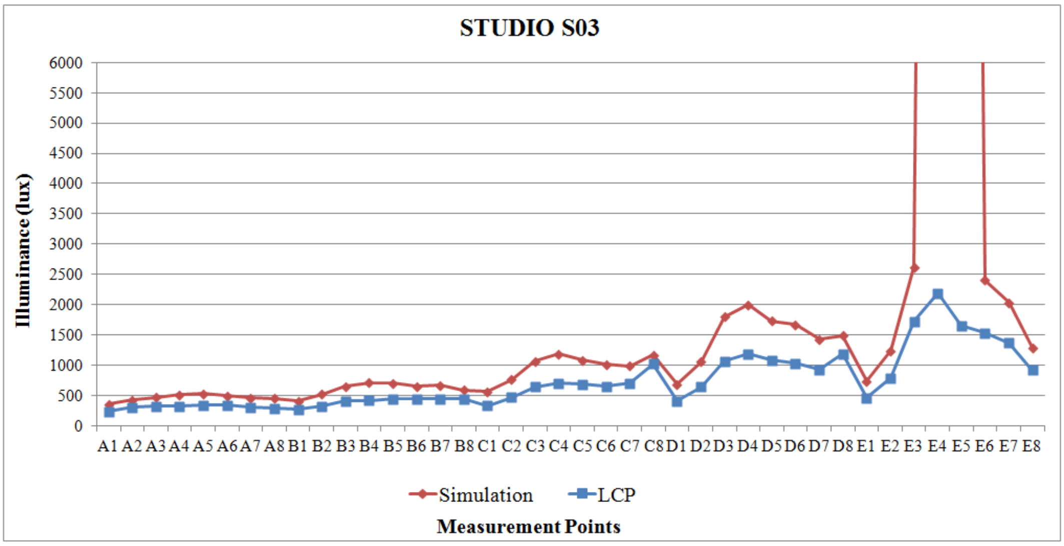


(b)

Figure C.7. Distribution of daylight illuminance for S03 with LCP on (a) May 4th and (b) June 21st at 13:20

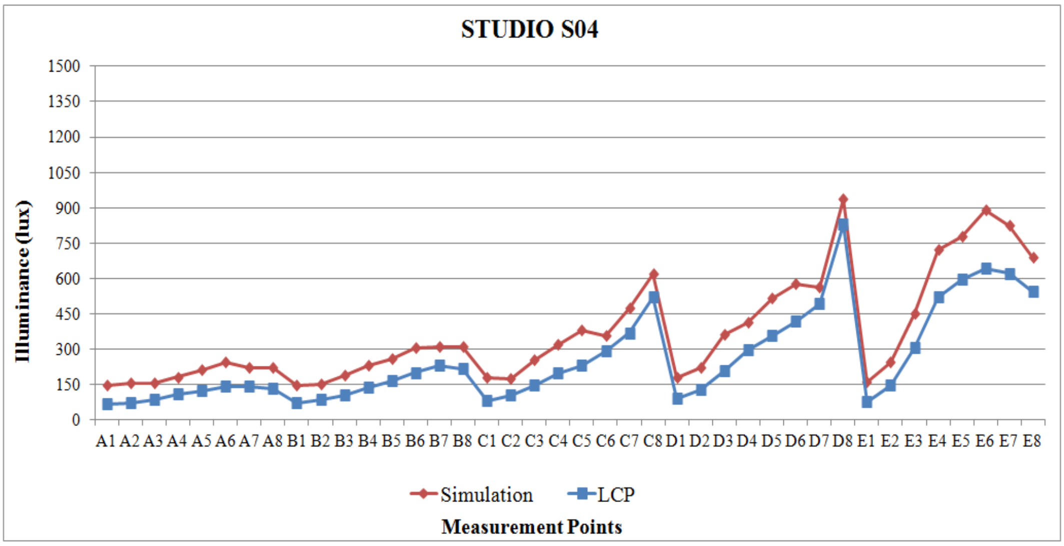


(a)

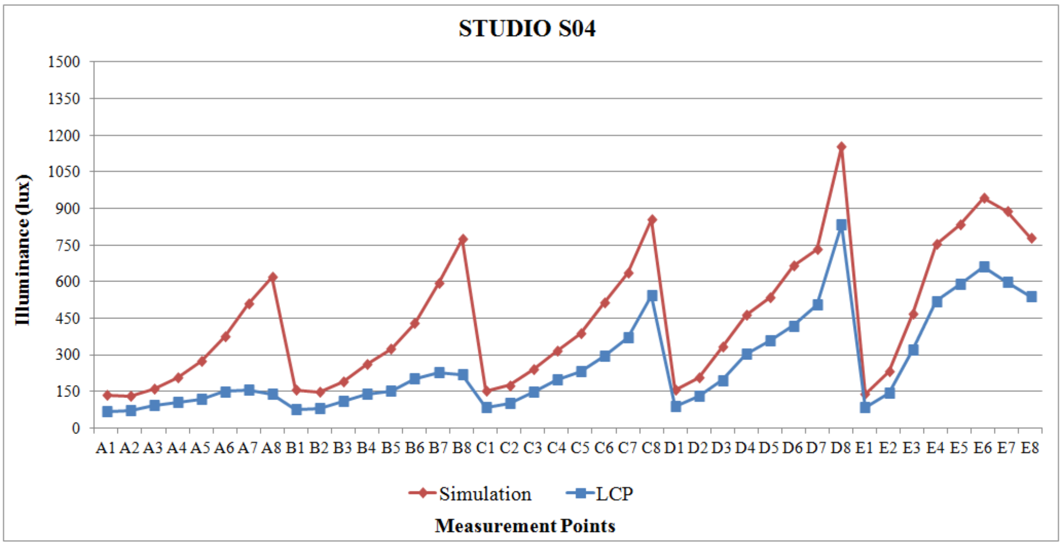


(b)

Figure C.8. Distribution of daylight illuminance for S03 with LCP on (a) May 4th and (b) June 21st at 16:45

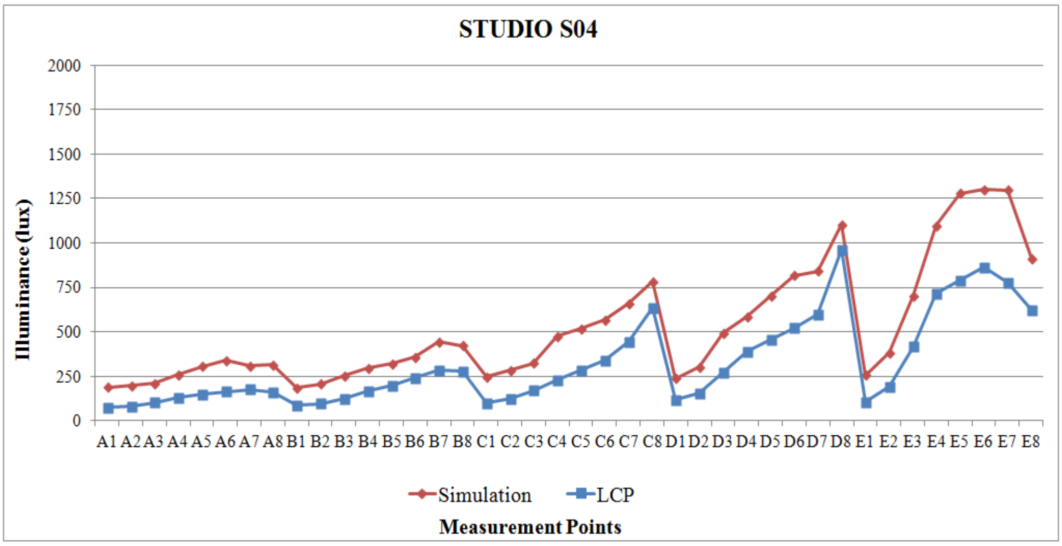


(a)

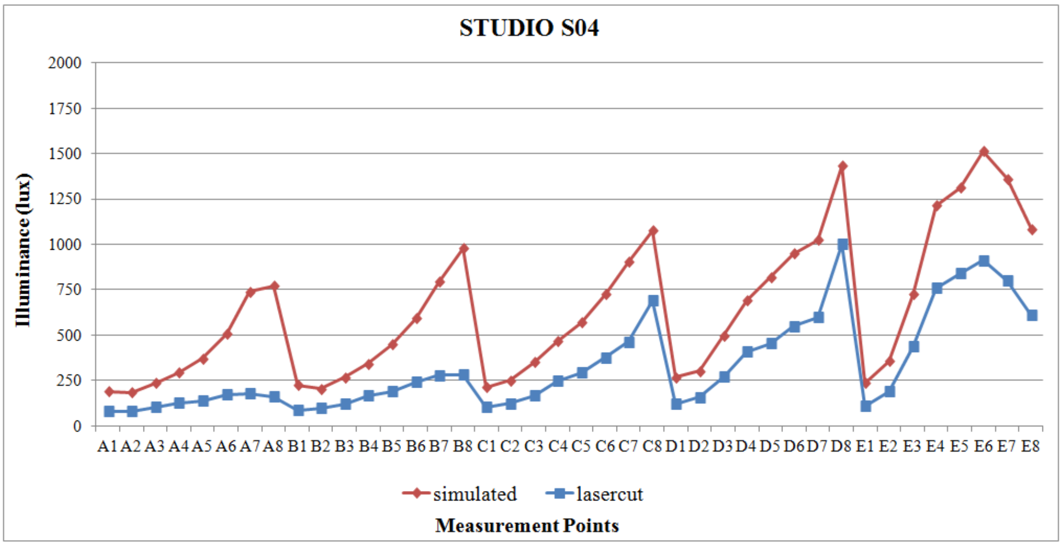


(b)

Figure C.9. Distribution of daylight illuminance for S04 with LCP on (a) May 4th and (b) June 21st at 10:05

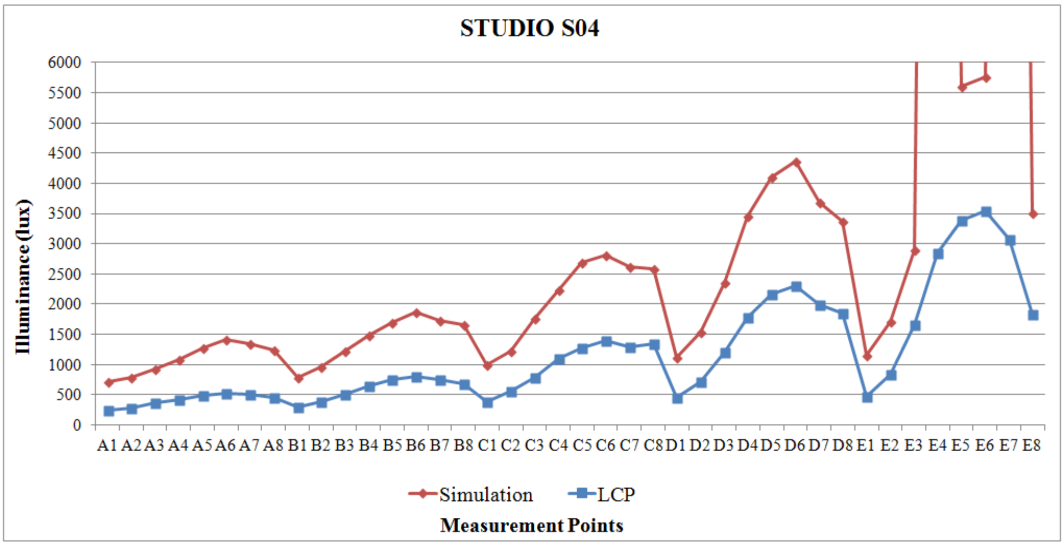


(a)

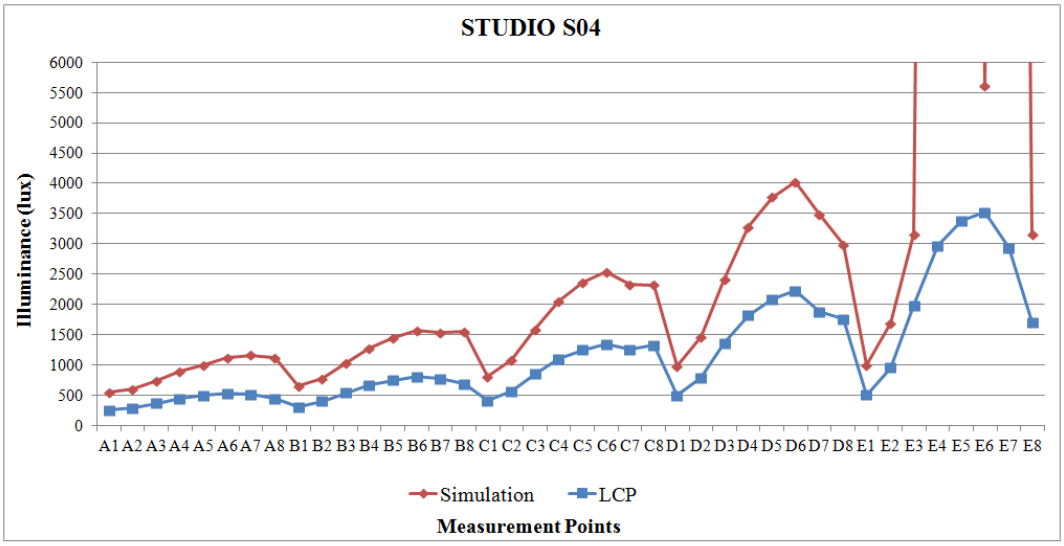


(b)

