SIMULTANEOUS IMPROVEMENT IN VISUAL AND ACOUSTIC PERFORMANCE BY MODIFYING COMMON DESIGN COMPONENTS IN LECTURE HALLS

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ABSTRACT

SIMULTANEOUS IMPROVEMENT IN VISUAL AND ACOUSTIC PERFORMANCE BY MODIFYING COMMON DESIGN COMPONENTS IN LECTURE HALLS

Providing indoor comfort conditions at optimum level in educational buildings increases the concentration, the desire for learning and occupants' performance. The learning environment's appeal for students and teachers are mostly derived from their visual and aural sensations. So, properly-designed lighting and acoustic conditions have become an important concern. Daylighting is a component of energy saving strategy. It provides visual performance and comfort to support executing tasks, additionally to achieve aesthetic and occupants' appraisal of the physical environment. However, too high background noise and low intelligibility lead to disturbance in hearing and understanding. Such problems mainly cause the lack of concentration, which disturb occupants' satisfaction with the indoor acoustic environment. Both students and lecturers raise their voices to communicate better when there is poor reverberation and clarity. Yet, measures and precautions to improve one aspect are not enough. Designers/researchers can establish an integrated approach to deal with the aspects of daylighting and acoustics under common design criteria; since, one design alternative developed to improve sound distribution modifies the visual performance either in an effective way or in an unfavorable way. It is necessary to propose common design alternatives, such as ceiling geometry, seating layout and material combination to conclude simultaneous enhancement in visual and acoustic performance. To achieve that, this thesis presents analyses of DIALux and ODEON models of a lecture hall proposing design component choices for ceiling geometry, seating layout, and material combinations. Simulation findings direct out attention to how to design a lecture hall in an integrated approach.

ÖZET

AMFİLERDE ORTAK TASARIM BİLEŞENLERİNİN DEĞİŞTİRİLMESİYLE GÖRSEL VE AKUSTİK PERFORMANSIN EŞ ZAMANLI OLARAK GELİŞTİRİLMESİ

Eğitim binalarında optimum düzeyde kapalı alan konfor koşulları sağlamak, konsantrasyonu, öğrenme arzusunu ve kullanıcıların performansını arttırır. Öğrenme ortamının öğrenciler ve öğretmenler için albenisi çoğunlukla görsel ve işitsel algılardan kaynaklanmaktadır. Böylece, iyi tasarlanmış aydınlatma ve akustik koşulları en çok endişe edilen konu haline gelmiştir. Doğal aydınlatma, enerji tasarrufu stratejisinin bir bileşenidir. İşlerin yürütülmesini desteklemek için görsel performans ve konfor verir; buna ek olarak estetik ve kullanıcılarının fiziksel çevresinin değerlenmesini sağlar. Bununla birlikte, çok yüksek seviyede arka plan gürültüsü ve yetersiz anlaşılırlık düzeyi, işitme ve anlama bozukluğuna neden olur. Bu tür sorunlar, konsantrasyon eksikliğine neden olmakta ve bu da iç mekânın akustik ortamıyla kullanıcılarının memnuniyetini bozmaktadır. Hem öğrenciler hem de öğretim görevlileri yetersiz yankılanma ve konuşma netliği olduğunda daha iyi iletişim kurmak için seslerini yükseltir. Bununla birlikte, bir yönü iyileştirmek için alınacak önlemler ve tedbirler yeterli değildir. Tasarımcılar / araştırmacılar ortak tasarım kriterleri altında doğal aydınlatma ve akustik yönleriyle başa çıkmak için entegre bir yaklaşım kurabilirler; çünkü ses dağılımını artırmak için geliştirilen bir tasarım alternatifi görsel performansı etkili bir şekilde ya da olumsuz bir şekilde değiştirir. Tavan geometrisi, oturma düzeni ve görsel ve akustik performansta eş zamanlı iyileştirme yapmak için malzeme kombinasyonu gibi ortak tasarım alternatiflerini önermek gerekir. Bunu başarmak için, bu tez, bir amfinin DIALux ve ODEON modellerinin analizlerini, tavan geometrisi, oturma düzeni ve malzeme kombinasyonları için tasarım bileşen seçimlerini sunmaktadır. Simülasyon sonuçları, bir amfinin entegre bir yaklaşımla nasıl tasarlanacağına dikkat çeker.

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CHAPTER 1

INTRODUCTION

In this chapter first, the theoretical frame work of the study is presented. Secondly, the arguments are explained in relation to similar previous studies. Following that, the objectives are mentioned as primary and secondary ones. Then, the procedure of the study is explained, and finally the contents of the study were briefly explained under the structure of the thesis.

1.1. Argument

The innovations related to the construction industry are increasing every year. Environmental quality of the interiors has become more effective on the people since they are spending at least 10-12 hours of the day at offices, schools, houses etc. Such studies emphasizing the indoor environment's effects on health, comfort and productivity are available in literature (Olesen, 2005). They mentioned that, well-designed interiors can both increase the visual performance and the ratio of concentration. When the optimum comfort conditions are satisfied, the motivation of learning increases at the educational places (Pereira & Raimondo, 2014). Nowadays the effects of the indoor environment on users have become a trending topic in the construction sector. The project details and interior designs are developed specifically focusing on users' needs.

Comfort conditions of buildings depend significantly on indoor environment elements such as ventilation, acoustics, lighting etc. An example study emphasized that, applying appropriate daylighting strategies to the buildings was an essential method to provide better visual performance indoor environment (Sarbu & Sebarchievici, 2013). The researchers predicted performance of such strategies with a computer model and searched for non-uniform distributions and unstandardized values which interrupted indoor environmental quality. Visual and acoustic performance criteria are analyzed according to their influence on human physiology. The results showed that, indoor conditions of spaces influence both comfort parameters in optimum values and health of occupants.

It is necessary to conduct similar studies about comfort conditions in educational buildings since they also have the high rates of potential to save energy. Daylighting is a component of energy saving strategies and determines mostly the visual performance in the indoor environment. Daylight quality greatly affects health, psychology, productivity and comfort of the occupants (Olesen, 2005; Parise, Martirano, & Di Ponio, 2013). As the active usage hours of educational buildings are high, it is possible to apply the various types of daylighting strategies to this kind of buildings to get benefit of daylighting in terms of these aspects (Brebbia, 2011). The strategies include both passive and active systems. For instance, shading device experiments provide a uniform distribution. Computer based models predict the illuminations and solar tracking systems detect the light comes to the sensors. Those applications are made to supply enough amount of light for interiors and helps to get comfortable environments. Visual performance increases students' mental concentration and motivates them to focus on the presentations. In addition, daylight makes people increase their visual response, performance and productivity (Meis, Nocke, Hofmann, & Becker, 2005).

Using daylight can be a crucial step in saving energy. Creating a comfortable space both visually and thermally is necessary to balance electric lighting while reducing energy demand (Yun & Kim, 2013). However, they have a more important role, which is its positive effect on human psychology (Parise, Martirano, & Di Ponio, 2013). A well designed indoors has influence on health, productivity and comfort of the users (CIBSE, 2014; Olesen, 2005). Light also provides mental and visual interaction necessary for regulating biological timing and physiological rhythm (CIBSE, 2002).

If visual performance caused by daylighting is one side of comfort conditions, acoustics is the other side. Acoustic performance in the learning environment is another design criterion, which focuses on the creation a comfortable audience area for the users. Uniform distribution of the acoustic parameters contribute to the focusing process of the listeners (students) and in this way it can improve the education and training by ensuring the physical environment (Blauert, 2005). The enhanced acoustic conditions in classrooms positively affect the students' interest and concentration to the lessons (Klatte& Hellbrück, 2010).

Problems which are related to acoustics mainly cause the lack of concentration. When hearing the voice, which comes from the source (lecturer) is definite and clear, all listeners can understand the words. Especially at the lecture halls, the problem that occurs frequently is when users are not satisfied with the indoor acoustic environment (Anderson, 2004). Though, uniform distribution of the acoustic parameters is easy and essential to apply to the lecture halls - that can be achieved by placing the source (lecturer) and receiver (students) at the appropriate seating layout and organizing their surroundings according to the wave of sound (Anderson, 2004). Further studies are carried on the differentiations of the seating layout and its effect on the acoustic parameters. The variations of the seating layout also essential for the different teaching scenarios at the lecture halls (Mealings Kiri T., 2014). This point of view is another way to develop their concentration, performance and productivity. These studies are to be developed by analyzing both visual and acoustic performance on the users since they affect the learning facilities. Both students and teacher raise their voices at poor acoustic conditions and the reverberation problems create lack of concentration. Similarly, lighting conditions affect students' visual ability since they spend their time mostly in classrooms.

To design high quality indoor spaces for educational buildings, it is essential to focus on the comfort conditions of the lecture halls in an integrated way (Barron, 2010). When improvement of the indoor environment by applying various daylight strategies and by balancing the acoustical conditions at every point of the space is considered together, the result can cause highly satisfied occupants and increase in their learning and work productivity.

There are such studies. For example, one study analyzed and discussed the performance of classrooms and the results of a series of investigations about thermal, visual, acoustic and ergonomic comfort. The researchers aimed to cover environmental comfort elements in an integrative way. They advised to achieve thermal, visual, acoustic optimizations. They selected each parameter and prepared comfort evaluations one by one. They conducted noise measurements at the selected classroom and compared them with NC (noise criterion curve) to determine the critical frequencies to be isolated from exterior surrounding. Then they determined the influencers on thermal comfort and got temperature measurements via HOBO data loggers, focusing on the effects of former classrooms, ceiling height and orientation of building. They also monitored daylighting conditions and distributions during a day. Then those values were compared with nominal standards. The results showed that those factors strongly depended on each other and a good project covered these elements with an integrative view for a healthy environment (Krüger & Zannin, 2004).

Another study compared the environmental and acoustic factors in occupied school classrooms, based on the acoustical improvement; however the lighting levels were predominantly below the recommended level required for demanding tasks (Mydlarz et al., 2013). It was expected to get values above satisfying levels when a design decision or a retrofitting application was considered. So, the emphasis could be on finding out one design idea/ or modification which combined and achieved the outcomes of visual and acoustic performance satisfactorily.

In the view of above limited number of studies, it was concluded that there are various types of daylight and acoustic strategies which can be applied in educational buildings, however, their quantified effects were limited and analyzed separately. One application was tested according to acoustical requirements; however, another application was analyzed regarding lighting levels. The impact of former design component was not tested regarding illumination. Such applications can be defined with main design components (such as room geometry, fenestration, ceiling, layout, surface covering materials, orientation etc.) which create a strategy to develop the conditions of an indoor environment. So, this thesis is focused on such selected design components which can cause improvement on both visual and acoustic performance; since there is a need for the combination of the two main indoor quality determiner, visual and acoustic performances. For example, during the process of considering an optimum surrounding for one daylight strategy, it is possible to develop the desired/necessary acoustical environment by the same modification. Yet, such studies are limited in this sense. The approach in this thesis covers to observe the simultaneous impacts of several design components in a case study, despite of the possibility of causing slight changes in quantified performance values.

1.2. Objectives

The purpose of this study is to analyze the existing visual and acoustic conditions of a lecture hall; and to test selected design components - namely, ceiling geometry, seating layout and materials - to simultaneously improve the daylight illuminance and luminance values in regard of visual performance, similarly, reverberation time and speech transmission index (STI) values in terms of acoustic performance. Since such selected design applications are tested to observe the simultaneous impacts, they are called here as common design components. The lecture hall facing Northeast and Northwest is located at İzmir Institute of Technology in the Faculty of Architecture. Measurements include horizontal daylight illuminance on task area, vertical illuminance and luminance on walls and whiteboard, and average T20 values for reverberation. Simulations are generated in DIALux and ODEON. Their output values are verified with the on-site measurements. Alternatives of ceiling geometry, seating layout and materials are proposed to reach optimum daylight performance requirements and satisfy acoustic performance.

The primary objectives are:

a) to evaluate the sample lecture hall’s current visual and acoustic conditions;
b) to determine design alternatives with proposed ceiling geometry, seating layout and materials which can jointly improve the daylight and acoustic performance regarding requirements in standards;
c) to analyze the impact of proposed common design components as mentioned above on visual and acoustic performance values;
d) to improve the visual and acoustical performance of a lecture hall with design modifications.

The secondary objectives are:

a) to indicate the importance of design components on the environmental conditions of a lecture hall;
b) to explain an integrated approach which is a concern in early design process,
c) to construct a bridge between certain issues of building physics and architectural design considerations;

1.3. Procedure

This study searches the relationship between acoustic and visual performance conditions. So, determining the basic parameters for acoustic and lighting is a concern in the process of this thesis. Once the parameters were determined, the design alternatives, namely ceiling geometry, seating layout and material combination were set up in simulation models to get the simultaneous improvements. The possible simultaneous achievements showed us the direct relation between lecture halls' physical qualities and the basic parameters.

At this point, several studies about room geometry and its inferences to the acoustic responses are the starting point of the research (Antonacci, 2012). Similar studies were carried on the visual performance change by the room geometry (Watts, 2013). However, the intersection of this kind of studies was not considerably prepared at the previous searches.

The material selection was another highly effective issue from physical qualities of the spaces that are directly related to the comfort conditions. For instance, one material that has a smooth surface is defined as reflective characterized surface at both acoustic and lighting material determination. That means the material selection and combination are also another common design alternative to develop them together (Citherlet & Hand, 2002).

Seating layout's variation and its effects on the visual and acoustic performance is another design component. The acoustic parameters may vary by the change of the positions (Mealings Kiri T., 2014). That is also a highly important issue for the glare problem at the visual comfort. Because the direction and position of the daylight can be harmful when it is directed on the user's vision area (Society of Light and, 2014).

Evaluations of the parameters effecting the visual and acoustic performance are carried on the case study. A lecture hall from, A112 İzmir Institute of Technology, Faculty of Architecture – A block was chosen for study in the variations. This lecture hall was designed but the material selection creates the glare problem both at morning and afternoon active usage hours. In addition, there is a speech intelligibility problem observed during the lessons. The uncomfortable conditions are one of the main reason that is decreasing the concentration to the lessons at this space.

The case study is a lecture hall for 100 students. The lecture hall has 134.1 m^2 floor area and a total four windows with the dimension of 220 cm x 130 cm, 230 cm x 130 cm, 180 cm x 200 cm and 80 cm x 200 cm. All the finishing surfaces are hard covering (painted plaster surface, wood and marble) and there is no curtain usage at the lecture hall.

This space's existing conditions are measured according to the ISO – acoustic standards and reference lighting measurements. The acoustic parameter measurements are done by Brüel + Kjaer system for measurements and analyses of Building Acoustics (BKSV, 2017). In addition, the lighting parameters are measured by lux meter and luminance meter. The results are compared with the international reference studies' recommended values. The distribution of the parameters is also be a model on the selected simulation programs, ODEON 13 and DIALux. Both the field measurement and simulation results are used as the main material for the case study.

The validations of the simulation models are done by comparison with the field measurements. This brings out a more detailed data collection on existing materials properties and at this way, the simulation model become a sufficient base to study the next steps of the research.

Last analysis is carried on the determination of the simultaneous effects of the design variations. The design and simulation tools are used to compare the changes and their effect ratios. Simulation tools are helpful to find out whether the changes optimize the case study according to the international standards and norms or not.

The search is limited only with one lecture hall and rather than analyzing all the lecture halls, one is selected to analyze in depth. The material combinations are to be derived, however most common ones are selected to see the results. The active usage hours of the lecture hall decrease the measurement timing options. Next, this subject is improved further by analyzing the impact noises and mechanical systems effects to the lecture hall. When the insulation materials at the walls, floor and ceiling is studied about background noise transmission, the search can be done also the simultaneous effect of the thermal comfort conditions.

The importance of this study is contributing the architectural design process at the educational buildings in terms of improvement in acoustic and visual performances by proposing design components.

To achieve this, there main design decisions, the form of the ceiling, layout of the seating arrangement and the material selection of the surfaces are examined according to the daylight strategies and acoustic uniformity conditions.

1.4. Structure

In the first chapter, environmental effect of visual and acoustic design issues and their necessity of providing optimum conditions are covered first ad following that the primary and secondary objectives of this thesis are introduced. Recent studies about lighting and acoustic design of the educational spaces are presented and the importance of the study is emphasized.

In the second chapter named “Literature Survey”, daylight and acoustic performance standards are researched and compared. Main comfort parameters are defined as achieving standard values on lighting; including illuminance, luminance and uniformity, on acoustic; reverberation time, speech transmission index and clarity respectively.

The third chapter, “Procedure for the Case Study at Iztech” consists field measurements were completed at the selected lecture hall from Izmir Institute of Technology. Lighting and acoustic models of existing conditions are prepared and validated according to the relative error and coefficient of determination values.

In the fourth chapter, “Proposing Design Components” presents the common components’ literature sources and application strategies on lecture hall in section and 3Dmodels.

The fifth chapter, “Results” includes findings of existing conditions in detail. False color mapping, illumination on floor area and working area is evaluated. Application of design components and their distribution maps are presented and analyzed. Each design component is compared between each other.

In the sixth chapter, design components and their effects are briefly discussed. Best and useful combinations are considered regarding their advantages and disadvantages.

Last chapter, Conclusion includes the remarks of the thesis and comments on further studies.

CHAPTER 2

LITERATURE SURVEY

2.1. Daylighting Design for Lecture Halls

A properly designed and adapted daylight design system has a positive effect on a school than any other design strategies. Seeing the impact of on human perception is the most essential part of the daylighting configuration. Regardless the productivity and support advantages, a well-designed daylighting in a school makes the healthier indoor environment and increases participation (Leslie, 2004).

2.1.1. Strategies, Standards and Design Issues

The school is the place where children and young adults stay at most of the day: a well-designed environment is essential for well-being and efficiency. In the design of educational buildings, providing a healthy interior environment is regularly not considered as a need. In existing school buildings, developed systems and energy saving solutions are frequently overlooked. (Rehva,2010).

Architects regularly use daylighting as one of styling components. Daylighting requires considering both main and specified parts of the objects. To achieve these, designers use well known daylight design strategies like defining the existing site daylight conditions, then considering options regarding the sun path. Following that determination, main living areas are to be placed depending on daylighting needs stated at guidelines. Whole this process is defined as the daylighting design, because it is a process to find the most useful and comfortable solution for the needs.

There are several standards and guidelines that are essential to be in accordance with.

- ISO- 8995:2002(E) Lighting of indoor work places

According to this standard, minimum illumination value for the lecture halls is 500 lux, UGR$_L$ value is 19 and R$_A$ value is 80. Remark for this places is lighting should be controllable (ISO-CIE, 2002).

- EN 12464-1: 2011 - Light and lighting - Lighting of work places - Part 1: Indoor work places

According to this standard, classroom and application room's min illuminance value is 300 lux, UGRL value is 19, U0 is 0.6 and Ra is 80. It is required to provide a controllable lighting installation. Auditorium and amphitheaters' min illumination is 500 lux and UGRL 19, U0 0.6 Ra 80, respectively. Lighting should be controllable for various audio-visual needs. Black, green and white board rooms' min illumination is 500 lux, UGRL 19, U0 0.7 Ra, respectively. Specular reflectivity should be prevented. The lighting should be suitable for vertical illumination of the teacher at the appropriate angle (TSE, 2013).

- Chartered Institution of Building Services Engineers (CIBSE), Code for Lighting

According to this standard, min maintained illuminance for the lecture hall is 500 lux, limiting glare rating 19, minimum Color Rendering (Ra) is 80 and lighting should be controllable (Carbon Trust, 2014; CIBSE, 2002).

- Building Bulletin 87 Guidelines for environmental design in schools

The lighting maintained in the teaching facilities is to be at least 300 lux in the working plane. (*BB87 Guidelines for Environmental Design in Schools*, 2003)

- Building Bulletin 90 – Lighting Design for Schools

According to this standard, standard maintained illuminance for general teaching space is 300 lux, uniformity ratio 0.8 and limiting glare index is 19. For teaching spaces with close and detailed work is 500 lux, 0.8 and 19, respectively.(Loe, Watson, Rowlands, Mansfield, & Wilkins, 1999)

- Building Bulletin 95 - Designing schools for the future

According to the standard, recommended background lighting levels is 350 lux in general and for detailed work such as painting, 500 lux is the maximum level. Further needs are to be supplied by task lighting.(*BB95 Schools for the Future - Designs for Learning Communities*, 2002)

- BS 8206-2 2008 Code of Practice for daylighting.

According to the standard, daylight factor is required to be 2% for classrooms with one direction lighted, and brightness levels between 300-500 lux is recommended (Erlalelitepe, Aral, & Kazanasmaz, 2011).

- BREEAM 2011

According to this standard, Teaching, lecture and seminar spaces required daylight factor is 2%, and area to comply is 80 % (m^2). Other requirements are either min uniformity ratio 0.4 and min point daylight factor is 0.8 %, or achievement of a view of sky from working height and room depth criterion is satisfied. ("breeam.com Health and Wellbeing," 2011) Lighting control by user is required to be accessible easily for the lecturer to control glare.

Room depth criterion: (Room depth / room width) + Room depth / window head height from floor level < 2/ (1-average reflectance of surfaces)

While analyzing these standards and suggested values for lighting, it is understood that, the optimum illuminance level for educational areas is around 500 lux given in Table 2.1. This value is determined from the interpretation of the CIBSE, ISO-8995:2002, BS 8206 and EN 12464-1 standards. Required illumination level is to be achieved at the working zone which is 80 cm above the floor level. The illumination on black, green and white boards are to be 500 lux according to EN 12464-1:2011. Specular reflections are to be avoided and arrangement is to be suitable for vertical illumination of the teacher at the appropriate angle (TSE, 2013). Unified glare rating (UGR) is a value that means the chance in direct glare occurs from luminaries. When UGR is higher, the chance of glare is getting greater (TSE, 2013). Recommended unified glare rating is 19 in all those standards. Color rendering index is the light sources' ability to demonstrate the real colors of the object in comparison with daylight and Ra value is the lower limit of it. So, while adding artificial lighting, lamps are to be chosen from minimum 80 color rendering index value. Lighting design of educational areas are to be designed regarded those items.

Table 2.1. Recommended values at related lighting standards

Related Standard	**Space type**	**Illumination**	**UGR_L**	**U0**	**R_A**
ISO- 8995:2002(E)	Lecture Hall	Min 500 lux	19		80
EN 12464-1: 2011	Classroom and application room	Min 300 lux	19	0.6	80
EN 12464-1: 2011	Auditorium and amphitheater	Min 500 lux	19	0.7	
(CIBSE), Code for Lighting	Lecture hall	Min 500 lux	19		80
Building Bulletin 87	teaching facilities spaces	Min 300 lux			
Building Bulletin 90	general teaching space	Min 300 lux	19	0.8	
Building Bulletin 90	teaching spaces with close and detailed work	Min 500 lux	19	0.8	
Building Bulletin 95	teaching spaces with general and for detailed work	Min 350 lux Max 500 lux			
BS 8206-2 2008	Classrooms	300-500 lux			

The most important issue while being in accordance with these standards is creating a design that results in the providing of visual performance conditions remain in the range of certain parameters.

2.1.2. Visual Performance Parameters

Visual effects and performances of a space is a personal impression related to amount, quality and distribution of the light coming through the eye. Visual performance can be improved at clear sight conditions without any eye tiredness. A well-designed visual surrounding provides a pleasant environment for the users and helps to increase their well-being. However, too bright or too weak lighted surroundings causes tiredness and a reasonable cause for sight problems. Similarly, an inappropriate distribution of light disturbs the eye sensitivity. Poorly lighted places might influence eye fatigue and concentration weakness in a long period (Şener Yilmaz & Köknel Yener, 2013). So, visual performance is to be considered according to international standards and aimed to protect the eye health of the users.

Visual performance is examined by several parameters. These are illuminance, luminance, uniformity and reflectance. The dimensions of the surrounding environments' decoration objects and the observation time are also effective at the visual perception of interiors. The users' eye health, visual characteristics and age are also factors that affect the visual performance quality.

Well-designed interiors are planned according to few standards like Building Bulletins, EN 12464-1: 2011 and ISO- 8995:2002(E). These standards mainly cover the needs of the users. While Building Bulletin versions covers the idea of lighting education places in general, EN and ISO standards are much more concentrated on the types and purpose to use the educational spaces. CIBSE recommendations are also useful on designing the plans and interior placements. At this study, both the task area and lecturer's presentation conditions at the white board are considered as two main target conditions that is to be evaluated. So, the following elements are detected from the international standards which are affect the daylight environment at the lecture hall. These are:

- The illumination value at the task area (approximately 80 cm above the floor level)
- The distribution of the light falls to the task area (luminance ratio, absence of shades etc.)
- Orientation and exterior environment
- Light sources' color rendering index depend on the usage of the space
- Direct and indirect glare

2.1.2.1. Illuminance

Illuminance is the sum of luminous flux per unit area on a surface from all directions over it. Illuminance is the sign of brightness and it directly reflects the intensity of the light. Its unit is Lux which is lumens per square meter (lm/m^2) and illuminance is described with "E". It is possible to obtain different illuminance levels from different surface color and reflectance degrees. So, this is a way to solve the illumination level design issues. In a daylight design, illuminance is calculated with the amount of light penetrating from a glazing to interiors. That causes to select the glazing material and frame according to the desired lighting distribution. If illuminance distribution is uniformly arranged in a space and recommended illumination levels are achieved, and energy consumption rates can be decreased.

Standard illuminance values for the teaching facilities are given at Table 2.1. In general, there are few scenarios that are essential for explore. Recommended values for educational buildings are stated in relevant ISO an EN standards and changing between 300-500 lux according to the activity. The most common activity is oral communication between teacher and students, which requires 300 lux as standard illuminance. When the teacher writes on board, it requires 500 lux in vertical direction to be clearly seen by students. During the presentations, students need to look on the screen and the surrounding needs to be in 300/10 lux. All the writing, reading facilities about working students are to be made in 300 lux. In other circumstances like group activity works, students write on paper or check the notes on the board, that requires at least 50 lux (de Bruin-Hordijk & Ellie de Groot, 2010).

2.1.2.2. Luminance

Luminance is the luminous intensity emitted from a surface per unit area in a given direction. This surface might exist or nonexistent plane. The light leaving the surface can be because of reflection, transmission, and/or emission. The standard unit of luminance is candela per square meter (cd/m^2). Luminance is used to define and specify a light emitted or reflected from a flat, diffusive characterized surface. It shows how much power of light will be captured by observer's eye who looking to the selected surface from an angle. So, it is a sign to find out how much bright a surface is seen by observers.

While having tasks in the classroom, luminance values are also to be arranged according to the recommendations. Hordijk and Groot defined the luminance's maximum level as 3000 cd/m^2 at classrooms and they stated that the luminance contrast at the visual field must be lower than 1:30 (de Bruin-Hordijk & Ellie de Groot, 2010).

Luminance distribution IES standard values are given in Table 2.2. When luminance measurements are given with those ratios, they became an indication of the spaces uniform light distribution and they mean the visual performance and glare conditions.

Table 2.2. Recommended luminance distribution according to IESNA Lighting Handbook standards (Source:(Rea, 2000)

Conditions	Luminance ratios
Maximum variation between task and immediate surroundings	3:1
Maximum variation between task and remote darker surface (e.g. walls, ceiling, panorama)	10:1
Maximum variation in luminance between light sources and surroundings	20:1
Maximum contrast (except if decorative)	40.1

2.1.2.3. Uniformity

Uniformity in lighting design is the ratio between the minimum value of illuminance level (E_{min}) and the average illuminance level (E_{avg}) in the region to be analyzed. The result shows the lowest level.

The uniformity of the daylight factors on a work plane can be defined in two ways. First one is the ratio between DF_{min} / DF_{avg}, and the second one is the ratio between DF_{min} / DF_{max}. And this ratio between DF_{min} / DF_{avg} should at least be 0.4 or the minimum point daylight factor should be at least 0.8 % (*Zumtobel- The Lighting Handbook*, 2013)

Uniformity of lighting in space can be attractive depending on the capacity of the space and kind of exercises. This quality is related to the users' density, profile and their activities done at that space. A totally uniform space is generally undesirable, because excessively uniform lighting may bring about distortion and stress. Illuminance proportions of task area and its surrounding environment is not calculated in lighting models (EN12464-1 2002, CIBSE 1997, IESNA 2000). Most of the lighting calculations gives the illuminance levels but the reflected light is also essential to consider the whole calculation and results process. For lecture hall lighting, there are suggested luminance ratios between the task area and its surroundings (EN12464-1 2002, CIBSE 1997, IESNA 2000). Room surface reflectance degrees are a vital part of a lighting system and they influence both the total result and lighting energy consumptions. As seen in Table 2.3, uniformity values for daylighted interiors should be at following ratios.

Table 2.3. Illuminance Uniformity Standards (Source:(Boubekri, 1999)

Source Document	**Uniformity Ratio Across Task Area**
CIBSE Code for Interior Lighting	0.8 min / average
British Standards Institute BS 8206: Pt 1 (1985) Code of Practice for Artificial Lighting	0.7 min / max 0.8 min / average
Deutches Institut fur Normung DIN 5035 Innenraumbeleuctung mit kunstlichem licht (1979)	0.67 min / average
Standards Association of Australia. AS 1680 Code of Practice for Interior Lighting (1976)	0.67 min / average
Nederlandser Stichting vor Verlichtingskunde Aavbevelingen vor Binnenverlichting (1981)	0.67 min / max
CIE Guide on Interior Lighting (1986)	0.8 min / average

2.1.2.4. Reflectance

Light reflectance value (LRV), shortly reflectance, is the ratio between reflected flux and incident flux that comes to a reference surface as IESNA defined ("IES," 2017). Falling light on a surface is absorbed, transmitted or reflected from this surface at different amounts. The reflectance of a surface gives the ratio of light reflected from the selected surface. The reflectance values of different materials (Table 2.4) are both used at general lighting simulations to find out the light distributed to the space by reflecting and at determination of luminaire reflectors (Jeffries, 2008).