Figure C.10. Distribution of daylight illuminance for S04 with LCP on (a) May 4th and (b) June 21st at 13:45



(a)

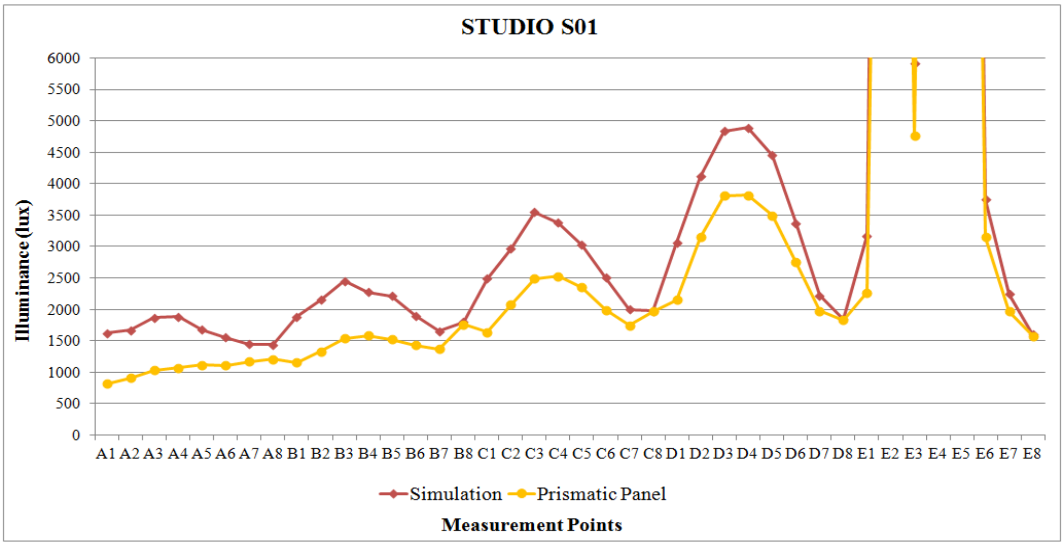


(b)

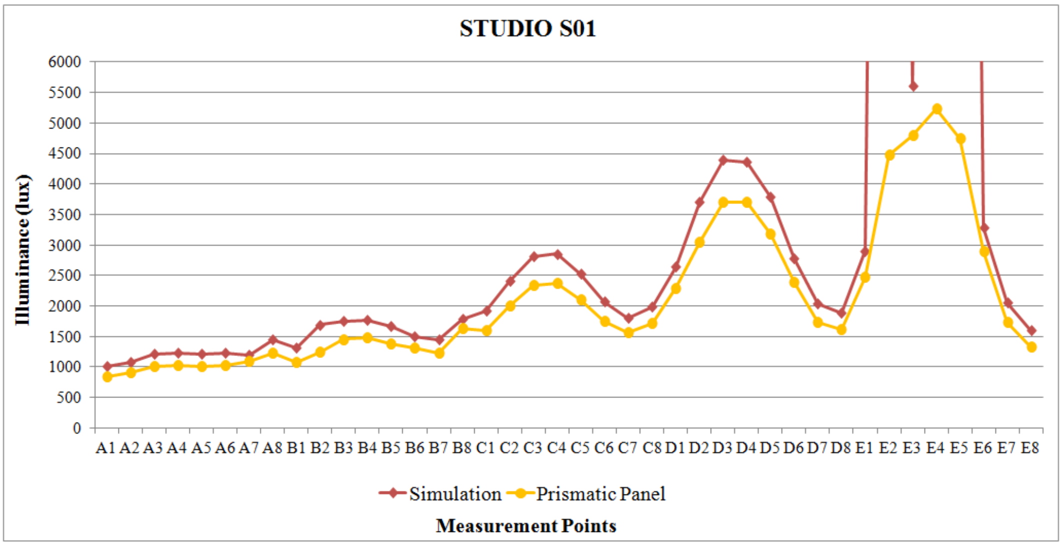
Figure C.11. Distribution of daylight illuminance for S04 with LCP on (a) May 4th and (b) June 21st at 17:00

APPENDIX D

DISTRIBUTION OF DAYLIGHT ILLUMINANCE AFTER THE PRISMATIC PANELS WERE APPLIED

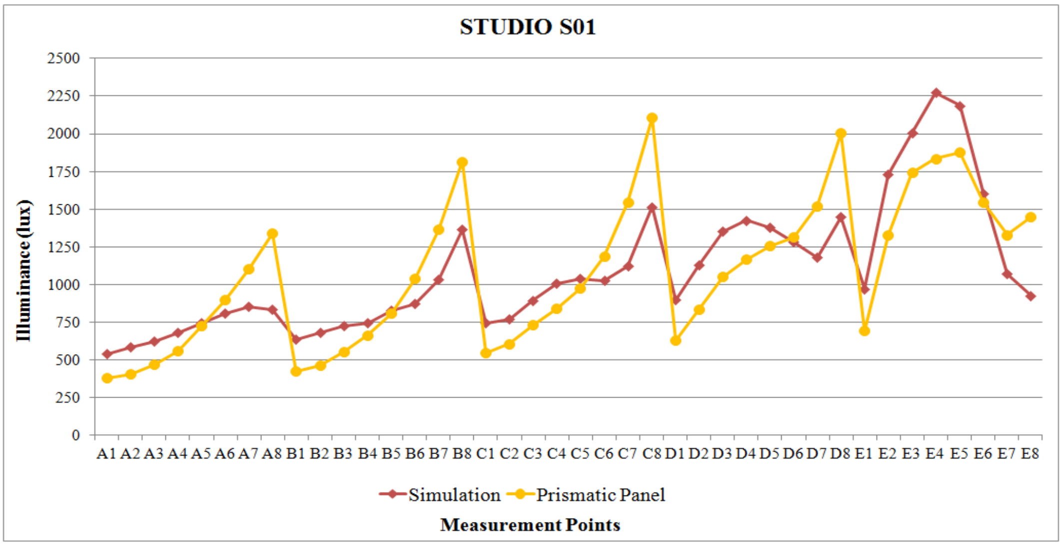


(a)

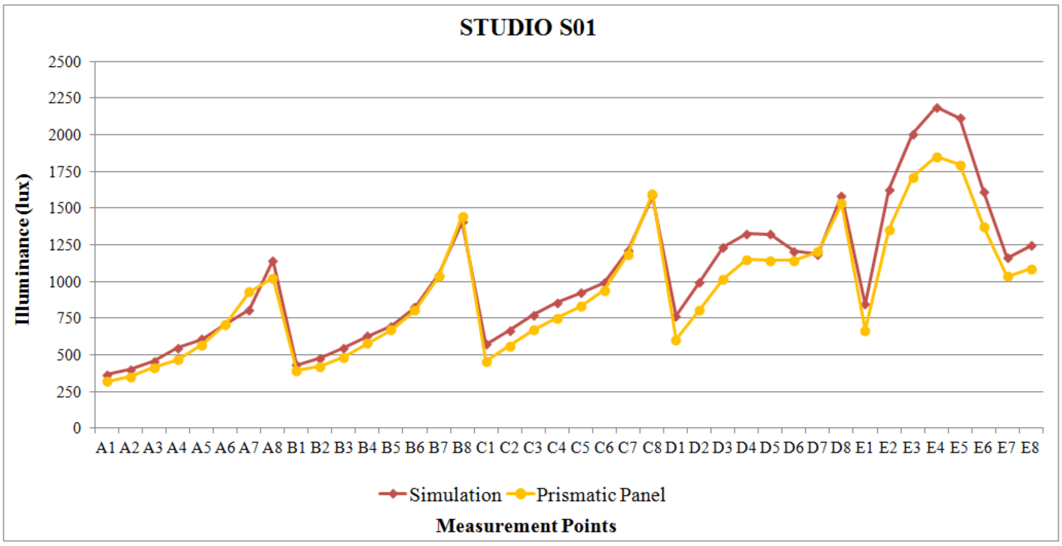


(b)

Figure D.1. Distribution of daylight illuminance for S01 with PP on (a) May 4th and (b) June 21st at 9:00

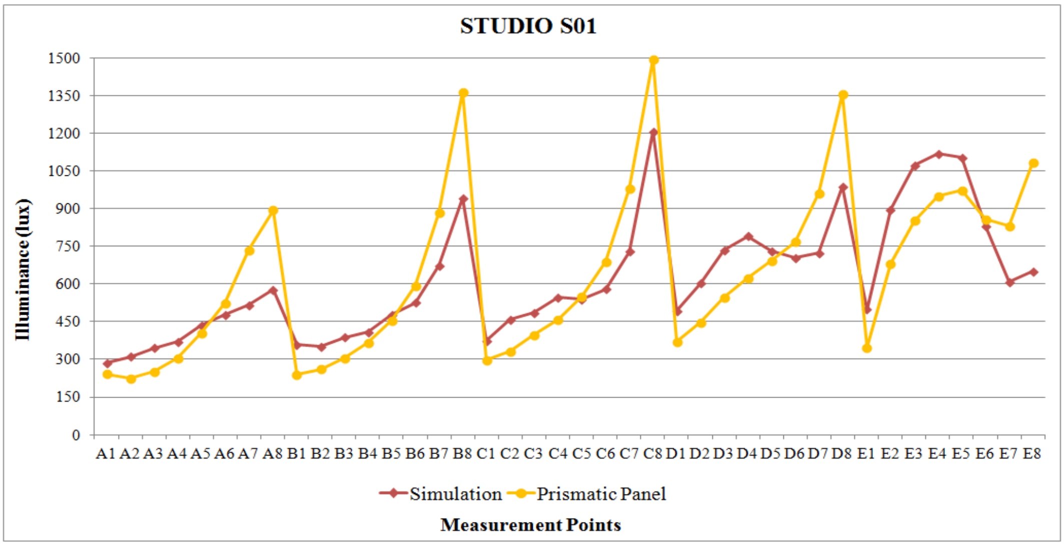


(a)

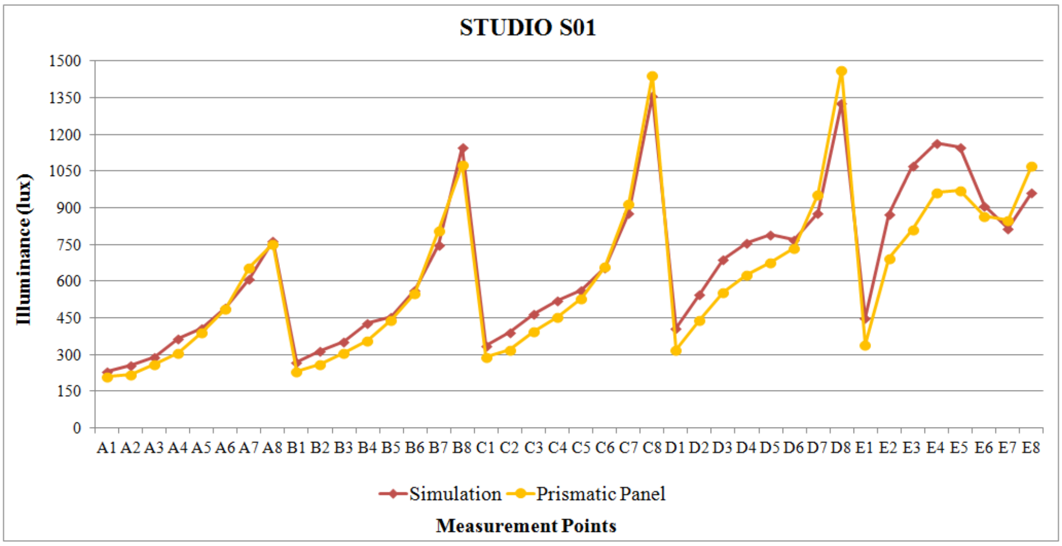


(b)

Figure D.2. Distribution of daylight illuminance for S01 with PP on (a) May 4th and (b) June 21st at 12:30

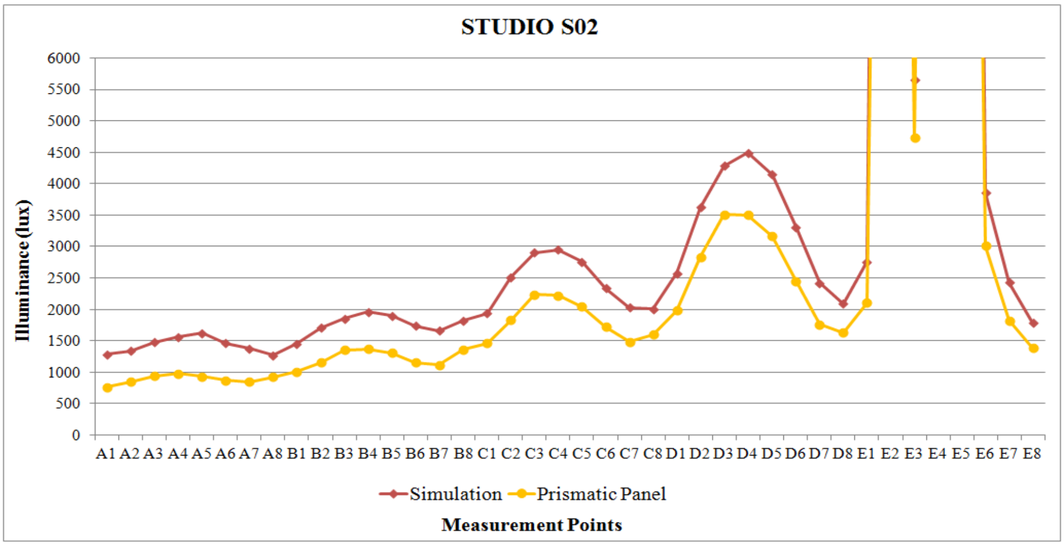


(a)