Table 2.4. Example materials and their light reflection qualities
(Source:(DIALux, 2016)

Material description	**Reflection degree (%)**	**Transparency (%)**	**Roughness (%)**	**Mirror effect (%)**
Wood flooring (fir wood-36)	59	0	10	0
Carpet floor covering (beige)	44	0	20	0
Carpet floor covering (dark grey)	18	0	20	0
Ceiling tiles (white)	70	0	50	0
Window glass, white plastic frame	10	90	0	100
Rough plaster (white)	50	0	50	0
Brick wall covering (red)	23	0	15	0

All surfaces and their materials have an optical quality. When light hits the materials' surface, changes occur in light distribution. Light comes through a surface may reflect, refract and absorbed at different percentages. Opaque materials partially reflect and absorb light. Transparent materials transmit considerable amount of light and partly absorb it. Reflection is the backward spreading of light that falls on the surface of materials. The reflection degree is the ratio between reflected light intensity and the intensity of the light coming to the surface of the material. Reflectivity is very high on metals with smooth surfaces and close to 100%. Light reflectance degree of a surface also depends on its color, roughness and material characteristics. So, while a partly rough surface example, a regular plaster surface reflects the light at 50%, it may reflect light by smoothing it and coloring it into white. Carpets chosen with dark colors may have 18% reflectance which is mostly enough to make a space in darkness. By this way, the selection of the materials and their surface qualities directly effects interior environmental lighting quality.

2.1.3. Daylight Simulation Tools

At the first step of daylighting design is to analyze the existing conditions. The site's annual solar latitude in terms of getting the sun light is examined and longitude values vary according to the building's orientation, which is also effective in terms of the ratio benefit from these rates. This data is detected in the development of design and in later stages and it is important to choose a suitable simulation program needs. So, at this section, three widely used daylighting simulation tools are overviewed.

The overview of these simulation tools builds on the case studies given at articles and characteristics given at their handbooks. The simulation tools are easier to use than solving equations or studying on scale models to understand the quality of design. They are practical, time saving and less money consuming ways to see the results of the design. Yet, using a simulation tool can be become useful only if its results are reliable.

Researchers that gather information about usability of simulation tools demonstrated that, when the user interface of a program is graphically understandable, simply navigated and easy to control the parameters, those programs become much popular(Attia, Beltrán, De Herde, & Hensen, 2009). Learning the general settings easily is another issue of choosing a program which is effective at beginning step. So, users prefer to choose programs when they have a simple but clear help menu, tutorial video and report sets or an online help process which can solve the unknown points in few seconds (Reinhart & Fitz, 2006). Those interactions become a self-teaching way for the designers and if a program supports that solutions, those ways become more effective than giving teaching courses in specific date and places. Their ability to apply the effects of sky conditions and surrounding elements' influences is a reason to use them before the construction stage. This is a reason for the program providers to update the libraries at each new standard and internationally accepted studies. In this way, the researchers may choose the relevant software and reach the latest information via them. Simulation tools are also a way to explore energy outputs of the design. Their performance strategies may include artificial lighting budget, maintenance and lamp lives as well as energy consumption charts. In this way, it is both essential to see the variations and evaluate options for the application. So, these simulation tools are explained briefly according to their performances, harmony with the real conditions, usability and correctness values.

2.1.3.1. Radiance

Radiance is a simulation tool that provides the analysis of lighting levels to predict the daylight distribution in determined conditions. It is used to determine visual quality, appearance and able to present most of lighting assumptions with color images, values and contour lines. It consists both simulated lighting options in various ways and rendering as well (Smith, 2006). The program incorporates geometry, libraries of materials, decorations, glazing, luminaires, time, specified day and sky conditions. Those input files make possible to create realistic 3D lighting models rapidly (Fritz & Mcneil, 2016). The objective is to give the designer an outline study that can also work with other well-known CAD programs and encourage them with the thought of productivity that comes by daylighting (Fig. 2.1). This program is one of the easy way to conduct daylighting techniques in building plan.

Radiance works with ray tracing method to produce whole lighting calculations. It uses Monte Carlo method to imply global illumination which is light falls to a sample surface or reference point at the modelled surrounding. The program leads the HDR imaging, at which the light levels are accepted as open ended values in literature rather than maximum integer fraction (G. G. Roy, 2000). It is possible to calculate spectral radiance, irradiance and glare index.

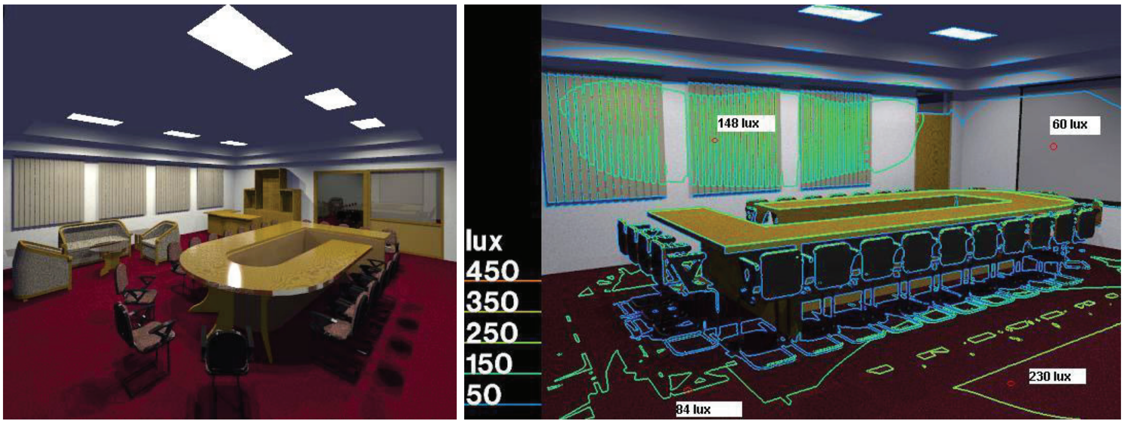


Figure 2.1. Example scenes from Radiance Simulation (illustration with contour lines as well as numeric values (Source:(Singh, 2002)

Inputs of Radiance include geometry (importing models from CAD files or script generated geometries), material texture and graphical options like HDR images. The program has four simulation methods. These are rendering, ray intersection finding algorithm, parallelization and animation (Fritz & Mcneil, 2016).

2.1.3.2. DIALux

The German Applied Light Technique Institute has developed the DIALux computer program to standardize the calculations made by using different methods and collect the armature data from companies. This provided to work on and compare the differentiation of the companies. DIALux works with radiosity method to calculate the light distribution (Witzel, n.d.). PovRay tools is used for visualization and, ray tracing method is added for visualization at the latest versions. It is possible to calculate direct light coming from dun and reflected light from surfaces by the help of radiosity method. Radiosity is one of the calculation type and it based on the energy preserving principle (Cohen & Wallace, 1993) (Sillion & Puech, 1994). It accepted that all light falls on to a surface is not absorbed, instead it is reemitted by the material’s surface. A surface is also can be defined as luminous source.

The program includes the luminaries and armeture information from many companies at its own database. It is also possible to construct different room shapes in DIALux, for instance rectangular, square, polygon, or different shapes determined / designed by the architects or users of the software and the program lets the user to choose from several shapes existing at the construction library.

Additionally to the room shape, the program, which supports adding many pieces of furniture to the place, is also an advantage to work with it. That takes into account factors such as lighting level, reflection and glare which can be seen on the furniture. (Fig. 2.2).

The program basically works in this order:

- Construction of the room
- Specification, furniture selection and material selection for the room
- Preparing the light and daylight situation (location, orientation and sky conditions data from various ways and/or placement of the desired lighting fixtures and lamps)
- Analyzing the room according to the inputs

Figure 2.2. An example scene prepared in DIALux (Source:(Kazanasmaz, Yelkenci, Yörük, & Dim, 2014)

2.1.3.3. Velux Daylight Visualizer

Velux is one of the professional simulation and visualization tool for daylighting design and analysis in buildings. It named as “VELUX Daylight Visualizer” and its main aim to call attention to the use of daylight in buildings. It is one of the helpful daylight design tools to predict and prepare the documentation of daylight levels and visualisation of the rooms to understand the real conditions of the design.

The Daylight Visualizer is an option of a modeling tool which is able to prepare 3D models. At this program, it is also possible to build the roof and facade windows are independent of the main model. The program is also able to import 3D models (in obj, dwg/ dwg format) generated by CAD programs in order to be in harmony with previous project development steps. This is also a flexibility opportunity to the model geometry.

Velux Daylight Visualizer is able to calculate luminance, illuminance and daylight factors for all sky types defined in CIE Standard General Sky (International Commission on Illumination). The outputs of the Daylight Visualizer are jpeg and other types of images based so it is practical to use the output schemes (Fig. 2.3). VELUX Daylight Visualizer has easiness to use by working together with lots of programs during import and export steps. Velux is also working on the same order with DIALux, construction-specification-preparing the lighting situation and analysis steps follow each other.

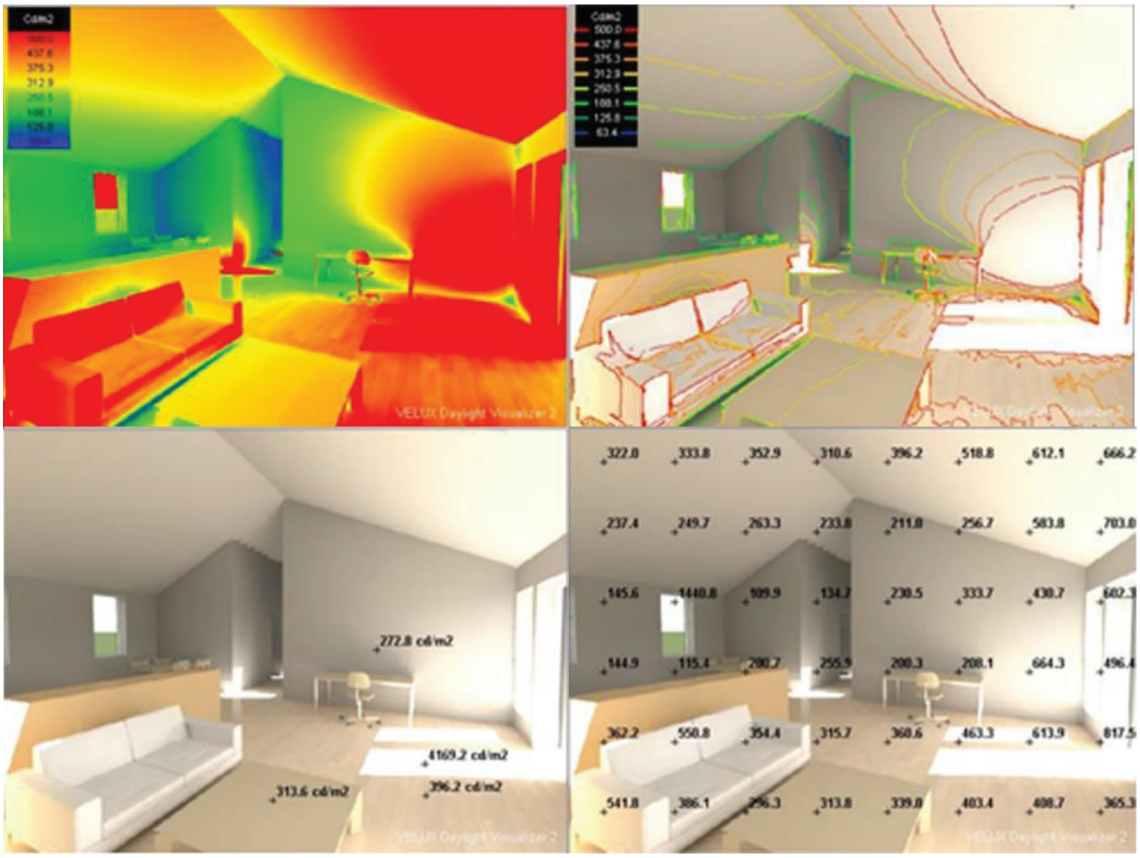


Figure 2.3. An example roof floor room study and its output schemes from Velux Daylight Visualizer - False color, ISO contour, user selected values and grid values options (Source:(Velux, 2017)

2.1.3.4. Capabilities of Daylight Simulation Tools

To find out the capabilities of these programs, it is essential to know about their calculation methods. The system in Velux works by Bidirectional ray tracing with photon mapping and irradiance caching, where DIALux prefers to work on radiosity and Radiance is on ray tracing, however, such a difference has no effect on the ability to calculate a simple room. All mentioned tools have the capability to calculate the output values of daylight factor, illuminance and the mean daylight factor (Table 2.5). When their user faces are analyzed, Velux's easiness of the toolbar is designed in a very simple system and DIALux has got the guide, project tree and CAD window placements. Radiance has the most complex project definition steps and options.

Every simulation tool can import the geometric model. This capability, workable import menu with other 3D programs, is another key point to select and use the program. Where Velux is able to accept drawings from .obj .skp .dwg .dxf format, DIALux and Radiance import .skp .sat .m3d .3ds files.

When considering daylight calculations, all of those programs are able to find out the illuminations at the reference points selected by the user. Rendering is another common quality among those programs. However, DIALux is able to calculate a grid area lighting results. This is one of the advantage while detecting the illuminations at reference area. Sky conditions are another certain parameter which is inevitable factor at daylighting design. Because field measurements are taken at certain dates and validation of the models has to be done exactly to that day's weather conditions. It is important to have the IES sky conditions at the toolbar of the programs and the widest range of sky conditions are existing at Radiance library. Output file options are another issue to conduct lighting strategies to further steps. DIALux and Radiance have a wide variety of export file options that consist graphic files, 3D models and video files.

Lastly, all of these programs are user friendly and open to free access. Their licenses can be taken as student or designers.

Table 2.5. Capabilities of daylight simulation tools

Calculation options			Daylight simulation tools		
			Radiance	**Velux Daylight Visualizer**	**DIALux**
Daylighting calculations	Reference points		✓	✓	✓
	Calculation grid				✓
	Rendering		✓	✓	✓
Sky conditions	CIE	Clear sky	✓	✓	✓
		Intermediate sky	✓		✓
		Overcast sky	✓	✓	✓
	Uniform sky		✓	✓	✓
	Partly Cloudy Sky			✓	
Import file options	dwg / dxf			✓	✓
	3ds				✓
	Skp			✓	
	Obj			✓	
	Graphic files (bmp, dib, jpg, jpeg, gif)				✓
	Object files (m3d, sat)				✓
	Luminaire files (Ldt, eld, ies, cib, ltl, uld)				✓
	Sensor points file (csv)			✓	
	R chart files (rtb)				✓
	gbXML files				✓
	STF files				✓
Outputs	Illuminance		✓	✓	✓
	Luminance		✓		✓
	Daylight factor		✓	✓	✓
	Daylighting contour plots		✓	✓	
	Photo-realistic renderings		✓		✓
Export file options	Skp				
	dwg / dxf				✓
	Pdf				✓
	RTF				✓
	Graphic files (jpg, bmp)				✓
	Video files (avi)				✓
	Object files (m3d, sat)				✓
	Stf files				✓
	Keyshot files (bip)			✓	
	EIC visualizer (exp)			✓	

2.1.4. Case Studies

Few studies are analyzed according to the field measurements and simulation based results as a case studies. These studies provide a general aspect on how to use and with which purposes choose simulation software at lighting analysis of educational buildings.

A research made at İzmir Institute of Technology was aimed to assess and promise an energy efficient lighting design with optimum shading devices to increase visual performance (Bayram & Kazanasmaz, 2016). This study has been carried out to explore best shading type with the combination of suitable slat angles, glazing quality and artificial layout. To achieve this, a sample room from mechanical engineering department was selected. Firstly, illuminance distribution of daylight and luminance values at certain points were measured in partly cloudy sky conditions. Those values are used to determine optical values of glazing and finishing materials. The number of reference measurement points was determined by using the room index formula and the location of the points was found by the CIBSE measurement method at approximately 80 cm above the floor which is the working level. The reflectance values of the materials were calculated with Lambertian reflectance formulation and those values are used in simulation as the main characteristics of the surfaces. Then, the simulation model of sample room is prepared and different types of scenarios including shading devices are involved to the simulation model. Luminaries, glazing type and other relevant inputs are also involved to the simulation. The outputs of this study concentrated on the fixing fluctuated and insufficient lighting conditions with the optimum scenarios. Usage of LED lighting and 50% glazing transmittance is find out as optimum conditions at indoor with high energy performance.