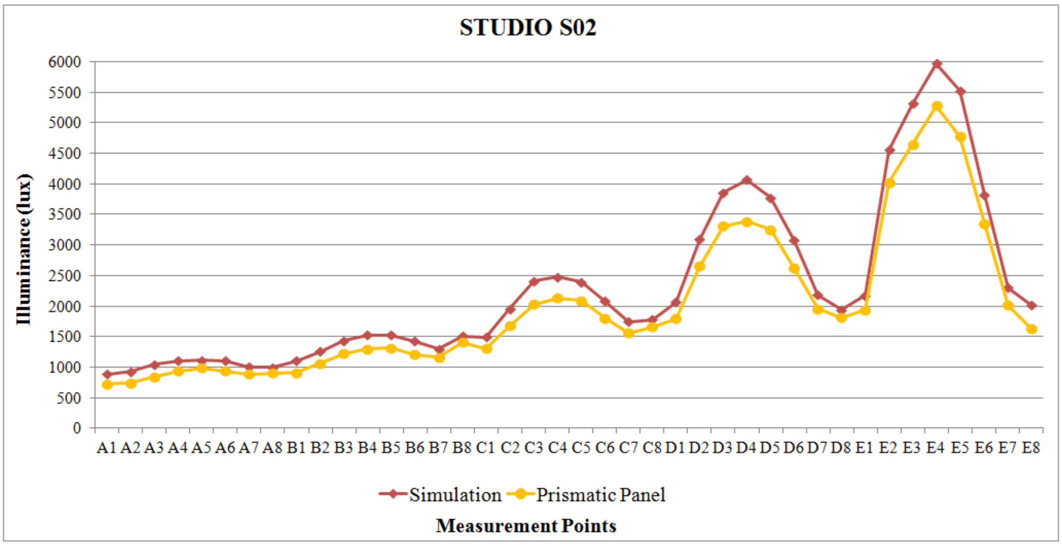


(b)

Figure D.3. Distribution of daylight illuminance for S01 with PP on (a) May 4th and (b) June 21st at 16:10

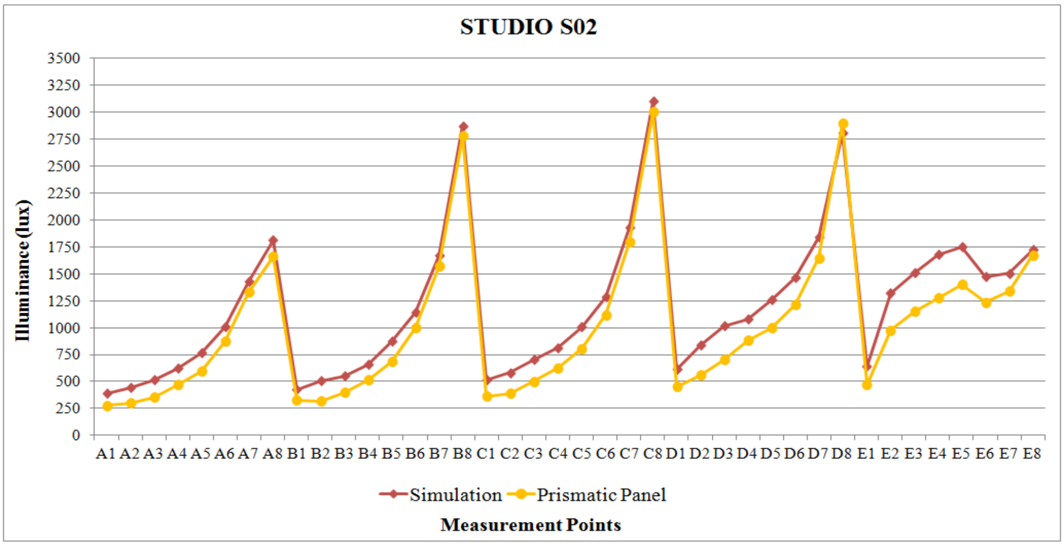


(a)

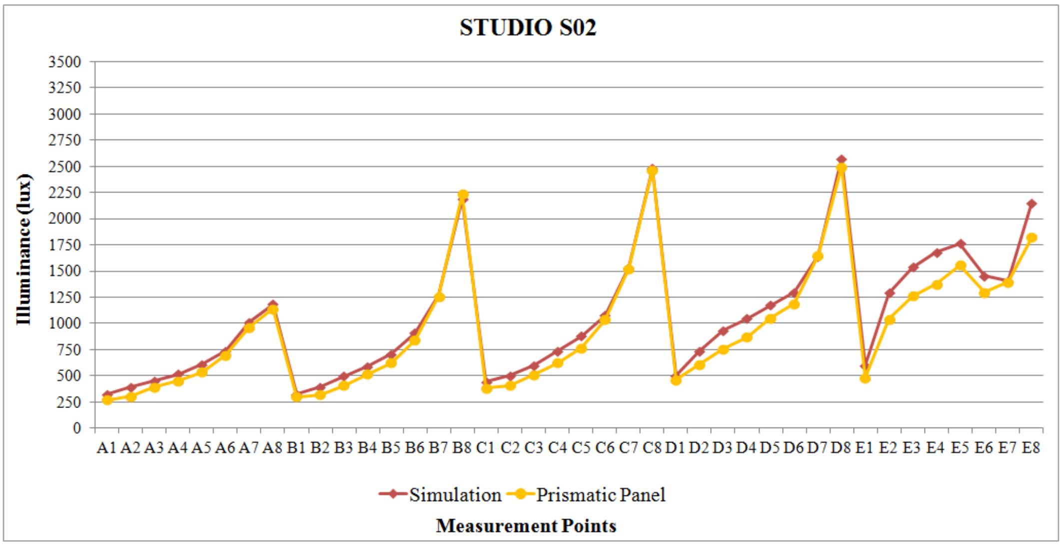


(b)

Figure D.4. Distribution of daylight illuminance for S02 with PP on (a) May 4th and (b) June 21st at 9:25

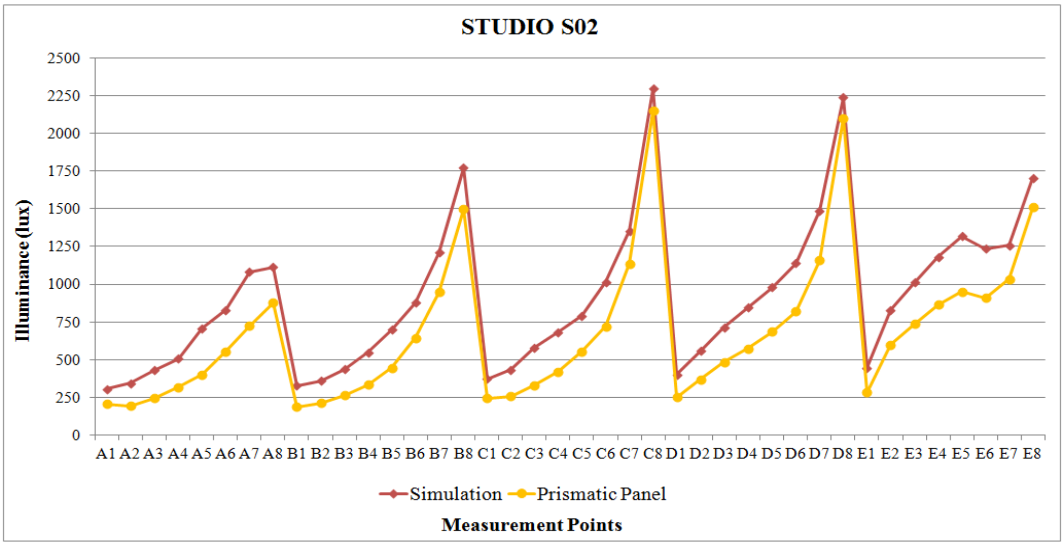


(a)

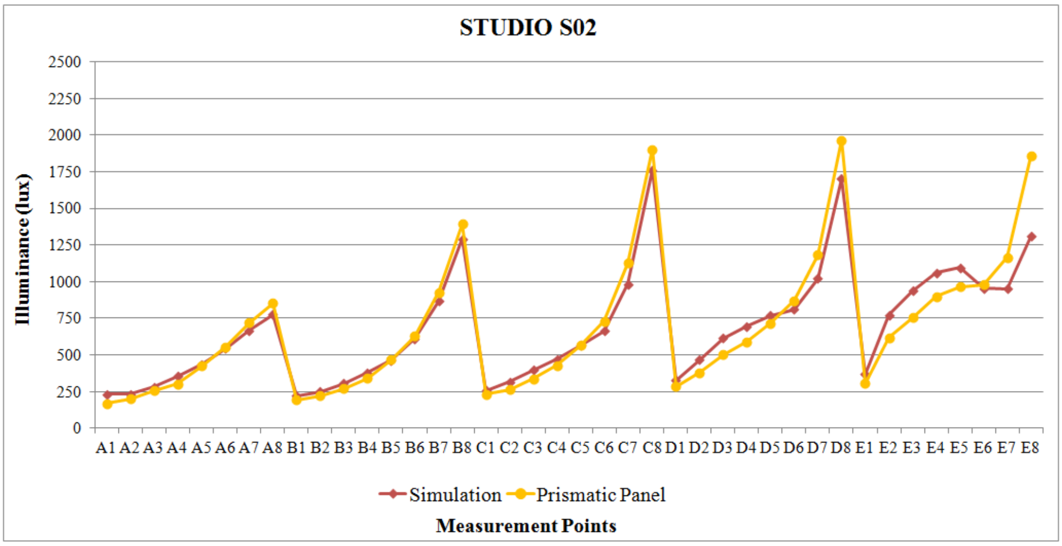


(b)

Figure D.5. Distribution of daylight illuminance for S02 with PP on (a) May 4th and (b) June 21st at 13:00

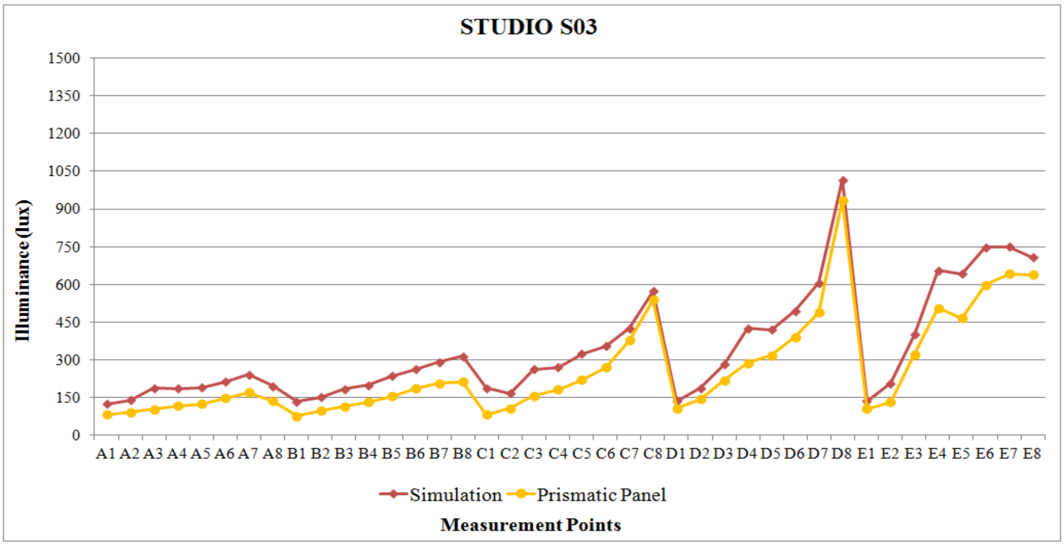


(a)

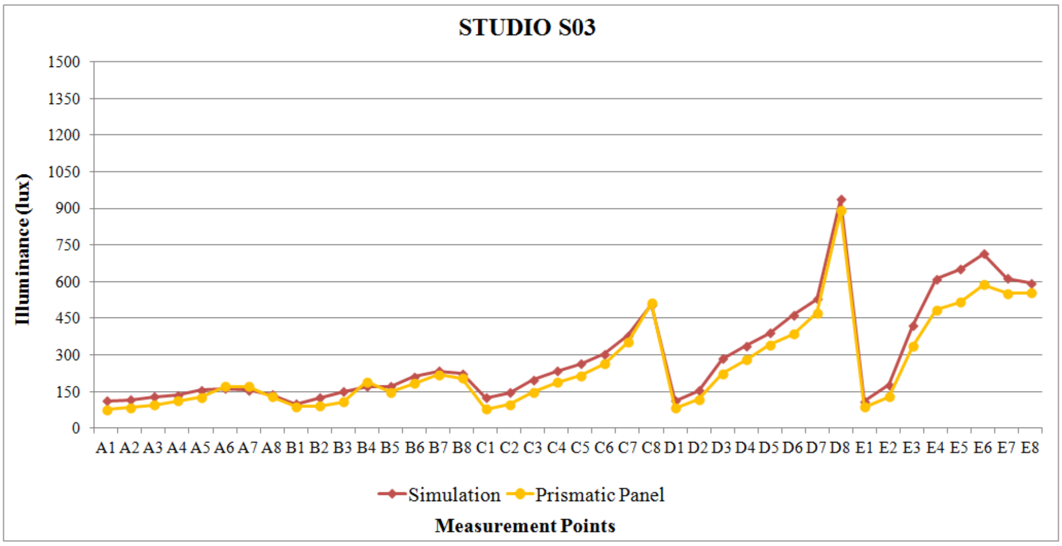


(b)