The study carried by Yılmaz, Akıncı and Sevindik was concentrated on the usage of DIALux lighting design software to simulate the illuminance distribution of a space (Yilmaz, Akıncı, & Sevindik, 2007). This study presents both the advantages and disadvantages of using a simulation program during design phase. Then the writers gave a case study about how to create a sample room and how to design and place the desired lighting elements into this space. The results made an important contribution to the student's understanding of the basics of simulation software.

Another study by Başkan and Sözen was aimed to present an example classroom lighting design that is both visually comfortable and energy efficient (Bostanci Baskan &

Şerefhanoğlu Sözen, 2006). The case was chosen from a high school and existing conditions are simulated according to field measurements at the first stage. Then, survey results among students showed the visual problems that were observed at the selected class. Lighting schemes were created to provide better conditions and differences between lighting schemes were compared at the results of this study.

These sample studies give the information about few lighting design programs, using simulation tools during analysis of current conditions and predicting the results of design phase components, and identifying these applications at teaching areas.

2.2. Acoustic Design for Lecture Halls

Interior acoustic qualities of the educational spaces have been researched for years. The high intelligibility level is the prior objective for learning in a classroom where students are present. Learning and teaching performance decreases when acoustic performance is poor due to reverberation time. A study prepared by MacKenzie investigated the effects of poor acoustics on students (MacKenzie & Airey, 1999). Educational buildings are expected to have a high level of understandability and concentration within the classroom. There are several researches made to determine the standards and recommended values at the certain parameters influence acoustic environment of educational places (Eggenschwiler, 2005).

2.2.1. Acoustic Design Strategies and Standards

Acoustic performance is one of the components of the internal environmental quality. It allows speech to be understood clearly and able to concentrate without disturbing and distracting the voices (K. P. Roy, 2011). Acoustic design needs is to be emphasized in all steps from design to operation to make buildings a healthy and productive work space. This is even more important in terms of schools where children spend most of their lives. Because children are not protected against unclear voices than adults. In addition, schools have four times more density than office spaces and are not very well-maintained (Healthy Schools Network, 2007). Schools with an inappropriate acoustical environment are a negative learning environment for many children.

Uncomfortable interiors affect children's health temporarily or permanently, and reduce school success. Schools are environments where learning and teaching activities take place. Children cannot learn that they do not hear, and teachers can understand children's needs by listening to them (Nelson & Soli, 2000). Students who are unable to hear or understand the information said by the teacher in the class cannot be expected to learn at a normal speed. There is a determined level of reverberation depend on volume and aim of the educational spaces for providing an acoustical performance (J Harvie-Clark, Wallace, Dobinson, & Larrieu, 2014). Improving acoustic conditions is to be attempted in environments that are insufficiently heard, like increasing lighting in schools that are not sufficiently lighted.

There are studies carried on acoustic need of schools. A sample research made by Catalina and Virgone was demonstrated the importance of materials' impact on acoustic and visual performance in schools (Catalina & Virgone, 2012). They chose glazing areas to search their impact on interior environment and aimed to give opinion to designers about differentiating glazing. As seen at research, there was an opposite relationship between acoustic and visual conditions, because glazing material both changed visual parameters via daylight and effected sound transmission. The results showed that, using glazing area up to 40% of the floor area creates an acceptable illuminance value at the interior. However, in such a circumstance, indoor SPL's acceptable limit should be 10-15 dB (A). The researchers developed simple two mathematical models and validated up to very accurate models ($R^2>0.99$) but only for a typical classroom example.

Another study completed by Mydlarz and Connetta is aimed to analyze the relationships between environmental and acoustic features of selected 12 different schools in England (Mydlarz et al., 2013). Determined classes were measured ranged in both user profiles, interior style and exterior factors. Most of environmental factors were affected the L_{aeq} (equivalent continuous noise level) which is directly decreases the speech intelligibility level (Table 2.6) and acoustic performance inside of classrooms. This study demonstrated those relations and could lead to provide the optimum environmental and acoustic limitations at the further researches.

Optimum acoustic needs are determined at international standards as given below.

Table 2.6. Recommended speech transmission index values for schools

Related standard	**Min STI level**
Building Bulletin 93 (Daniels & Bodkin, 2015)	0.6
DIN 18041:2004-05 (Eggenschwiler, 2005)	0.56

Table 2.7. Comparison of background noise and reverberation time for schools (Source:(Toksoy, 2015)

Reference source		**Volume of the room (Vs, m^3)**	**Max background noise - dB (A)**	**Max Reverberation Time (s)**
USA	(ASA, 2002)	Vs<283	35	0.6
		283<Vs<566	35	0.7
		Vs ≥ 566	40	-
		Corridor	45	-
EU	(Özbıçakçı, Çapık, Gördes, Ersin, & Kıssal, 2012)	-	45	-
FRANCE	(Zannin & Marcon, 2007)	Vs<250	38	0.6-1.2
		Vs>250	38	0.4-0.8
GERMANY	(ASA, 2002)		30-44	0.8-1.0
BRASIL	(ASA, 2002)	150 < Vs ≤ 300	40-50	0.5-0.7
BELGIUM	(ASA, 2002)(Daniels & Bodkin, 2015)	-	35-40	-
TURKEY	(ASA, 2002)(Daniels & Bodkin, 2015)	-	45	-

There are average reverberation time values in different studies and standards (Table 2.7). They vary between 0.5 to 1.2 s depending on the volume of the room. Maximum background noises are another factor effects the internal acoustic environment. They are given between in a range of 30-50 dB (A) which is wide for comfort conditions. The lower background noises, the higher speech intelligibility. At this study, the background noise is accepted constant since the concept is not covering the noise control solutions.

2.2.2. Acoustic Performance Parameters

The combination of user profile, the space and the purpose of use determine the items chooses room acoustic performance (Zannin & Marcon, 2007). So, a specific subject, the parameters of well-designed acoustic environment for educational places has been researched for many years.(Paradis, 2016) Classrooms are places designed for both school age young peoples and adults. Nowadays, classrooms are using with different devices like interactive media responding tools and video-presentations that increases the significance of classroom acoustics.

A well-designed acoustics for learning supports verbal communications, which requires low noise levels and lower reverberation times for intelligibility (Nelson & Soli, 2000) (J Harvie-Clark et al., 2014). Before, classrooms may have been developed without sufficient thought of acoustical standards. Noise sources influences learning and teaching facilities include:

- outside of the school (vehicular activity and plane flyover)
- the passages (pedestrian activity and discussions at corridors)
- different classrooms (may include other sound sources)
- mechanical hardware (compressors, boilers, and ventilation),
- inside the classroom, itself (reverberation time) (Paradis, 2016)

Regarding those parameters, some of the comfort conditions are to be achieved by treating the whole building. However, room acoustics performance can only be treated by the interior design strategies. In this way, the reverberation time of the interior, the speech intelligibility level of the lecturer and the speech intelligibility is significantly improved and the international standard can be achieved.

Acoustic performance depends on lots of parameters calculated in literature and other standards. However, since the focal point of this study is the lecture halls, several of them are chosen which are critical and must be in the recommended levels. These are reverberation time (RT60)-main parameter, speech transmission index (STI) gives the speech intelligibility and C50, clarity value is the clearness of the speech.

2.2.2.1. Reverberation Time

Reverberation time is the prior element of room acoustics and it is the time required for sound to decay 60 dB after the sound source is closed (Jack Harvie-Clark & Dobinson, 2013) (Daniels & Bodkin, 2015). Reverberation is a critical parameter to find out the speech intelligibility and the perception of music and is used to optimize or standardize sound pressure level estimations (Fig. 2.4). It is generally defined as decay time and given in seconds. However, if the decay is linear, it is also useful to find out 20 dB decay and multiple this value by 3 or measure 30 dB decay and multiple it by 2. Then, those values are defined as T20 and T30 values (TSE, 2009). Reverberation time (RT60) is a widely-used parameter and optimized according to aim of spaces in literature.

For a practical measurement, generally, only the time passed for the reflections in room to decay by 20 dB (T20) or 30 dB (T30) are measured. Following, those measurements are extrapolated to time passing through 60 dB of decay. So, reverberation time can be converted from T20 by multiplying it 3 times or T30 by multiplying it 2 times. Since T20 and reverberation time is found in the same decay path and values from logarithmic calculations, reverberation time can be used to determine, analyze and compare acoustic perception of a place.

Reverberation time take longer to die in a reflective surface covered room. As opposite, when the room is too absorbent, the reverberation time is short than standard values. However, the reverberation is also related with volume of the room and receivers' hearing of acuity (Eq. 2.1). Reverberation time is calculated by Sabine method:

$$\mathrm{RT}\ 60 = \frac{24 \ln 10^1}{c_{20}} \frac{\mathrm{V}}{\mathrm{S}\alpha} \approx 0.1611\ sm^{-1} \frac{\mathrm{V}}{\mathrm{S}\alpha}\ (\mathrm{s}) \tag{2.1}$$

Where RT60 is reverberation time (s), c_{20} is sound speed (in 20°C), V is volume of space (m^3) and Sα is total absorption of room (m^2). (Kurtay, Eryıldız, & Harputlugil, 2008)

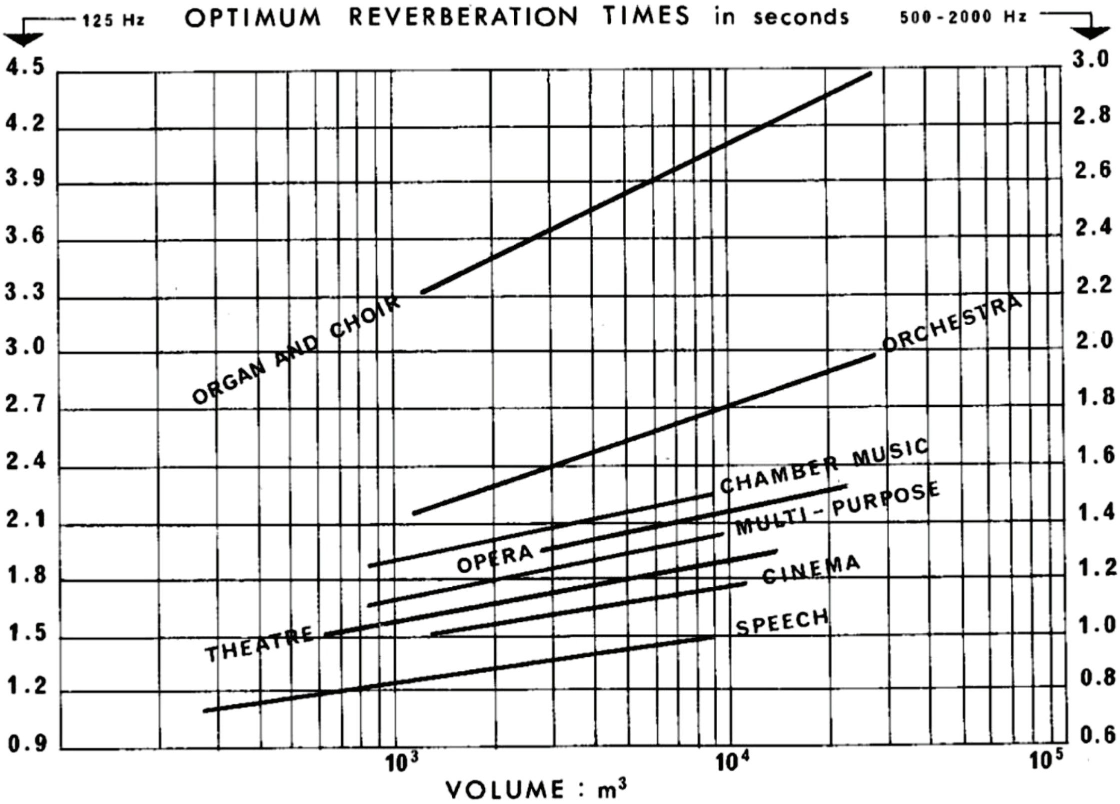


Figure 2.4. Optimum Reverberation Times in seconds
(Source:(Moore, 1978)

2.2.2.2. STI- Speech Transmission Index

Speech transmission index (STI) is the value to give speech transmission quality. It is measured between 0-1 and STI technique is determined in the IEC 60268-16 standard. This parameter gives the ability of the acoustics which show the characteristics of the speech. Barnett presented common intelligibility scale (CIS) with speech transmission index (Table 2.8, Eq. 2.2) based on this relationship (Barnett & Knight, 1995).

$$CIS = 1 + \log(STI) \qquad (2.2)$$

Both speech transmission index and common intelligibility scale are a measurement way of understanding words, sentences said by the presenter.

Table 2.8. Speech Transmission Index Variation
(Source:(Barnett & Knight, 1995)

	STI (according to IEC 60268-16 standard)	**CIS**
Bad	0-0.3	0-0.48
Poor	0.3-0.45	0.48-0.65
Fair	0.45-0.60	0.65-0.75
Good	0.60-0.75	0.75-0.88
Excellent	0.75-1.00	0.88-1.00

Speech intelligibility related to

- The sound pressure level
- The frequency response of the channel
- Background noise (NC) level
- Echo (reflections with delay > 100ms)
- The reverberation time
- Masking effects (NTI Audio, 2016)

STI is an internationally accepted standard as quantifier of intelligibility of speech and it is become a main parameter to detect in closed spaces acoustic environment (Houtgast & Steeneken, 1971).Its prediction is made in acoustic simulation tools and it is calculated with specific instruments in field measurements.

2.2.2.3. C_{50} – Clarity

C_{50} (clarity) is the energy ratio of sound that is early arrived energy (in the first 50 ms) to remaining energy (Jack Harvie-Clark & Dobinson, 2013). It is generally given with C_{80}, however when C_{80} is much more about music quality, C_{50} is about clarity of speech (Table 2.9). It is given in dB. This parameter helps to give acoustic conditions of a room understood by other parameters like reverberation time and supports the information specified on speech quality. C_{50} is a descriptive of the shape or proportions of the decay curve (Eq. 2.3). To provide the speech quality in a space, approximately 3 dB change in C_{50} value will make a noticeable change in most of cases. (EASE, 2009)

Table 2.9. Correlation for C_{50} and STI
(Source:(Cavanaugh, Tocci, & Wilkes, 2010; J Harvie-Clark et al., 2014)

Weighted C_{50}, dB	-6	-3	0	+3	+6	+9
STI	0.3	0.4	0.5	0.6	0.7	0.8
% Alcons	34	20	12	7	4	2.5
Category	Poor	Fair		Good		Excellent

C_{50} is calculated with following formula:

$$C_{50} = 10 \log\left(\frac{D_{50}}{1 - D_{50}}\right) \tag{2.3}$$

Where C_{50} is clarity (dB), and D50 is ratio between early to total sound energy, namely definition in (%) ("Room Acoustics - Acoustical Parameters Measurement," n.d.) Clarity values are essential to as first indicator of speech quality. Clarity index is found to be positive for the places that have a constant reverberation with a specified source – receiver relationship (Cabrera, 2007). When reverberation time and clarity index are examined, a mainly positive relationship is founded.

2.2.3. Acoustic Simulation Tools

Simulation tools are widely-used methods for analyzing acoustic results of the interiors. It is possible to set up the geometry of the room and input all the variants effects the interior environment like materials and background information as well as the sources detailed features. These actions are helpful including planning and development information gathering phases, demonstrating, analyzing options and design substances phases. Some of those simulation programs also gives audial results, which means it is possible to listen the sound coming through a specific position. This can be extremely useful when a musical purpose is to be achieved or any specific presentation system is to be installed. Though, the acoustic simulations are used by a wide range of professionals, architects, researchers and material companies. At this point of study, two of well-known acoustic simulation tools are summarized and their capabilities are compared for the analyze of speech quality in lecture halls.

2.2.3.1. Odeon

Odeon is one of the widely-used room acoustic software. It works with open and closed spaces and main principle is ray tracing method (Fig. 2.5). It consists not only standardized source, musical instrument, speech and speaker library but also material library that has different surface's absorption and reflection coefficients at octave bands (Naylor & Rindel, 1992).The acoustics can be simulated, described and listened from room auralisation tool in it.

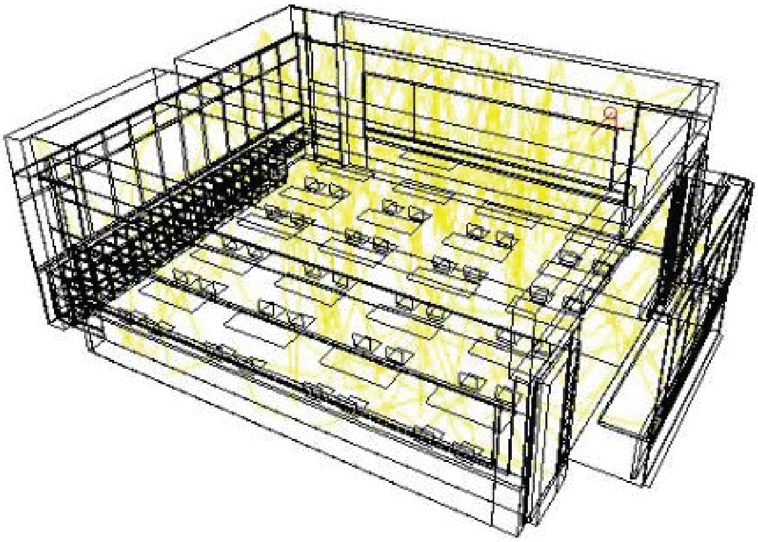


Figure 2.5. Modelling and ray investigation example in Odeon acoustic simulation software (Source:(AA LAB, 2017)

Simulating in ODEON follows those steps. The closed area is modeled in Sketch-up or any other 3D modeling program. Then, for instance in sketch-up, the model exported to ODEON a par extension file with Odeon plug-in, as a quickest and best quality way. Odeon- Import menu also accepts dxf, 3ds, stl and cad files. It is also possible to create the model in Odeon Editor window with writing the coordinates of each point.

Preparing a model in the best way means making model without any extra lines or point and this is one of the item to get the best simulation result from program since it detects all the faces. After preparing a well-prepared model, if it is a closed space, it is to be checked with ray 3D investigate rays' menu for detecting the holes at the room. Those holes may conflict the rays coming through source and false the results. Then, the materials need to be assigned to each face up to design in each frequency from Material list menu. If a specific material is determined by designer, new materials can also be input the program. Source(s) and receivers are placed depending on the ISO 3382 standards, the usage aim of the spaces and the volume of spaces from Source-Receiver list menu. If any extra information about specific listener points are required, they can also be positioned at this step. Background noise is set up per frequencies. Then the first calculations are started. If the room exists and the model needs to be calibrated, the materials, source-receiver relationships, background noise levels, source's quality, and 3D orientation is to be optimized according to the field measurement results. Material optimization and reflector surface definition are made at calibration and design steps in Odeon.

2.2.3.2. Ease

Enhanced Acoustic Simulator for Engineers (EASE) is one of the acoustic simulation software developed for professional practice. It can work both at inside rooms and at open areas. The program works with ray tracing method and followed by those steps. The geometry is either prepared at skp or dxf format, and imported into the EASE. The geometry can also be prepared or edited in the EASE toolbar drawing module by adding each point's coordinates. The faces and whole geometric model can be checked by check data options in case of defining the coordinates wrongly or conflictions. Then, the material assignments, average absorptions per frequencies, are done depend on design. The background levels and needs are defined into program and sources and receivers are places according to ISO 3382 recommendations. When speech is simulated ISO 3382 speech is selected as source but if the electroacoustic design is done, selected speakers' gll format data files are used as sound sources. Lastly, the simulation runs to evaluate results.

It is possible to get reverberation time calculations quickly or other parameters' results by running the simulation (Figure 2.6). These parameters are Direct SPL, Total SPL, STI, D/R ratio, RaSTI, Critical distance, clarities (C7, C50, C80, CSplit), SPL levels (L7, L50, L80, LSplit), Arrival times, Alcons and for electroacoustic results, Loudspeaker Coverage Overlap and Loudspeaker Aiming are calculated.

The calculations are both can be done at reference points and on all surfaces or an audience area specified by the designer. However, specific reference points, the listener seats are quickest way to explore the problems and evaluate specific locations performance in detail. Calculations are presented in 1/3rd octave bands and both graphic and numeric outputs can be exported in text and graphic files format.

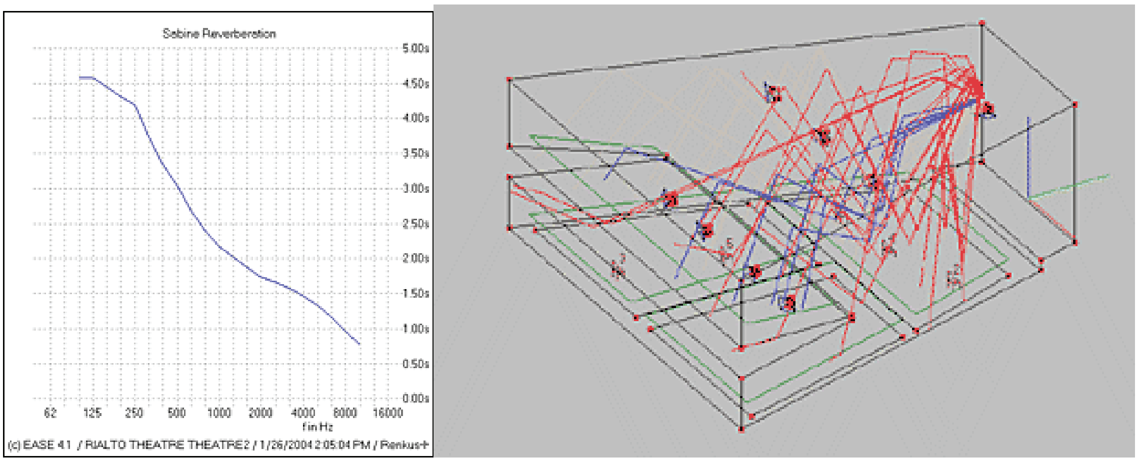


Figure 2.6. Modelling example and reverberation graph in EASE acoustic simulation software (Source:(EASE, 2009)

2.2.3.3. Capabilities of the Acoustic Simulation Tools

Odeon and EASE are two well-known acoustic simulation programs. Designers and professionals use and chose them according to the project needs and its limitations. Since the projects may include detailed or simplified models up to the material placement, it is essential to choose the optimal tool to simulate correctly (Chr Gade, Lisa, Lynge, & Holger Rindel, 2004).

Both of those programs work with ray tracing principle. In order to analyze the model, the programs need the material reflectance values as input (Naylor & Rindel, 1992). They update the material libraries regularly, however some designers create their own material with absorbency quality and may include their own libraries. Odeon and Ease are able to allow that, yet Odeon's material editor window easy and practical to use.

The output list of these two programs are listed in Table 2.10. Both of those programs are able to import 3D models which is essential to check a designed room's responses easily in the planning phase. It is possible to export 3D models in dxf format in each of them. This became useful in complex and detailed project to find the exact places of the different materials coded in simulation library. Then those materials are to be exported in detail drawings in the exact places.

Table 2.10. Capabilities of programs
(Source:(Christensen & Koutsouris, 2013; EASE, 2011)

Calculation Options		Acoustic Simulation Tools	
		EASE	ODEON
Import file options	dwg/dxf		
	Skp		
	(speaker file) gll		
	(Material absorption file)		
Outputs	EDT (Early Decay Time)	✓	✓
	SPL (Sound Pressure Level)	✓	
	C7 (Clarity)		
	C50 (Clarity)	✓	✓
	C80 (Clarity)	✓	
	STI (Speech Transmission Index)	✓	✓
	RASTI (Rapid STI)	✓	✓
	D 50 (Definition)	✓	✓
	LF80 (Lateral Energy Fraction)		✓
	Lj Average		✓
	Alcons (Articulation Loss)	✓	✓
	Articulation Index	✓	
	Privacy Index	✓	
	Direct and Total SPL	✓	
	D/ R Ratios (Direct / Reverberant Ratio)	✓	
	Critical Distance	✓	
	Arrival times	✓	
	Loudspeaker Coverage Overlap	✓	
	Loudspeaker Aiming	✓	
	ITDG (Initial Time Delay Gap)	✓	
Output file options	Skp		
	Graphic files		
	Pdf		

The most important issue while choosing a software is its reliability to results and its outputs. Recent searches made in closed rooms, amphitheaters and conference halls still compares the results and designers choose the software depend on type of usage (Remillieux, Corcoran, Haac, Burdisso, & Svensson, 2012). For instance, when a source is newly produced or tried, Ease has integrated programs works with it that allows to create characteristics. However, at speech auralisation, both of them include sources defined as ISO 3382 standards. Odeon is more user friendly than EASE while comparing their user faces, however EASE is widely used on sound system designers and Odeon is much more preferred in speech quality estimations. So, Odeon is chosen to be simulate acoustic environments result in this study's lecture hall.

2.2.3.4. Material characterization in acoustic simulation tools

The material qualities differ depend on the texture and surface qualities. These details effect the absorption and reflection coefficients of each material in different frequencies (Table 2.11). To provide an international standard, some of common materials are measured at laboratories or during researchers and their absorption coefficients are published in literature. Simulation tools are also updated according to the recent studies and this makes the simulation models work better.

Table 2.11. Materials' sound absorptions per frequencies (Source:(Christensen & Koutsouris, 2013; EASE, 2011)

Material specifications		Absorption coefficients								
Reference	**Material Description**	**63 Hz**	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**	**8000 Hz**	**α(w)**
(Harris, 1991)	Marble or glazed tile	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	**0.00**
	Carpet heavy, on concrete	0.02	0.02	0.06	0.14	0.37	0.60	0.65	0.65	**0.20**
	Drapes, heavy velour	0.14	0.14	0.35	0.55	0.72	0.70	0.65	0.65	**0.60**
(Kristensen, 1984)	Double glazing, 2-3 mm, 10 mm gap	0.10	0.10	0.07	0.05	0.03	0.02	0.02	0.02	**0.05**
	Painted plaster surface	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	**0.05**
	Ventilation grille (approx. per sq. m.)	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	**0.60**
(Christensen & Koutsouris, 2013) Dalenback, CATT	50 mm thick wood-wool,200 mm from ceiling	0.49	0.49	0.63	0.83	0.97	0.99	0.96	0.96	**0.85**
(Kristensen, 1984)	Wooden floor on joists	0.15	0.15	0.11	0.10	0.07	0.06	0.07	0.07	**0.10**

CHAPTER 3

PROCEDURE FOR THE CASE STUDY AT IZTECH

This chapter involves two parts namely, physical conditions and the analysis of existing conditions. First part is a description of the subjected lecture hall which explain the details of field measurements of the case. The analysis includes both daylight and acoustic environment of the lecture hall. The explanations of the measurement process are presented and the steps of the modeling phase is given for each simulation part.

3.1. Physical Conditions

This study is conducted in an educational building named block A in Izmir Institute of Technology, Faculty of Architecture. A lecture hall in this building is selected because of its medium size, involving suspended ceiling and a raised audience platform and its deficiencies observed in vision, light and sound reflections. The faculty is located at the west part of the campus and consists of five blocks including design studios, laboratories, classrooms and offices. Selected lecture hall is located on the A Block's first floor and named as A112 (38° 19' N, 26°37' E). It has 134.1 m^2 floor area and it is rectangular shaped (Fig. 3.2). It is facing north and west. It has two main windows on the west wall and each of them is around 3 m^2. There are two windows on the north façade and one 1.6 m^2 and the other one has 3.6 m^2 glazing area. All windows are double glazed and have aluminum frame with one opening part at each. The window ratio (total window area / total wall area) is around 21.22 % at west façade and 23.74 % at the north façade. The story height is 3.8 m. The suspended ceiling used at the lecture hall lowers the used to 3.3 m.

3.1.1. Lecture Hall

A112 is located at the first floor of A Block, Faculty of Architecture. It is mostly used during presentation and technical calculation courses like building physics and mathematics. The lectures are arranged both between 08.45-12.30 and 13.30 –17.15, which is the active used times of this lecture hall. Current conditions of the lecture hall are presented in photo of place seen in Fig. 3.1. Existing physical environment is presented in plan and section view at Fig. 3.2.