Figure D.6. Distribution of daylight illuminance for S02 with PP on (a) May 4th and (b) June 21st at 16:25

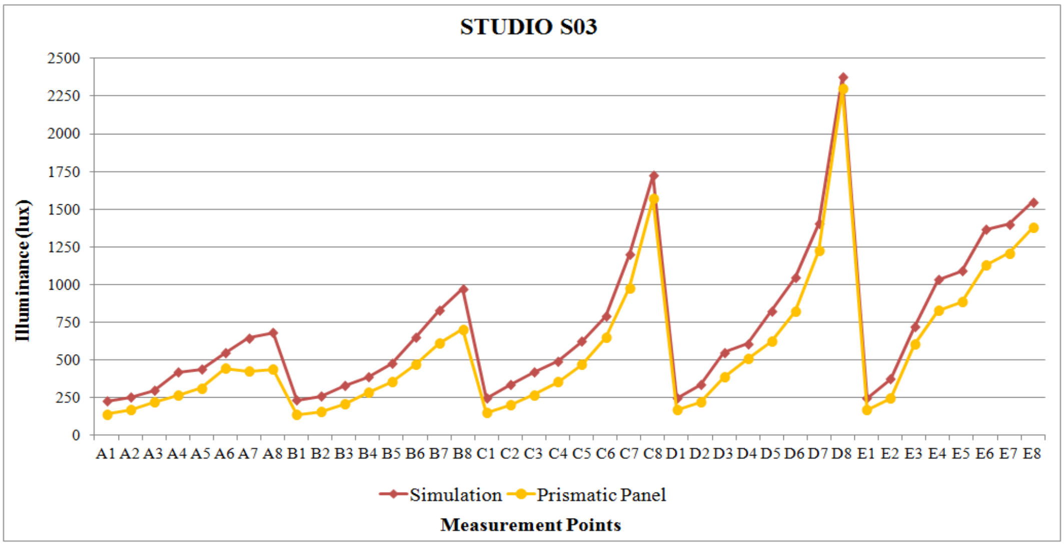


(a)

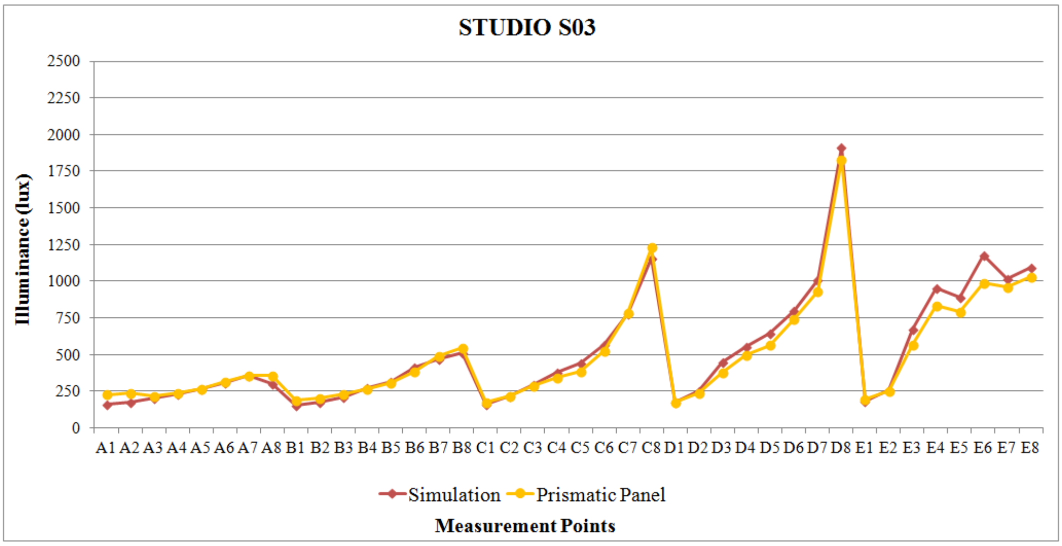


(b)

Figure D.7. Distribution of daylight illuminance for S03 with PP on (a) May 4th and (b) June 21st at 9:45

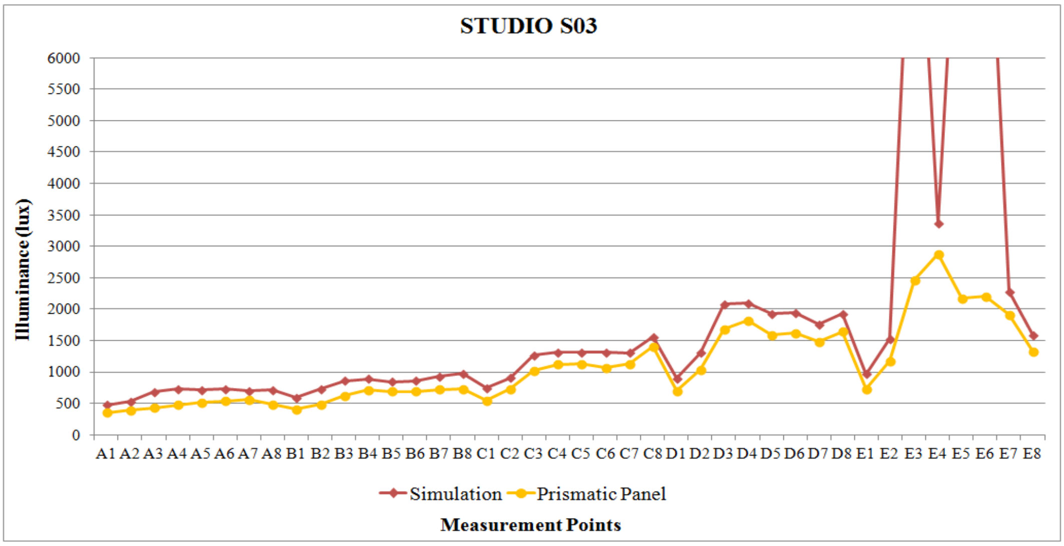


(a)

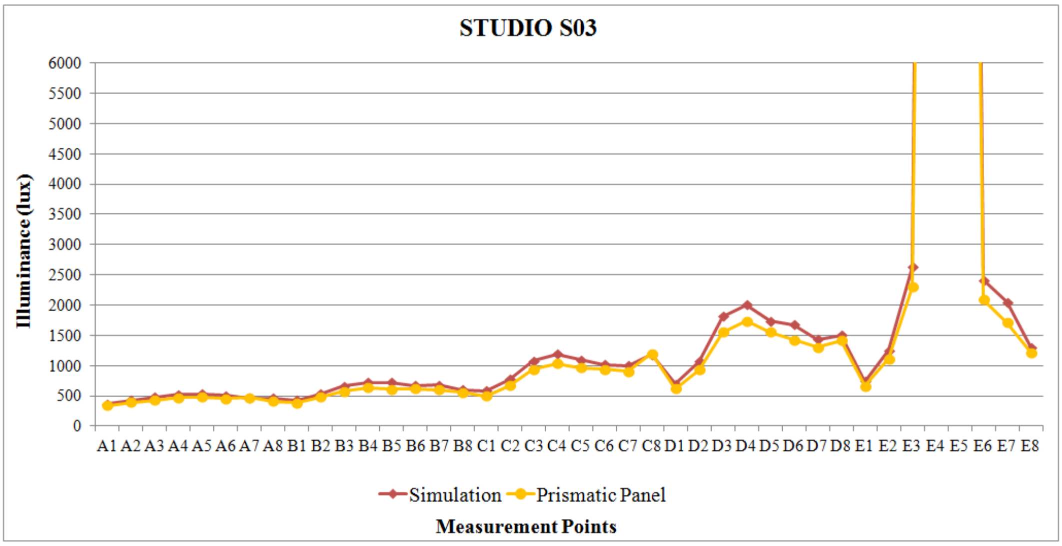


(b)

Figure D.8. Distribution of daylight illuminance for S03 with PP on (a) May 4th and (b) June 21st at 13:20

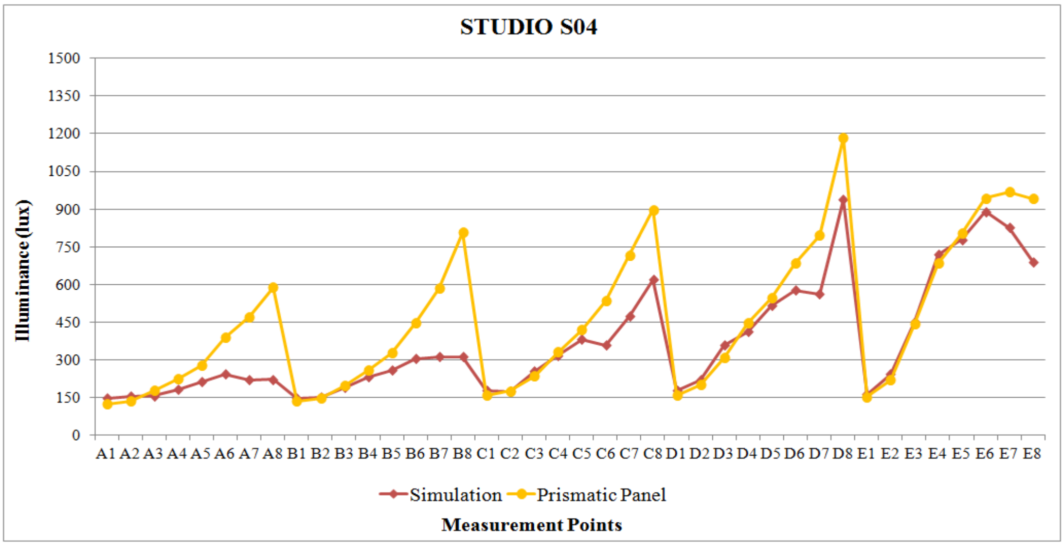


(a)

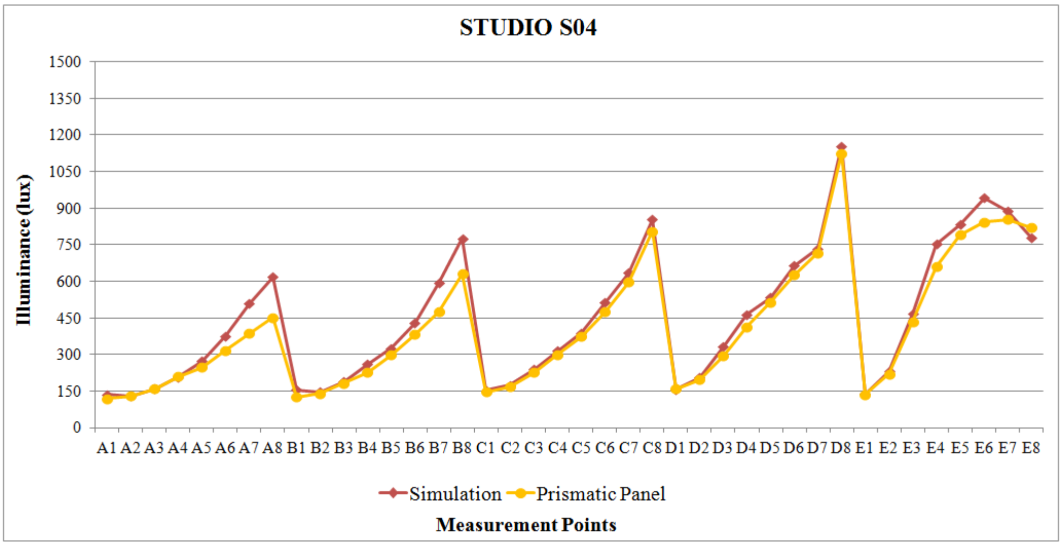


(b)

Figure D.9. Distribution of daylight illuminance for S03 with PP on (a) May 4th and (b) June 21st at 16:45

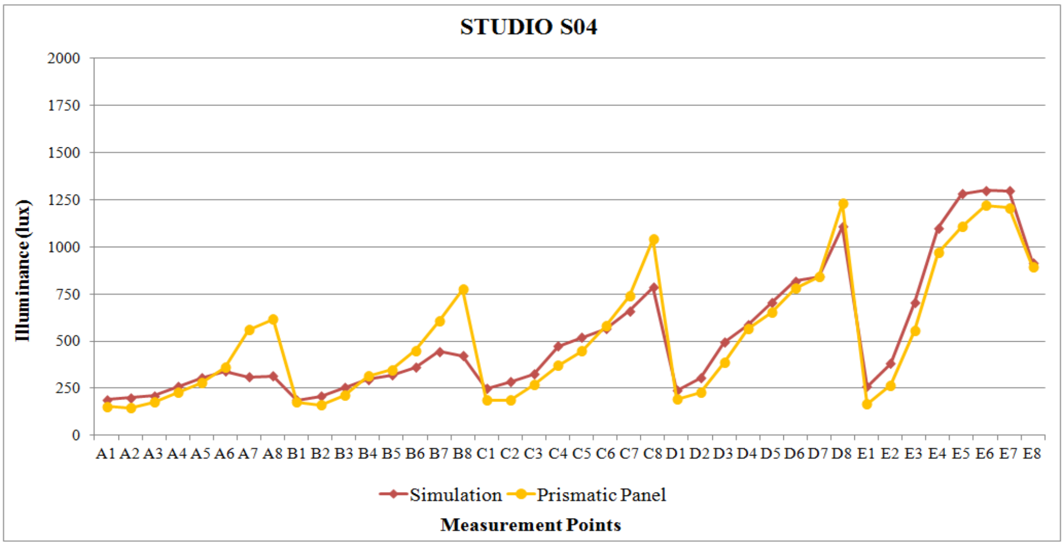


(a)