Figure 3.1. A view from selected lecture hall

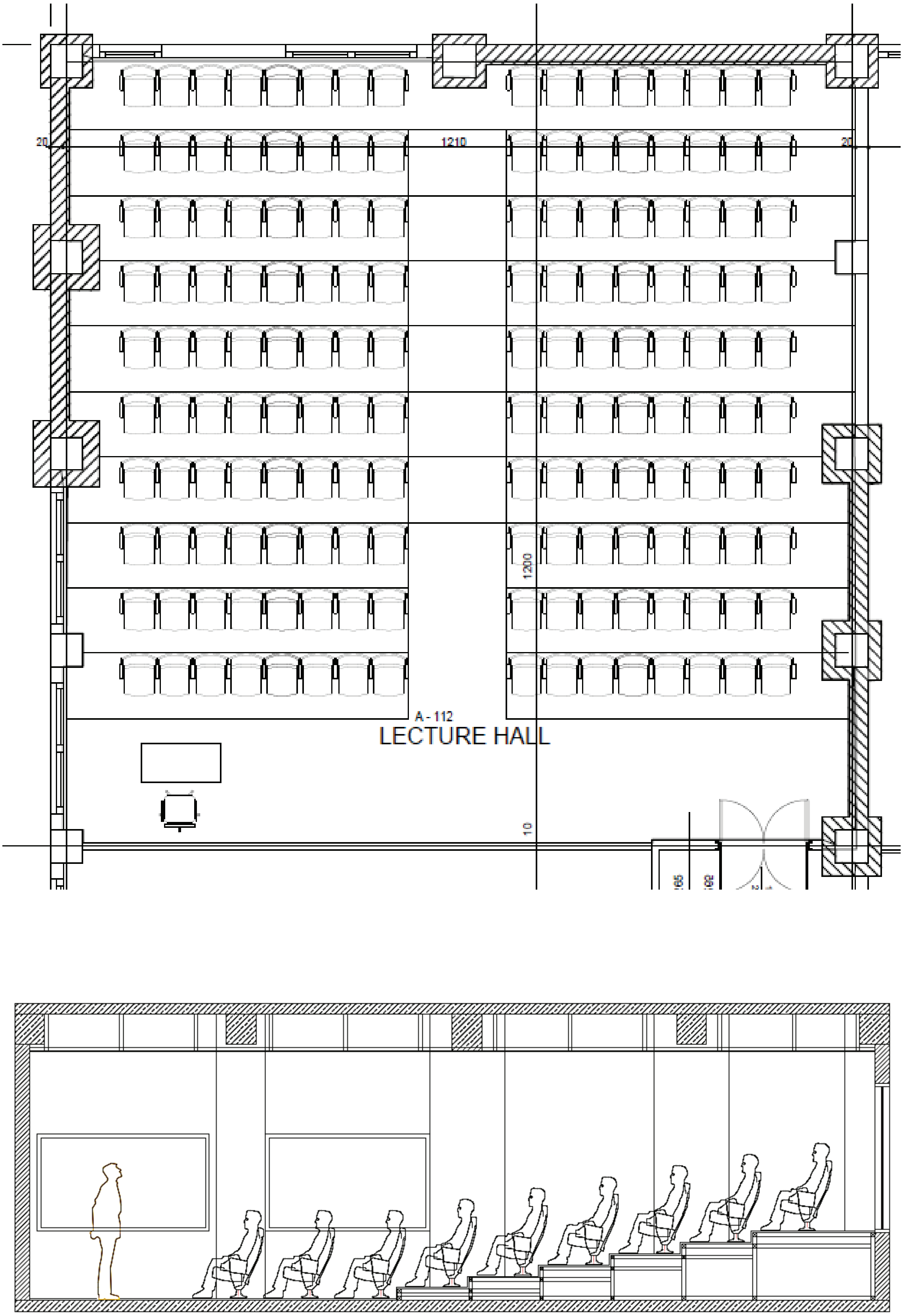


Figure 3.2. General layout plan and section of lecture hall

3.1.2. Climatic Conditions for Izmir

The case study is located at 38° 19’ N and 26 ° 37’ E, and has 78 m altitude (Table 3.1). İzmir is in hot Mediterranean region and features the dry summer subtropical climate characteristics. İzmir classified in “*Csa”* class which means mild with medium seasonality according to Köppen Geiger climate classification (Köppen, 2011). The general features of İzmir is similar to characteristics of western continents between 30°-45° latitudes. Winters are in medium temperatures and non-stable, occasionally rainy because of polar front (Fig. 3.3). Summers are both hot and dry with the effect of semitropical high pressure (“Izmir Weather Averages,” n.d.).

Table 3.1. Geologic data for field
(Source:(“Izmir Weather Averages,” n.d.)

Geo data for the selected location and time	
Height	78 m
Latitude	N 38° 19’ 27.83’’
Longitude	E 26° 37’ 48.72’’

When the dry bulb temperatures (°C) are analyzed for İzmir, it was seen that, the highest daily average temperatures observed at May and June, following July and August (“Climatic Design Information,” 2009). According to the field measurement day, following sun angles data (Table 3.2) and geological information are calculated.

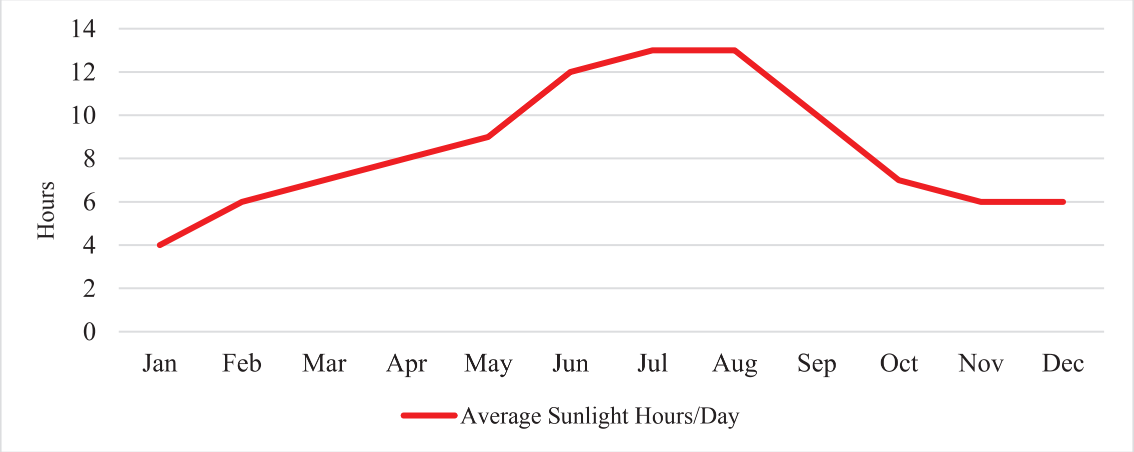


Figure 3.3. Climate conditions of İzmir (Altitude:25 m)
(Source:(Benli, 2016)

Table 3.2. Sun angles at solstices, equinoxes and measurement dates (Source:("SunCalc.org," n.d., "SunEarthTools.com," n.d.)

Measurement Reference date and time	**11:00**		**12:30**		**15:30**	
	Altitude	Azimuth	Altitude	Azimuth	Altitude	Azimuth
March 21th	40.07°	130.91°	50.26°	159.68°	41.95°	225.73°
June 21th	57.52°	107.29°	72.19°	142.34°	57.87°	252.25°
September 21th	42.32°	134.55°	51.30°	165.03°	39.99°	229.63°
December 21th	20.88°	147.61°	27.44°	169.07°	20.30°	213.56°
September 30th	39.79°	137.93°	48.00°	167.22°	36.71°	227.79°
November 4th	29.56°	147.02°	35.86°	172.35°	25.42°	221.14°

3.2. Analysis of Existing Conditions

At this study, examined parameters are grouped into two sections, daylight and acoustic environment analysis.

In order to get the real conditions for daylight, illumination levels and uniformity ratios are measured. These parameters are examined according to the relevant standards. Acoustic parameters are simulated from the T20 averages obtained from four receiver points and LAeq, LLeq values recorded at the lecture hall. Those parameters are used to create existing condition models of the lecture hall.

3.2.1. Field Measurements

Identifying the current conditions of the selected lecture hall was the first step of the analysis. So, current lighting and acoustic environment conditions of the lecture hall are recorded at the field measurements. These values were used for the validation of the simulation models at Section 3.2.2.

3.2.1.1. Daylight Conditions

At this part of study, daylight conditions of the lecture hall were measured to calibrate daylight simulation modelling. Two days were selected for field measurements. September 30th, 2016 was a sunny day and November 4th, 2016 was an overcast day. The daylight measurements were carried out by following the CIBSE practical guidance. Field measurements were accomplished to get the illuminance values at the reference points. The amount, distribution and location of the measurement points were calculated respecting to room index CIBSE recommendations. Room index was found out by the ratio between room floor dimensions and room height. The measurement layout was placed at a certain distance from walls. The rest center area was divided into rectangles and the reference points were to be located to equally divided rectangles (CIBSE No:3, 2012). The measurement points were placed at the center point of each rectangles and named respectively. The measurement layout is given at Fig. 3.5.

The field measurements were carried out respecting to CIBSE standards. Two main illumination meter and luminance meter were used to determine certain values at the reference points (Figure 3.4). A digital illuminance meter is used to measure quality and brightness of daylight falling to task area. This instrument has a silicon photo diode detector that calculates the data in high accuracy. It automatically turns into zero when the receptor unit is turned on, when the power button is activated, it directly starts to measure. It is used to validate existing daylight conditions of the lecture hall. A luminance meter is also used to measure a various types of luminance conditions especially when calculation the reflectance of surfaces and measuring the values on the white board. It has SLR (Single Lens Reflex) design to find out the actual values at the measured area.

Figure 3.4. Illuminance meter and luminance meter
(Source:(Konica Minolta Sensing Americas, 2017)

The results were taken twice on Sept 30th (between 10:30 - 11:30 and between 15:00 – 16:00) since the weather was sunny and the shadows were changing during the day. The second measurement was made on November 4th at midday (between 12:00 - 13:00) while the whole day was overcast and the illumination levels were almost constant. All the measurements were taken from a constant height (0.80 m) -from floor finishing surface and above of the each raised platform's tread surface- which is the working level. The defined points at the white board were also measured and noted to improve the results while proposing design components.

A grid system measurement points is prepared at constant height from the floor level including raised platform (Fig. 3.5). In this way, calculation points are arranged on the surface of desks. In total, 7x7, 49 measurement points are determined and named between A to G and 1 to 7 to describe easily. Constant distances are arranged between measurement points respecting to the floor dimensions of the lecture hall. The distance between A1 to B1 is 1.275 m and the distance between A1 to A2 is 1.35 m.

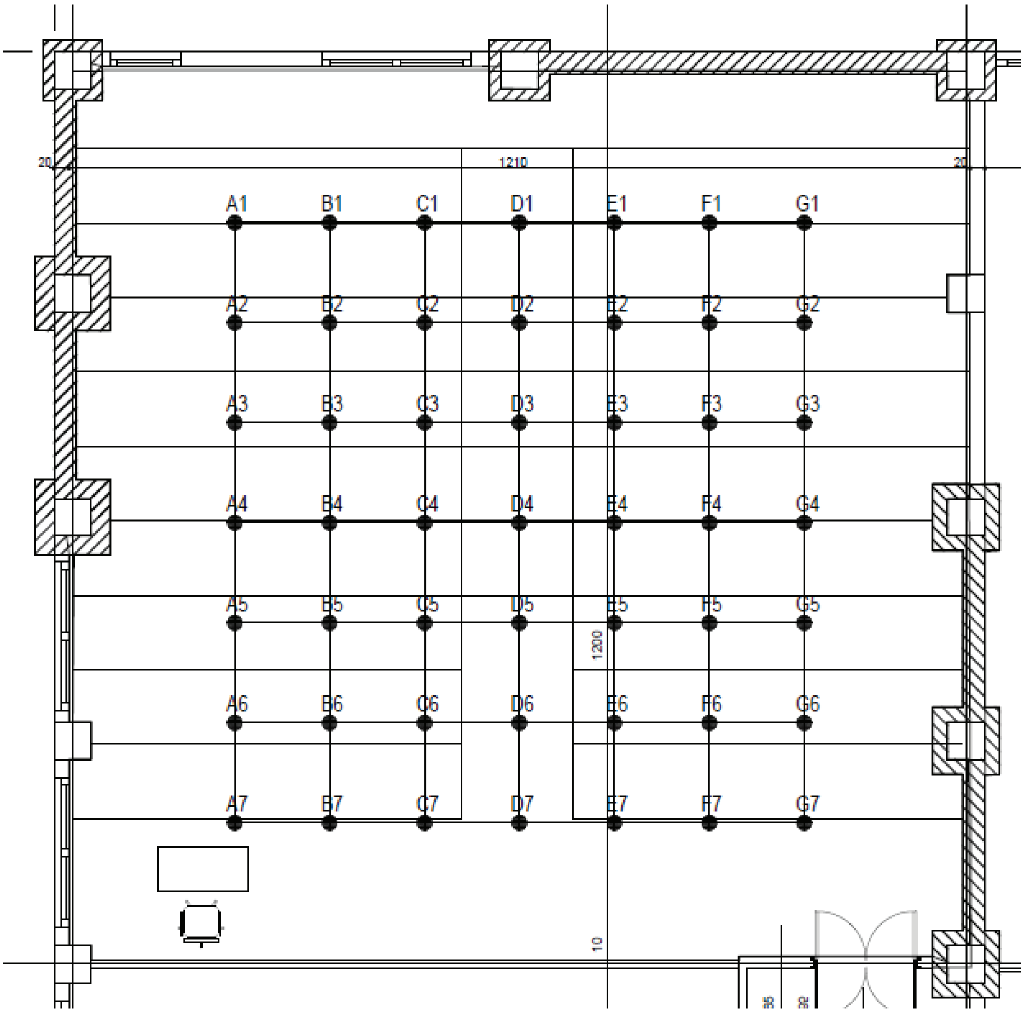


Figure 3.5. Layout of measurement points

Following the field measurements, the reflectance values of each material is calculated. Reflectance and transmittance of each surface were examined according to given equation 3.1 (Fontoynont, 2014).

$$L_{surface} = \frac{\mathrm{E \ x \ \rho}}{\pi} \tag{3.1}$$

Where L is luminance (cd/m^2) , E is illuminance (lux) and ρ is reflectance of the material.

$$\tau_{nn} = \frac{L_{in}}{L_{out}} \tag{3.2}$$

Where “"τ_{nn}” is transmittance of clear glazing (Eq. 3.2), “L_{in}” is luminance measured at the interior (cd/m^2) and “L_{out}” is luminance measured at the exterior (cd/m^2). Transmittance of glazing is calculated around 70%.

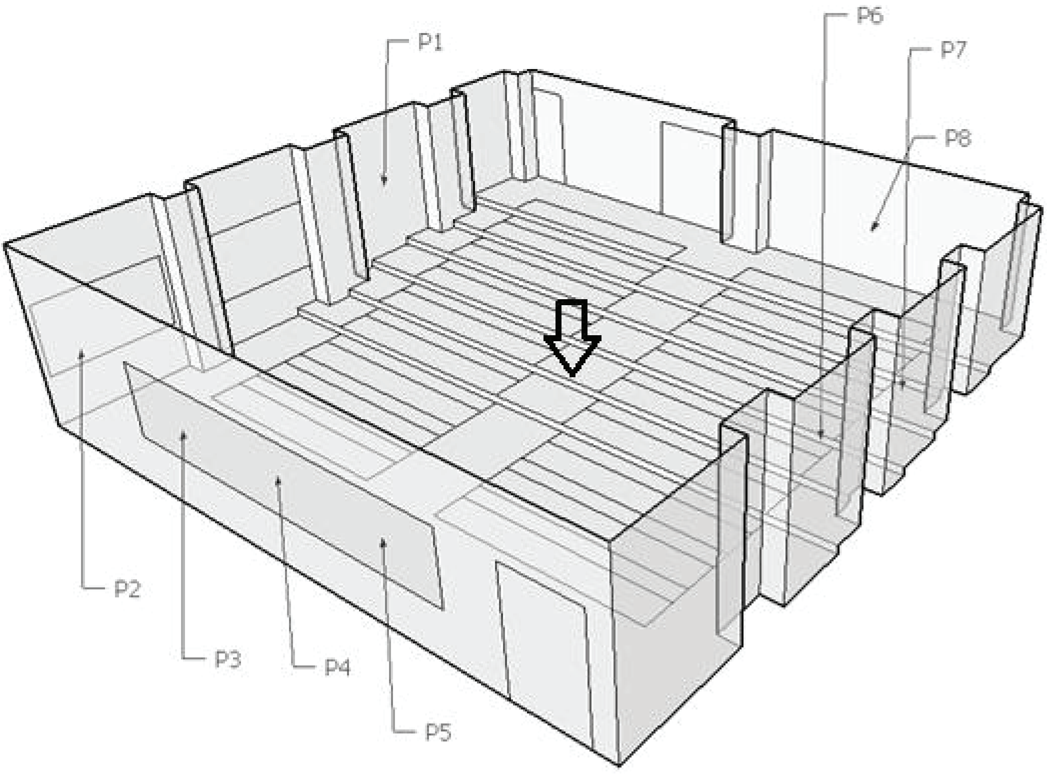


Figure 3.6. Luminance measurement points

Luminance ratios are to be provided at appropriate levels to ensure visual performance. To achieve this, it is required to examine factors including light sources and reflectivity of all surfaces. So, vertical illuminance measurement points are determined up to the seating layouts and possible white board placements. Then, a seat which is located at the center of the audience area and marked by an arrow in Fig 3.6 is arranged as a view point and luminance values are measured at that points illustrated in Figure 3.6. Measured luminance values are given in Table 3.3 and calculation of the reflectance values obtained from field measurements are given in Table 3.4.