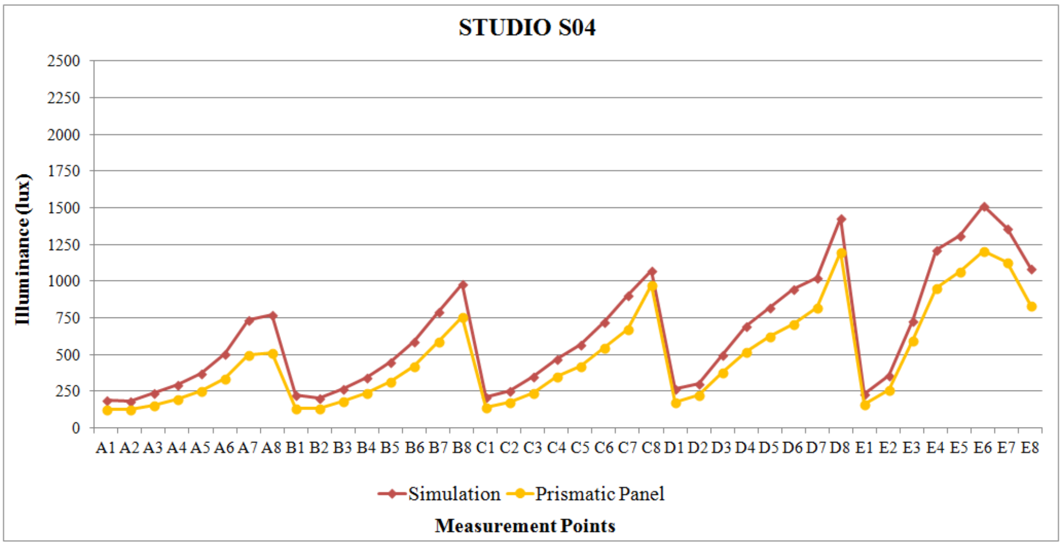


(b)

Figure D.10. Distribution of daylight illuminance for S04 with PP on (a) May 4th and (b) June 21st at 10:05

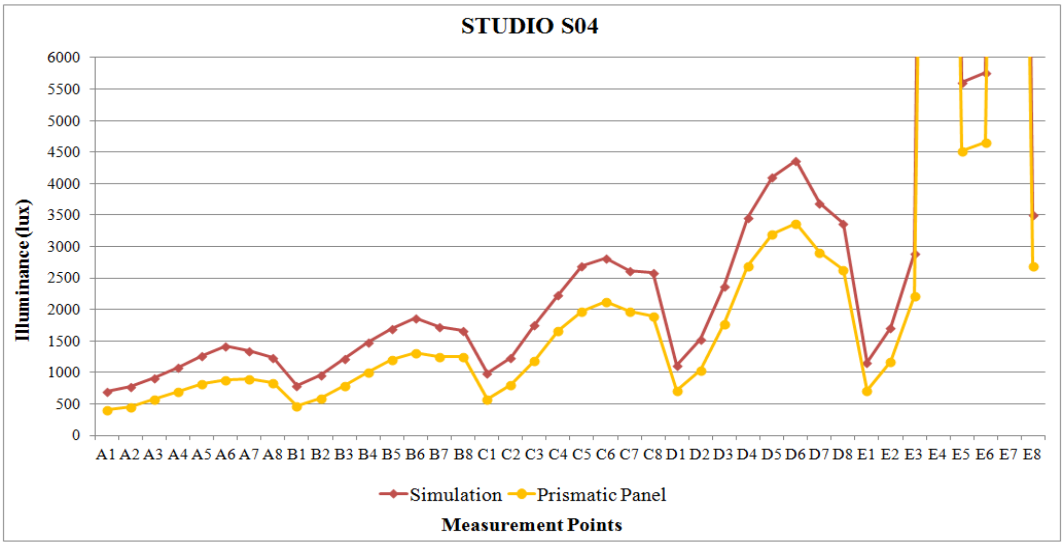


(a)

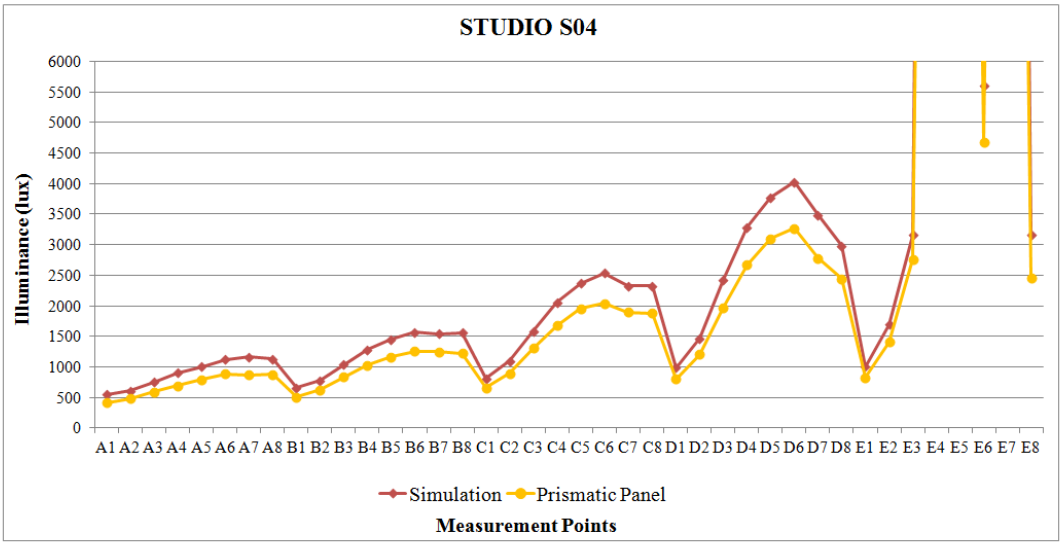


(b)

Figure D.11. Distribution of daylight illuminance for S04 with PP on (a) May 4th and (b) June 21st at 13:45



(a)

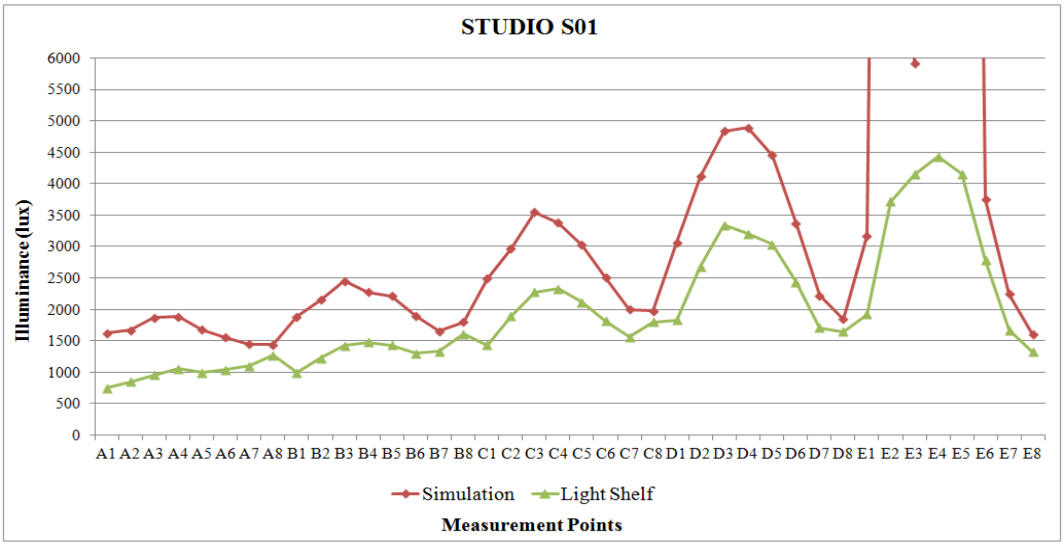


(b)

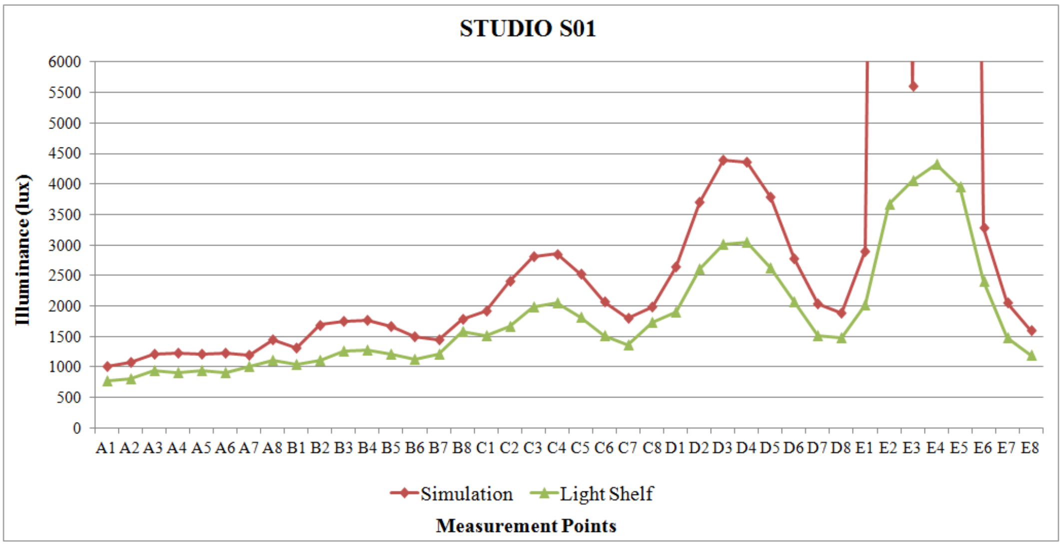
Figure D.12. Distribution of daylight illuminance for S04 with PP on (a) May 4th and (b) June 21st at 17:00

APPENDIX E

DISTRIBUTION OF DAYLIGHT ILLUMINANCE AFTER THE LIGHT SHELVES (LS) WERE APPLIED

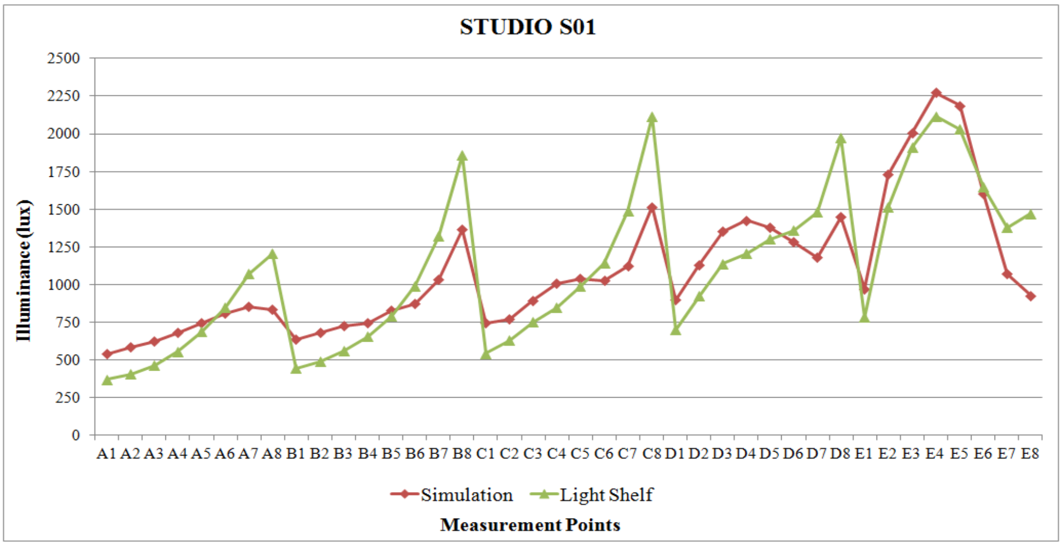


(a)

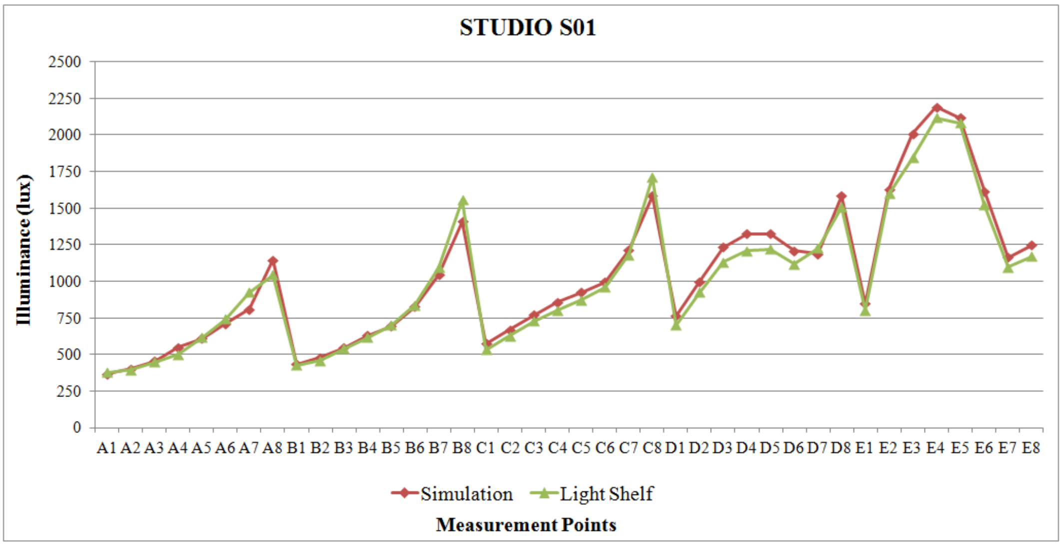


(b)

Figure E.1. Distribution of daylight illuminance for S01 with LS on (a) May 4th and (b) June 21st at 9:00

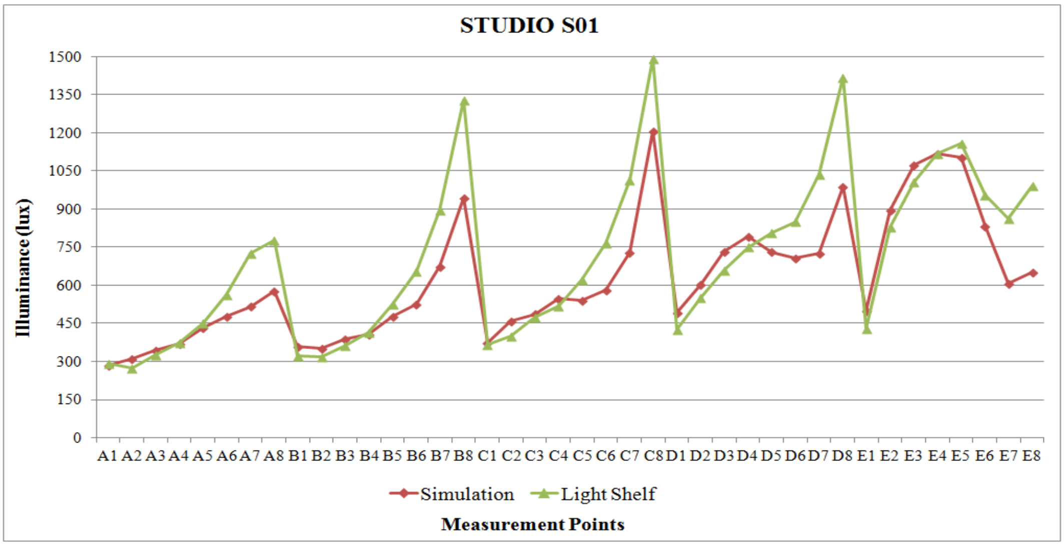


(a)

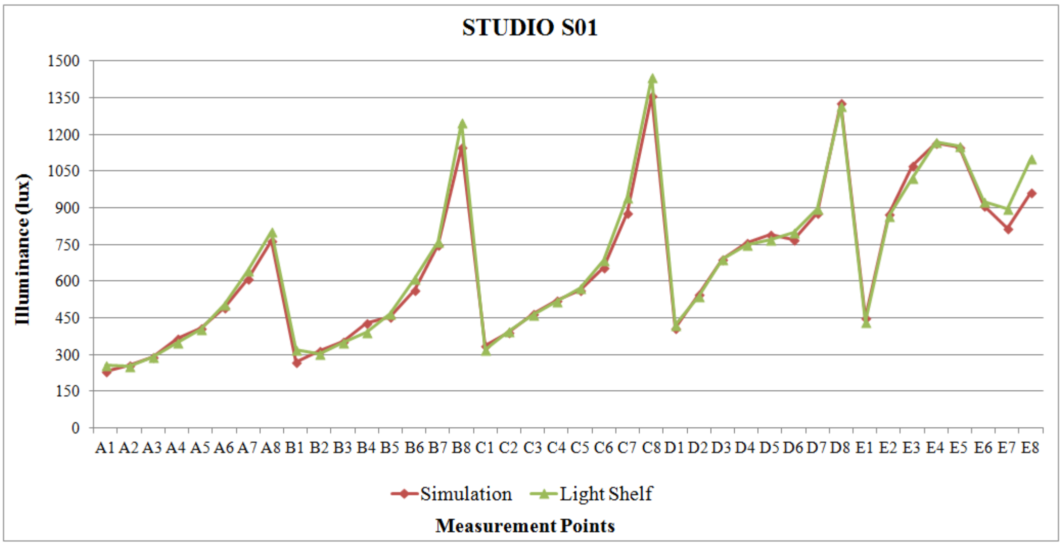


(b)

Figure E.2. Distribution of daylight illuminance for S01 with LS on (a) May 4th and (b) June 21st at 12:30

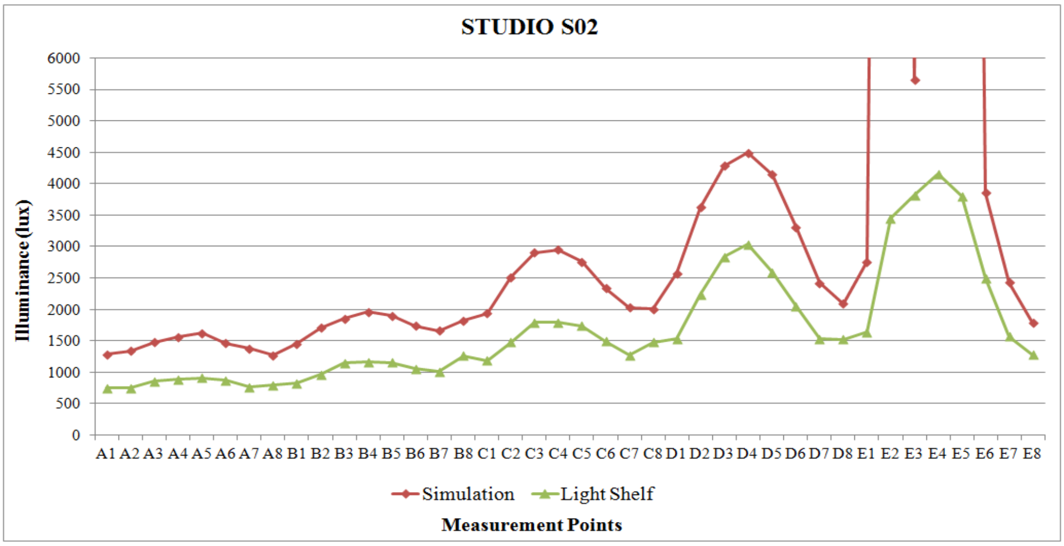


(a)

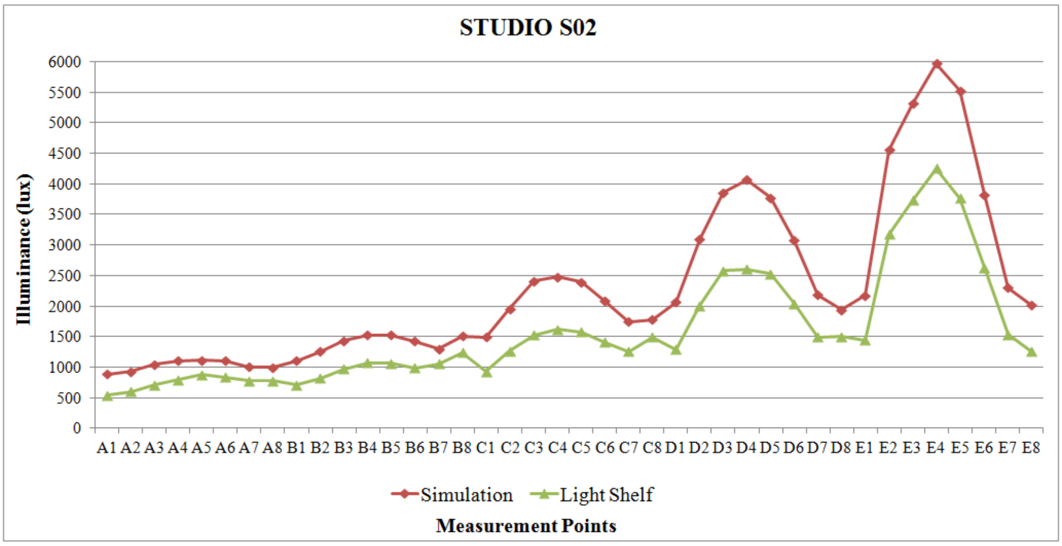


(b)

Figure E.3. Distribution of daylight illuminance for S01 with LS on (a) May 4th and (b) June 21st at 16:10

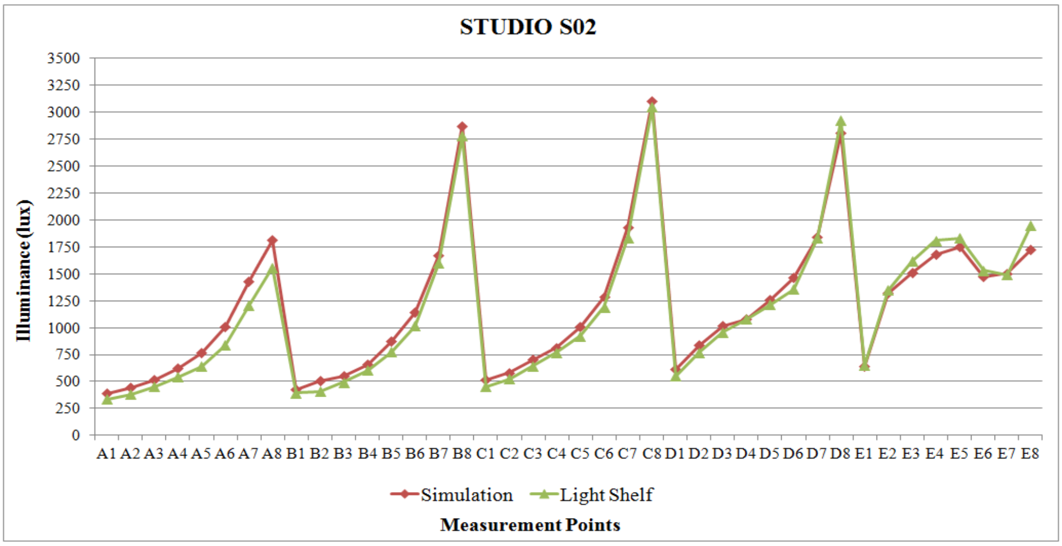


(a)

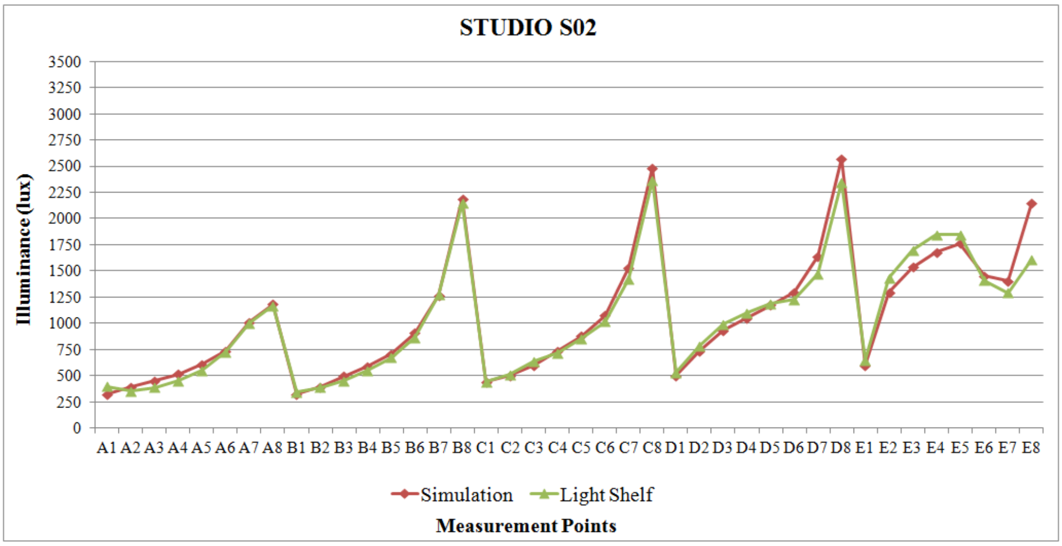


(b)

Figure E.4. Distribution of daylight illuminance for S02 with LS on (a) May 4th and (b) June 21st at 9:25