Table 3.3. Luminance points and measured values in cd/m^2

Measurement point	**Luminance value (cd/m^2)**
P1	40.2
P2	271.4
P3	101.7
P4	45.1
P5	37.3
P6	41.2
P7	32.4
P8	16.5

Table 3.4. Reflectance of the surfaces from field measurement

Surface material	**L (cd/m^2)**	**E (lux)**	**Reflectance of the material (ρ)**
Wall	747.9	2541	0.924
Door	16.66	299.3	0.174
White board	223.8	936.2	0.750
Wood desk	335.1	1848	0.569
Floor covering- marble	448.2	2196	0.640
Floor covering – vinyl	50.34	538.5	0.293

3.2.1.2. Acoustic Environment

There are several methods to determine the reverberation and other acoustic parameters in closed spaces. Those studies widely used ones are single and integrated impulse response methods, interrupted noise method and Brüel & Kjaer's filtered burst method (Jambrosic, Horvat, & Domitrovic, 2008) (Remillieux et al., 2012). At this study, the field measurements are taken via interrupted noise method.

Acoustic field measurements are mainly arranged according to ISO-3382 and ISO 140 details which are measurement of room acoustic standards. In general, auditorium, lecture theatre and halls are measured with minimum 6 microphones for 500 number of seats (ISO, 2009). Yet, for this lecture hall, 4 receiver points were determined to for that size of floor area and audience area to find out the T20 average. Those points are placed covering the whole audience area and should be 0.90-1.2 m high from the middle of the ear height for seated people arranged up to the floor or raised platform level.

As a sound source, Brüel + Kjaer 4296 Omni Power sound source, 2716 amplifier and 2260 Sound Analyzer were used (Fig. 3.7). Measurement process was completed using the Brüel + Kjaer measurement system. At first, sound source was started and it stabled its situation. Then, sound source was switched off and the decay was started. This decay was recorded by microphones. Then measurement was finished and data recorded.

B+K 4296 Omni Power sound source

B+K 2716 amplifier

B+K 2260 Sound Analyzer

Figure 3.7. Brüel + Kjaer system room acoustic measurement tools (Source:(BKSV, 2017)

Those microphones (receivers) were placed not too close to the sound source to prevent effects of direct sound. Microphones are placed at least 1 m away to get a distance between selected surface and closest reflective surface which is floor. Since T20 vale measurement was used to calculate RT60-reverberation time, at least 35 dB above the background noise level was produced to find out the decay curve.

The field measurements were made on 09.05.2014 at 15.30 in empty occupancy condition to determine the values ceiling tiles' absorption coefficients according to field measurements for room acoustics. The following results are taken from 4 receiver points located at the lecture hall given in Fig. 3.8 and Fig. 3.9.

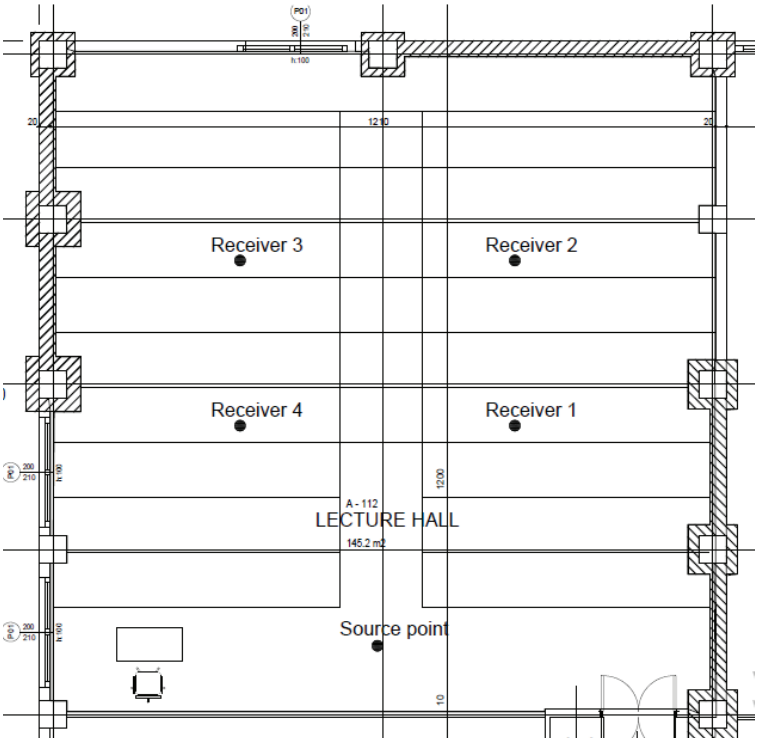


Figure 3.8. Source and receiver placements of acoustic field measurement

Main parameter about acoustic characteristics of this lecture hall, reverberation time graph shows that, the optimum reverberation values are much closer to the standard values at speech frequencies 500-1000 Hz. However, RT60 is higher at low frequencies. Those distribution is used at the validation of existing conditions of the lecture hall's acoustic model.

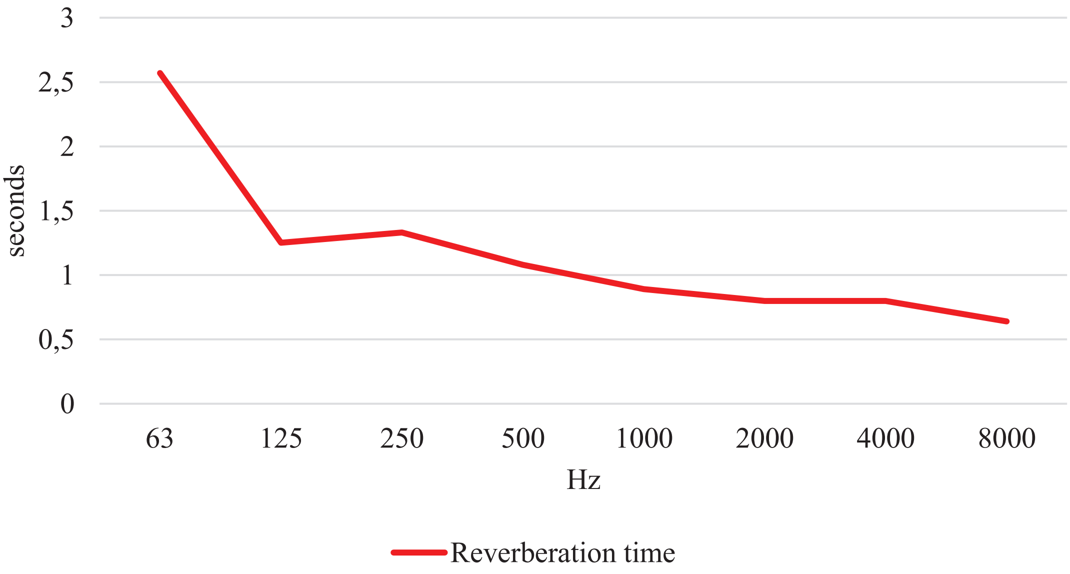


Figure 3.9. Reverberation time- measurement results of lecture hall

3.2.2. Simulation Modelling

At this part of the study, two simulation tools are selected to analyze the design components. In DIALux, the lecture hall's daylight simulation of existing conditions is simulated. In Odeon software, acoustic environment is simulated similarly. Then, results of field measurements are used to calibrate those models.

3.2.2.1. DIALux Model

Daylight simulation model is prepared using DIALux software (Fig. 3.10). At the first step, geometry of the lecture hall is modelled from the relevant plans and existing interior details. Then, existing material types are found at DIALux material library. Field measurement day's date, time and sky conditions are set up into program. Then, glazing options and information about exterior environment is defined into simulation. This model is run and firstly errors are checked. In further steps, the simulation model's errors are fixed and results are compared with field measurements. Comparison between DIALux model and field measurements are presented in Fig.3.11 for each reference point. Particularly, the simulation outputs were greater than the field measurements at all measurement dates.

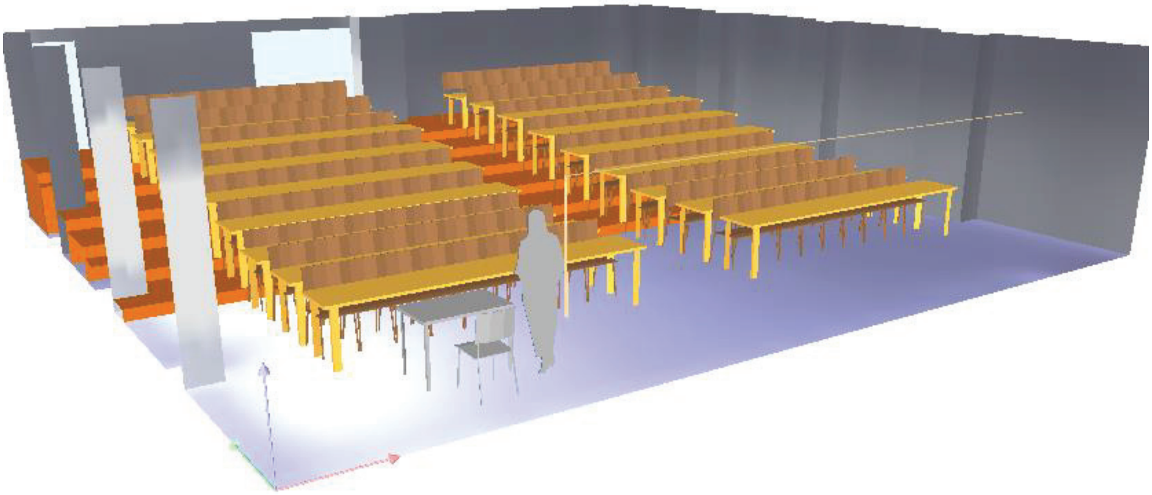


Figure 3.10. Simulation model in DIALux

To validate the model, the reflections, the details of sky conditions are slightly changed to match the exact conditions of those days. At each time, the estimations are compared with measurements and they are checked according to relative error. Relative error is a quantitative verification formula which is used in the first step of validation process (Kat & Els, 2012). Percentage of relative error of two items is given in Equation 3.3).

$$\% \text{ RE} = \left|\frac{p-m}{\text{m}}\right| \text{x } 100 \tag{3.3}$$

Where RE is relative error (Eq. 3.7), p is predicted value and m is measured value of

$$\text{RE} = \frac{p-m}{\text{m}} \tag{3.4}$$

Accordingly, average relative errors were calculated as 2.75% for 30.09.2016 at 10:30-11:30; 3.28 % at 15.00-16.00; 7.13% for 04.11.2016 at 12.00-13.00. Subsequently, scattering diagram, in other words linear regression analysis, is also prepared to compare measured and simulated illumination values for validation (Montgomery, Peck, & Vining, 2015). Regarding this validation process, the coefficient of determination (R^2) values ranged between 79% and 96% for all simulations on 30th September at 10.30 and at 15.00; and on November 4th at 12.00, showing the high accuracy of the simulation model. This meant that knowing the illuminance at a point by the simulation gives an almost 79- 96 percent chance of predicting their values on the measurement (Fig. 3.12) The overall simulation outcomes fit the field measurements very well, since percentage of obtained R^2 shows the closeness to the field measurements (Figure 3.13). Finally. the material characterizations based on reflectance values which were detected at the final model is given in Table 3.5.

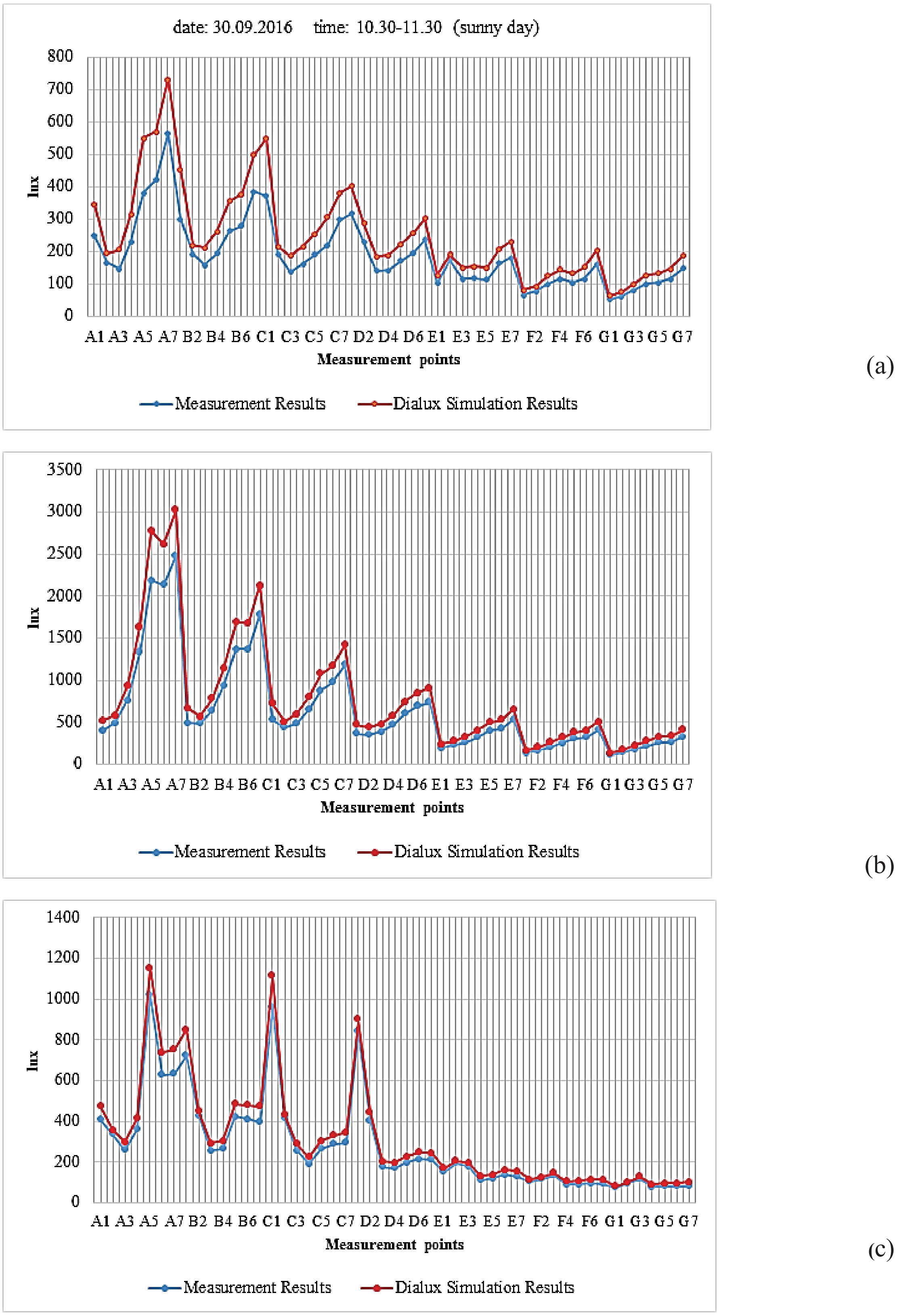


Figure 3.11. Comparison of field measurements and simulations (a) 30.09.2016; 10.30-11.30 (sunny day); (b) 30.09.2016; 15.00-16.00 (sunny day); (c) 04.11.2016; 12.00-13.00 (overcast day).