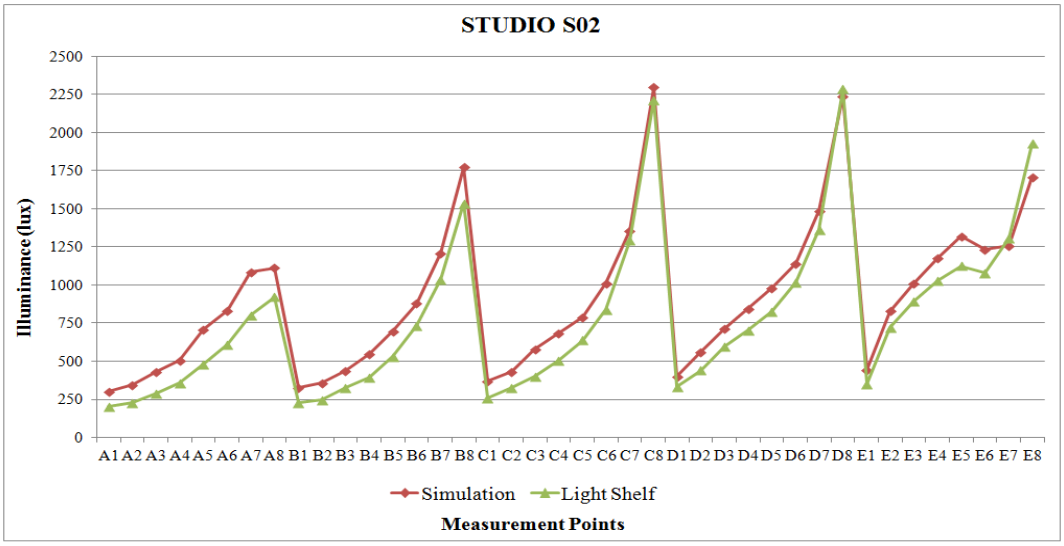


(a)

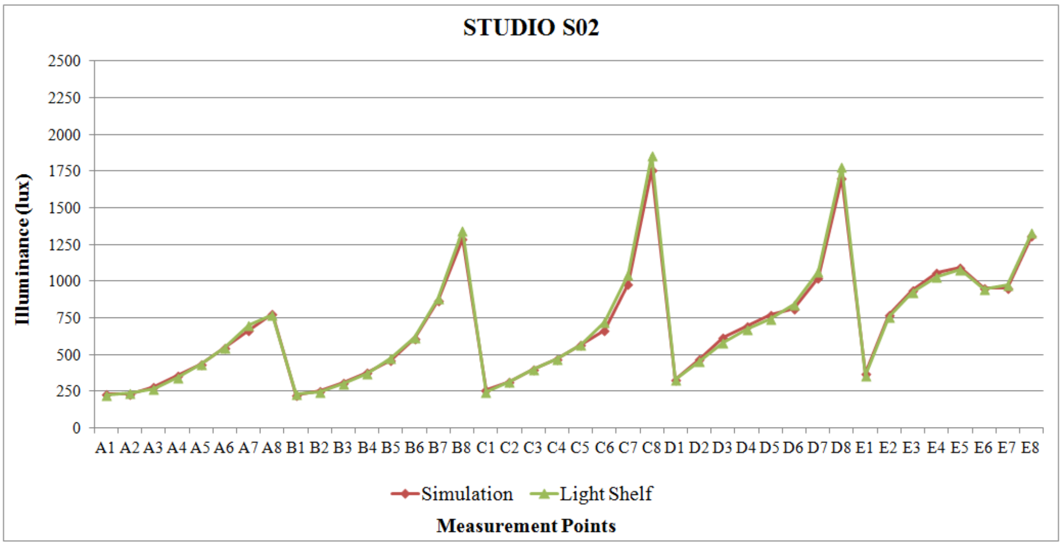


(b)

Figure E.5. Distribution of daylight illuminance for S02 with LS on (a) May 4th and (b) June 21st at 13:00

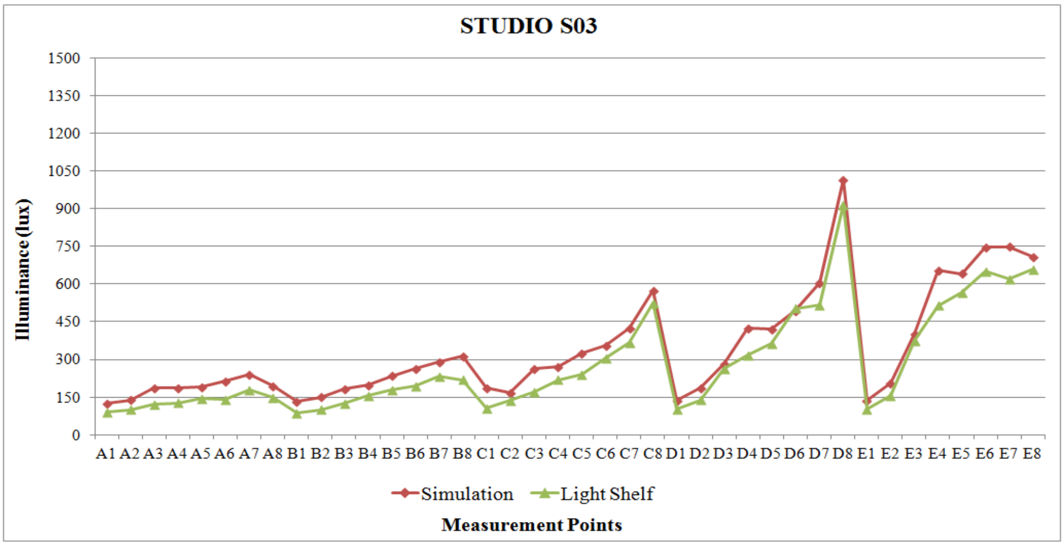


(a)

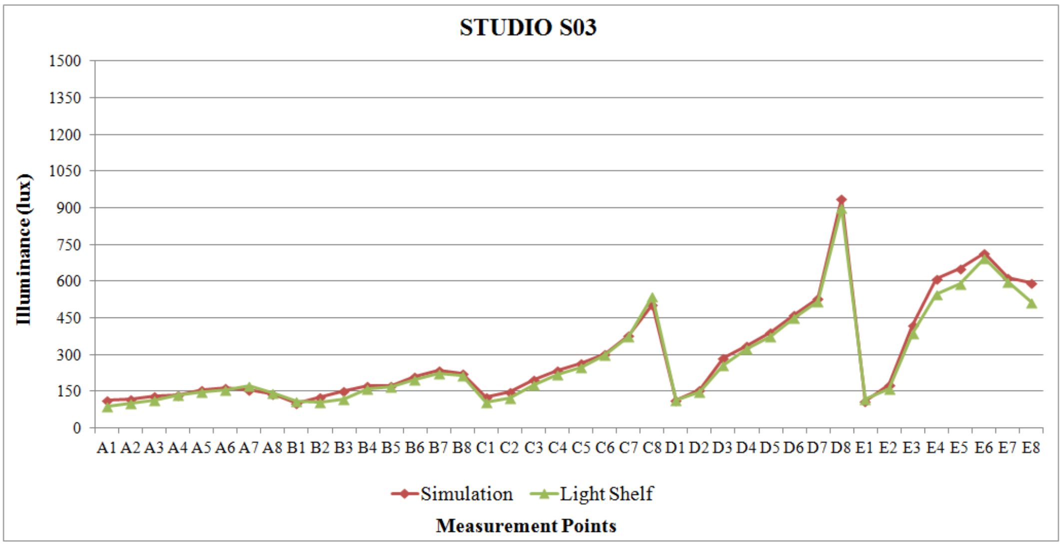


(b)

Figure E.6. Distribution of daylight illuminance for S02 with LS on (a) May 4th and (b) June 21st at 16:25

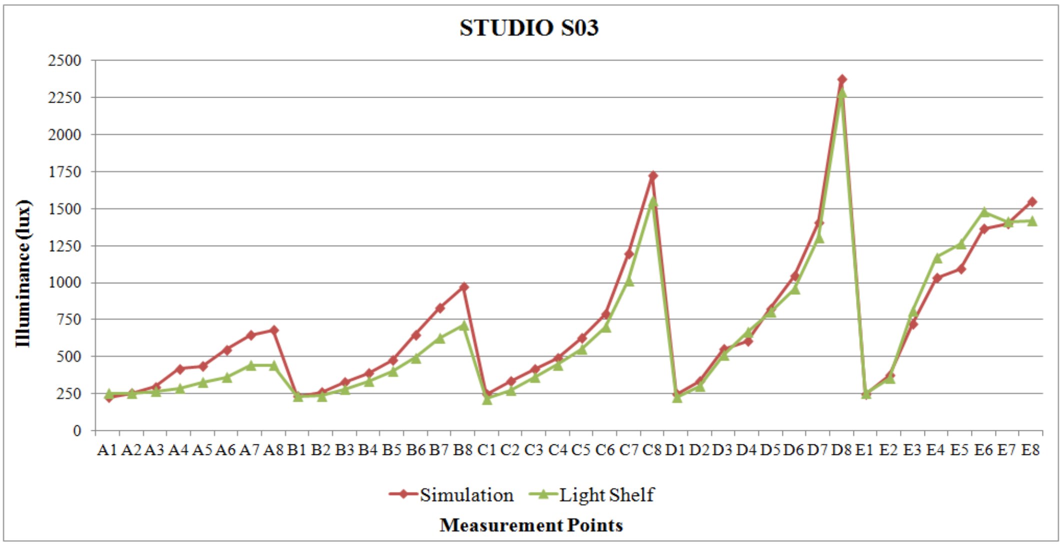


(a)

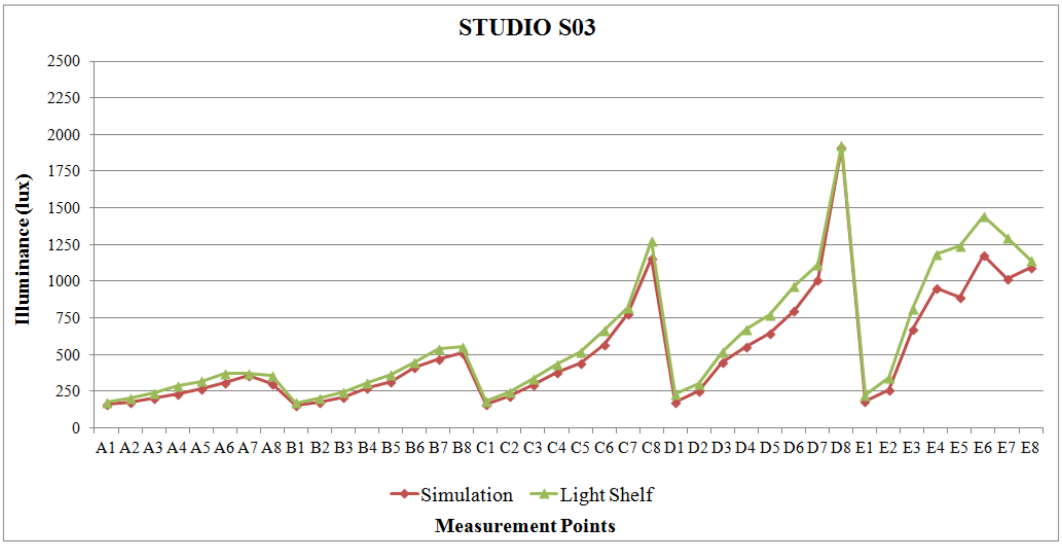


(b)

Figure E.7. Distribution of daylight illuminance for S03 with LS on (a) May 4th and (b) June 21st at 9:45

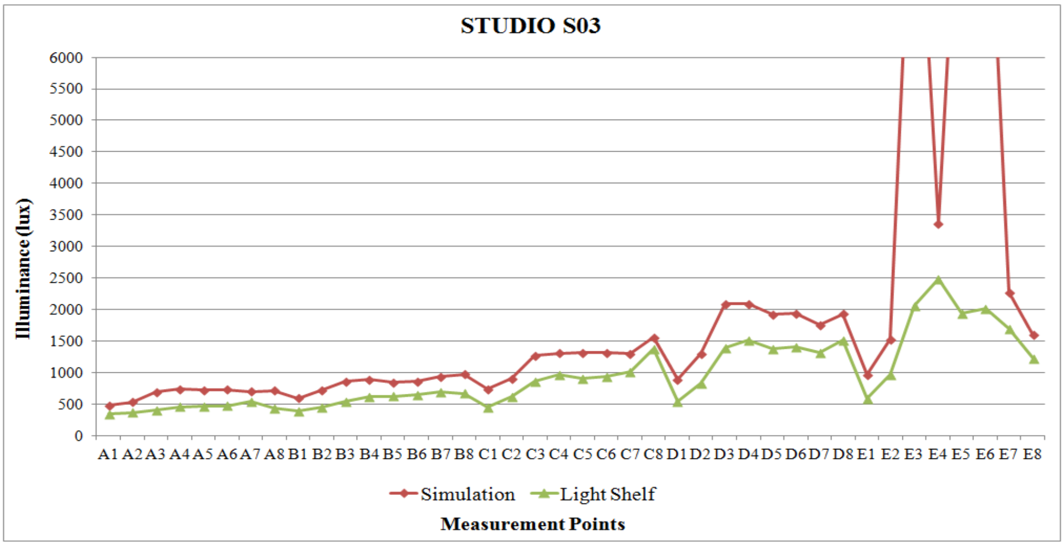


(a)

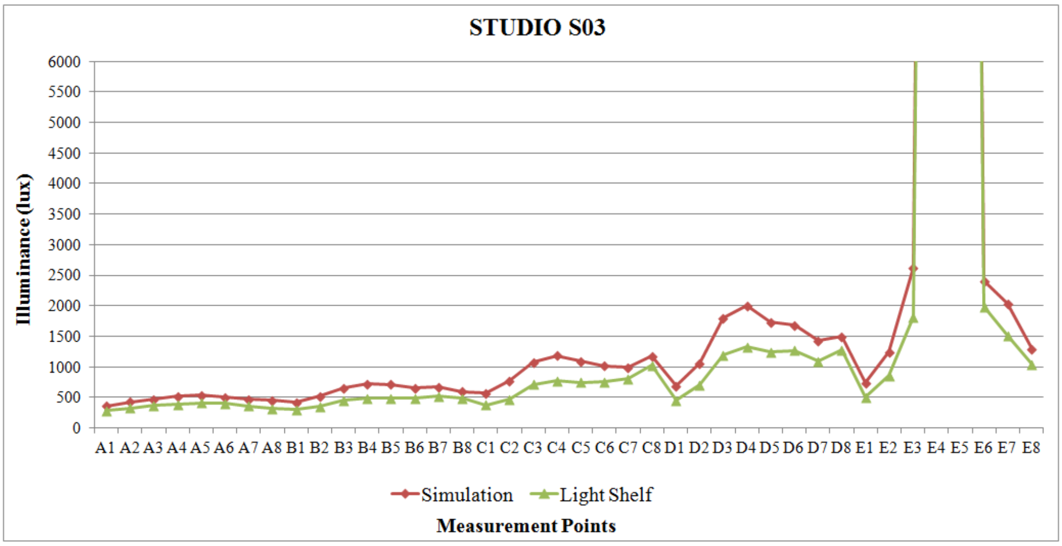


(b)

Figure E.8. Distribution of daylight illuminance for S03 with LS on (a) May 4th and (b) June 21st at 13:20

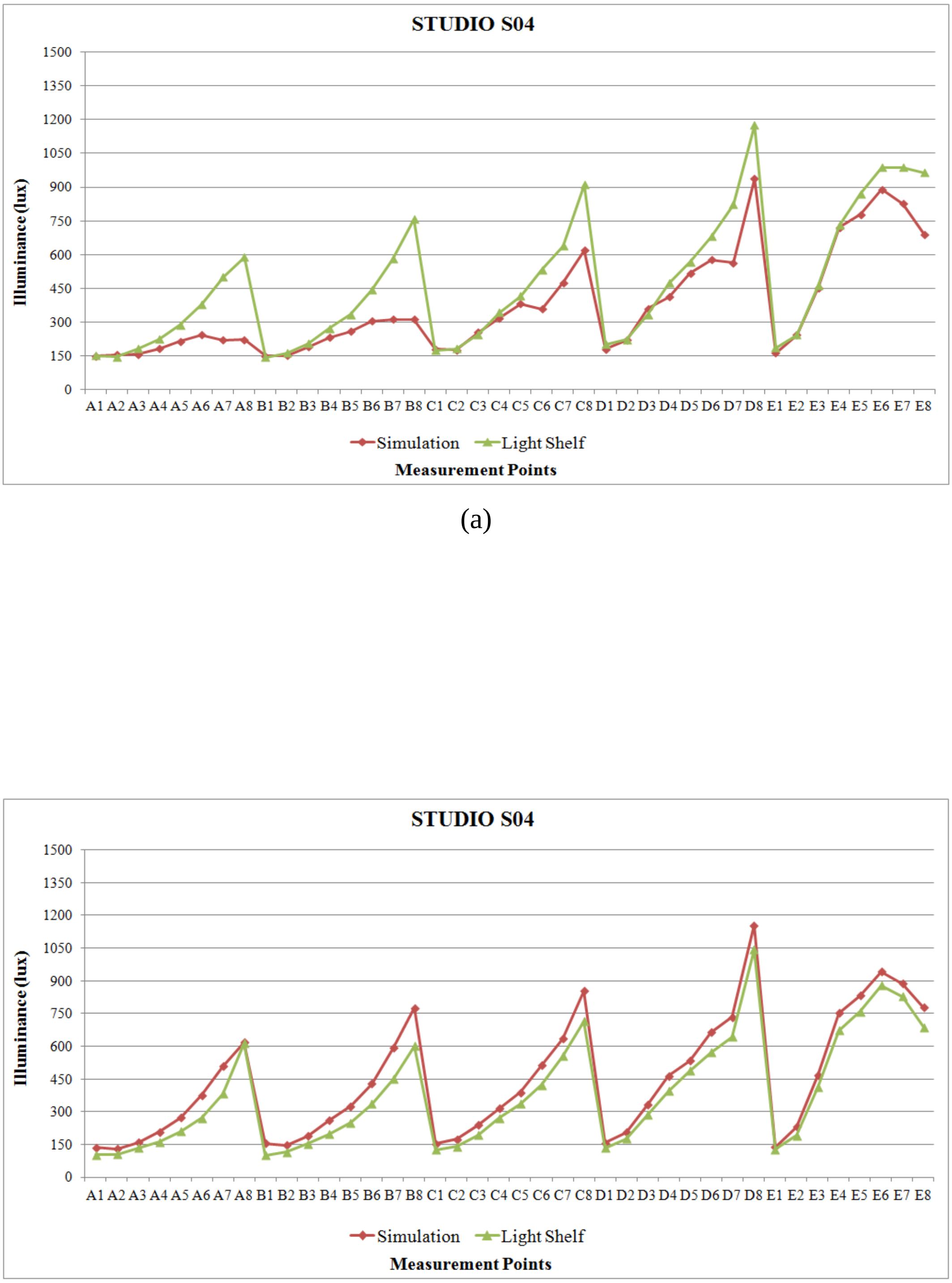


(a)



(b)

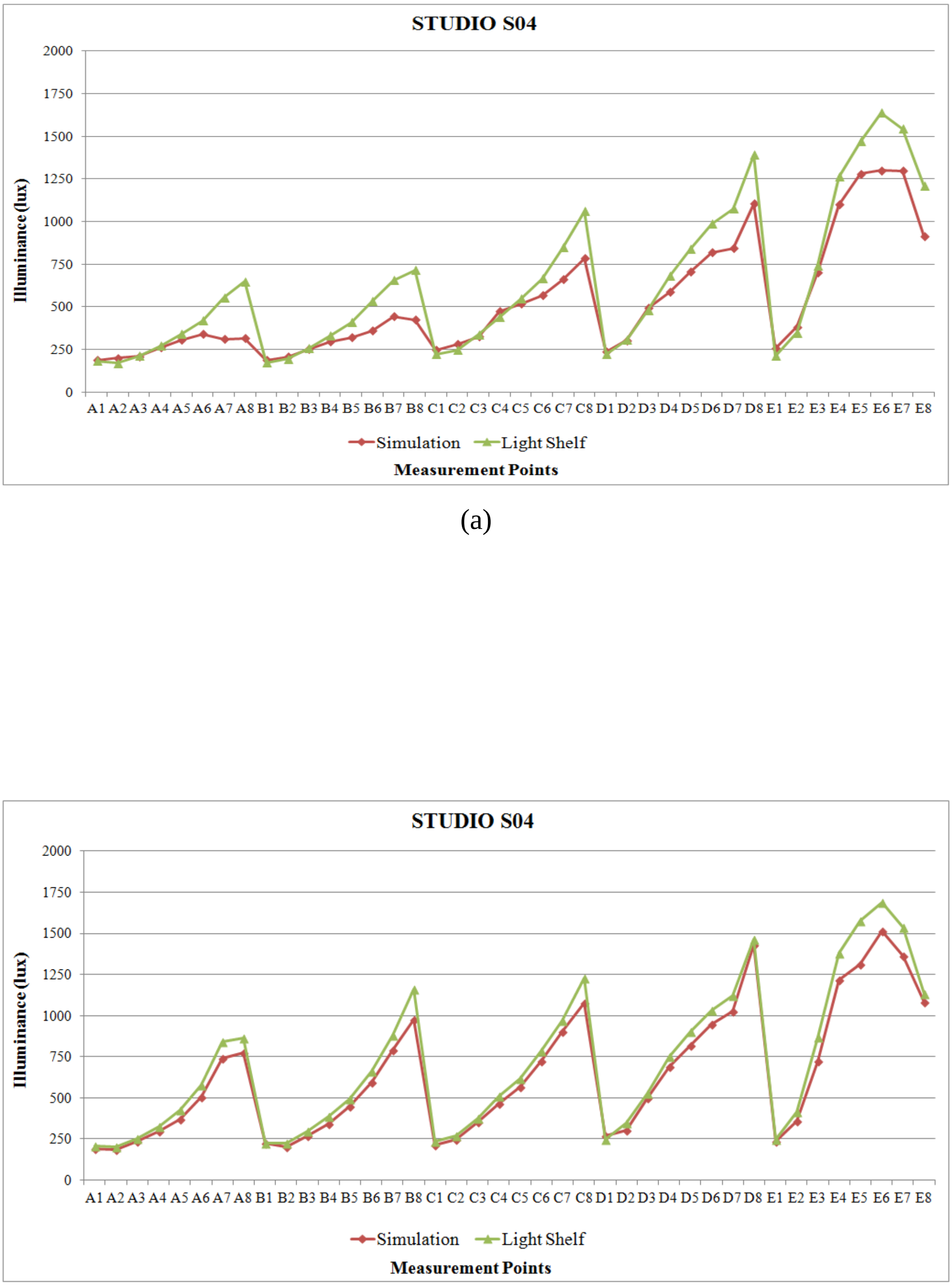
Figure E.9. Distribution of daylight illuminance for S03 with LS on (a) May 4th and (b) June 21st at 16:45



(a)

(b)

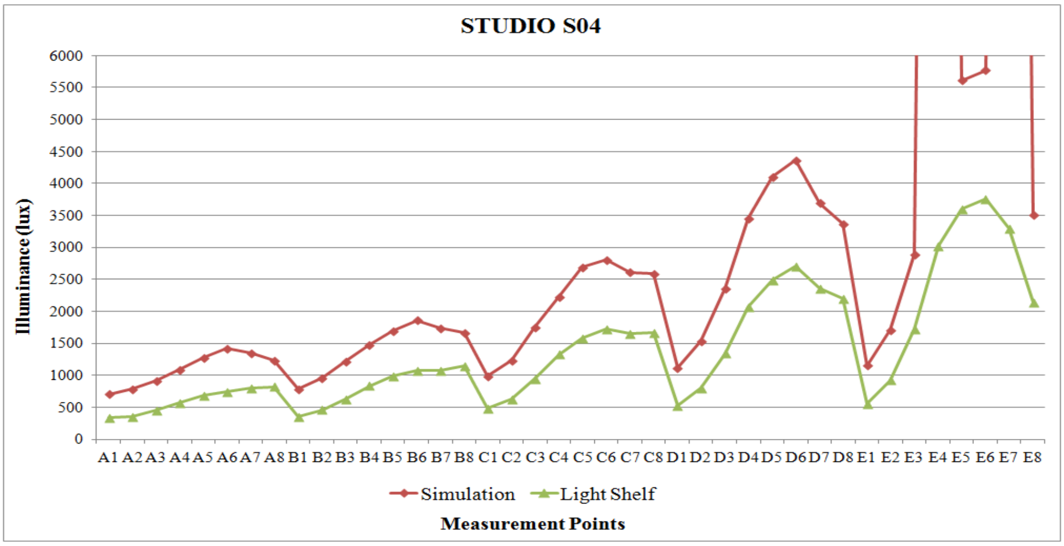
Figure E.10. Distribution of daylight illuminance for S04 with LS on (a) May 4th and (b) June 21st at 10:05



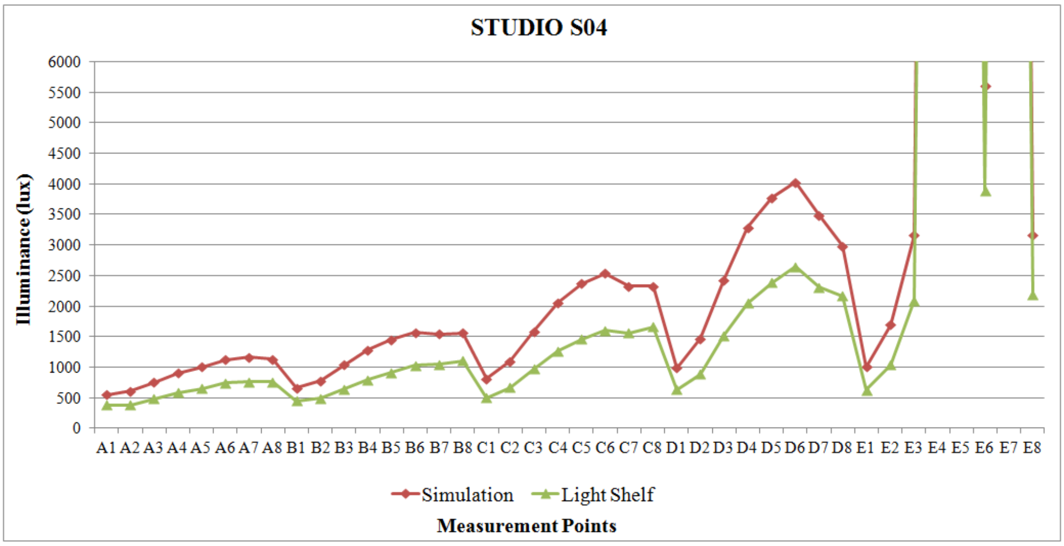
(a)

(b)

Figure E.11. Distribution of daylight illuminance for S04 with LS on (a) May 4th and (b) June 21st at 13:45



(a)



(b)

Figure E.12. Distribution of daylight illuminance for S04 with LS on (a) May 4th and (b) June 21st at 17:00