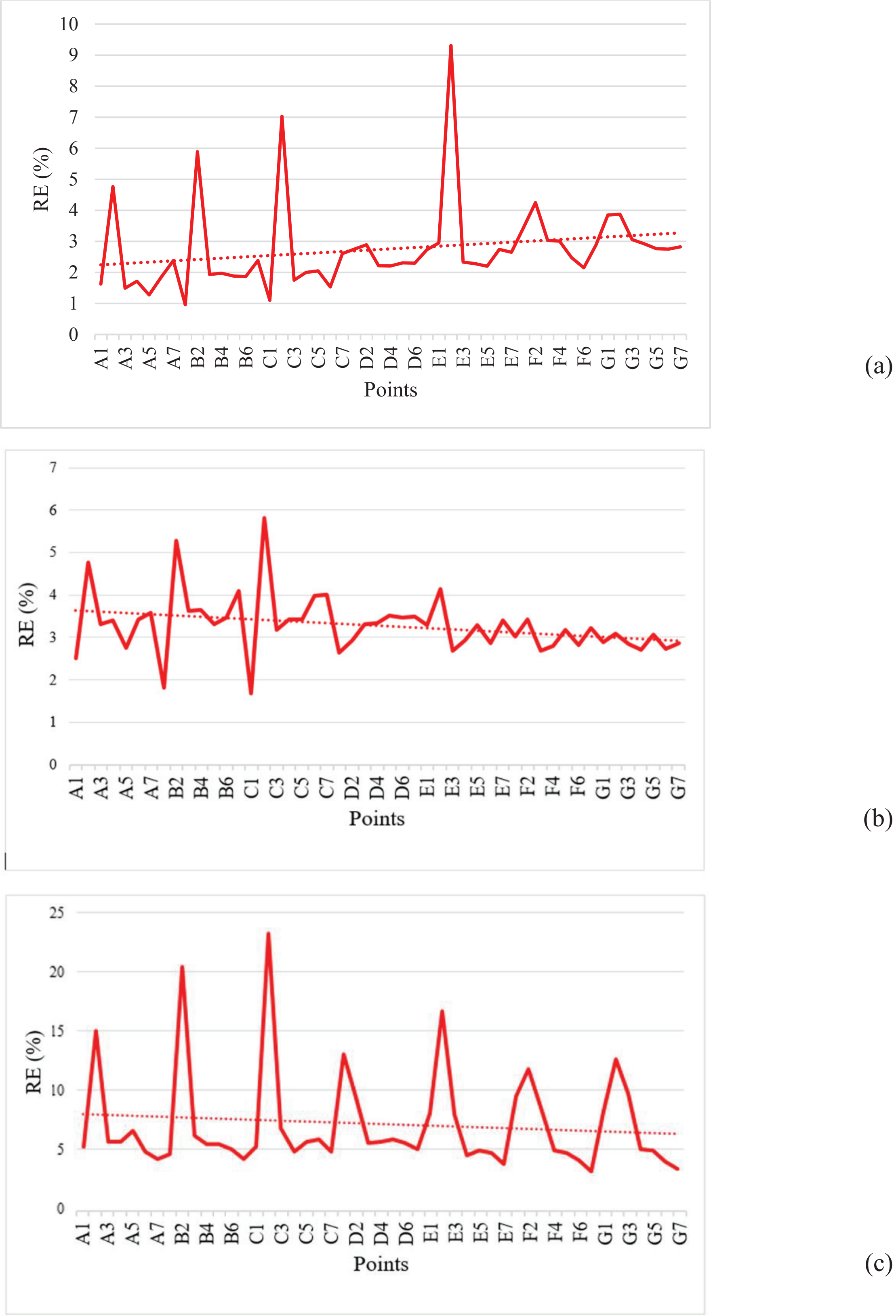


Figure 3.12. Relative errors (a) 30.09.2016; 10:30-11:30; (b) 30.09.2016; 15.00-16.00; 04.11.2016; 12.00-13.00.

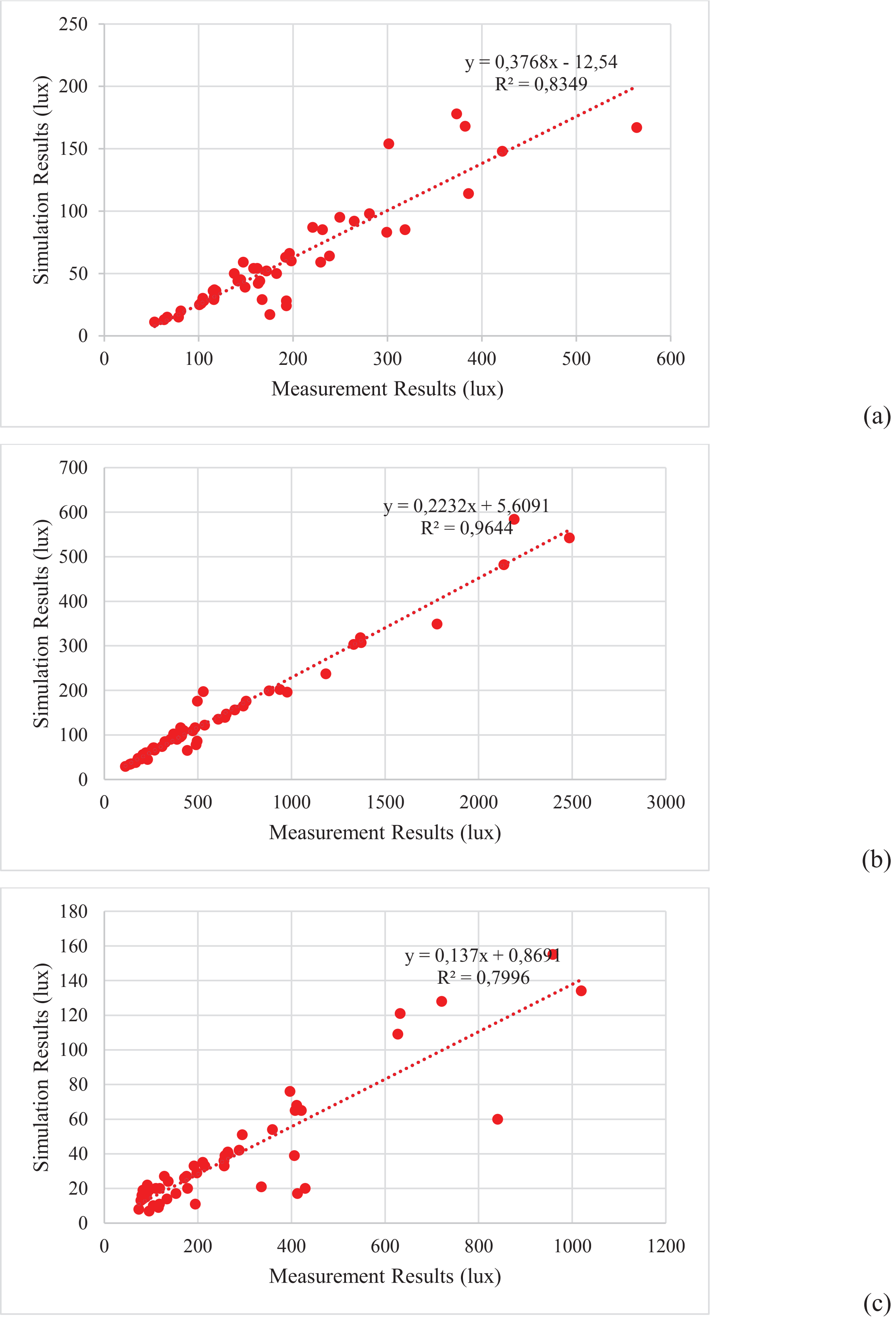


Figure 3.13. Scatter plot diagram for validation (a) 30.09.2016; 10.30-11.30; (b) 30.09.2016; 15.00-16.00; (c) 04.11.2016; 12:00-13.00.

Table 3.5. Model material specifications at DIALux

Model specifications					
Material descriptions		DIALux Material code	Material Description	Reflectance (%)	Visible Transmittance (%)
Interior environment	Ceiling	Plaster (light)	Ceiling tiles	68	-
	Main Floor	Marble	Marble tiles	64	-
	Raised Floor Covering	Vinyl	Sitting area platform covering	29	-
	Wall	9001 (cream white)	Painted plaster surface	90	-
	Door	Wood	Dark wood door panel	17	-
Furniture	Student Desk	Wood	Light wood covering	56	-
	Student Chair	1001 (Brown-beige)	Colored wood covering	28	-
	White board	White color	White color	75	
Glazing System	Window	Glass	Glazing	-	70

Regarding Table 3.5, most of the materials existing on the lecture halls has higher reflectance degrees, however, some of them like dark wood panel has lower reflectance because of its color. Ceiling tiles has lower light reflectance degree than needed to provide a uniform daylight distribution, so it decreases the daylight transmittance to the inner parts of the room. Yellow and orange colored student chairs are also another widely-used finishing surface and their choice of color decreases the inner reflections and this brings a fluctuation in illuminance distribution.

3.2.2.2. Odeon Model

The room acoustics of the existing conditions of lecture hall is simulated in ODEON software (Fig. 3.14). Acoustic model of the lecture hall is obtained through five steps. Those are geometry, material assignment, source-receiver identification, room acoustics settings, and calculation.

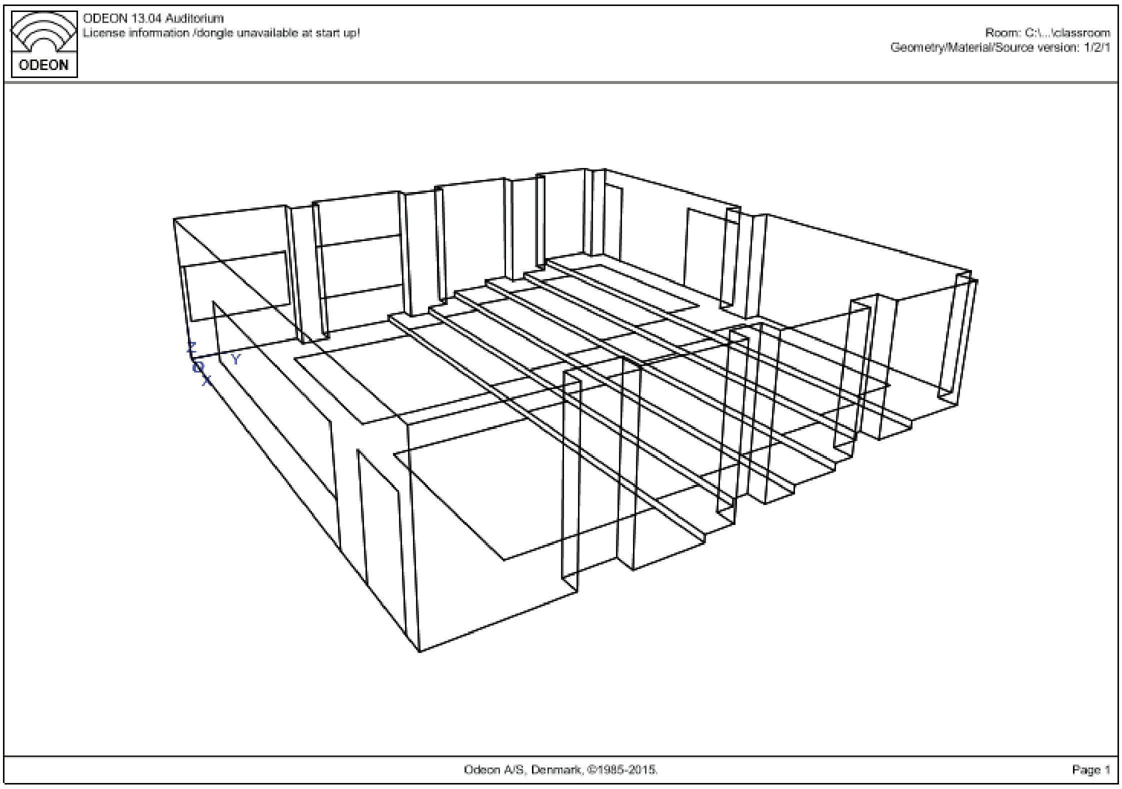


Figure 3.14. Simulation model in ODEON

At first, the geometry of lecture hall is exported from SketchUp and via SketchUp to Odeon plug-in. Geometry is checked with ray investigation in case of errors. Existing materials are identified clearly. Type of plaster, glazing surface quality and other finishing materials are listed. Then their equivalent material descriptions are chosen from Odeon library and online literature review. Absorption coefficients at each frequency between 63 Hz to 8000 Hz are added to Odeon material library and those qualities are assigned to the surfaces (Table 3.6). Then, measurement position of lecturer is placed as source and its type is selected as “BB93-Raised Natural” to simulate lecturer’s speech at the lecture hall. The receivers simulate students and their positions are arranged according to the measurement layout (Fig. 3.15).

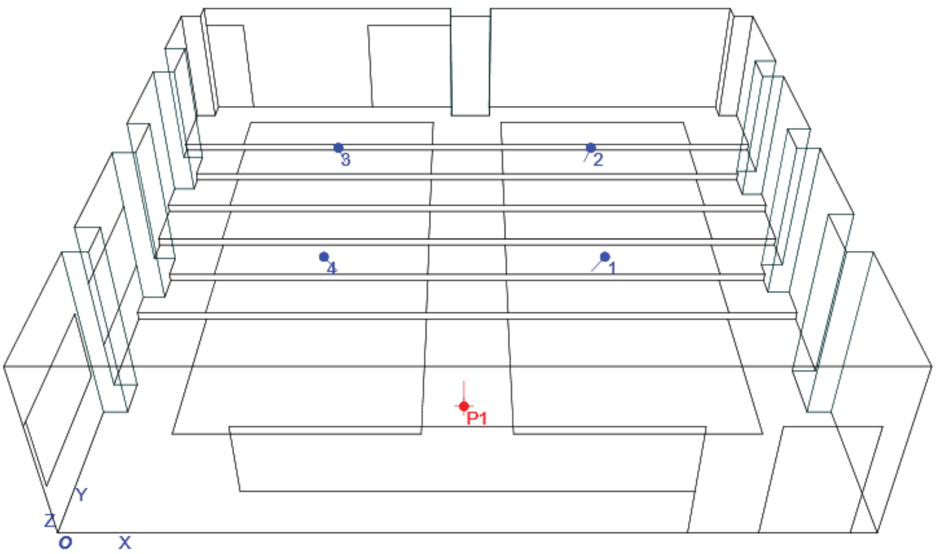


Figure 3.15. Positions of sound source and receivers

Room acoustic's simulation settings are arranged. To do this, background noise level is determined as NC 35 dB since both the building is not so loud and its limit is 45 dB in regulations (Toksoy, 2015).

Table 3.6. Model material specifications in Odeon
(Source:(Bobran, 1973; Harris, 1991; Kristensen, 1984b; www.acoustic.ua, 2016)

Material specifications		Absorption coefficients							
Code	Material Description	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
2001	Marble or glazed tile	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02
4000	Lime cement plaster	0.02	0.02	0.02	0.03	0.04	0.05	0.05	0.05
10003	Double glazing, 2-3 mm glass,10 mm gap	0.10	0.10	0.07	0.05	0.03	0.03	0.02	0.02
10007	Solid wooden door	0.14	0.14	0.10	0.06	0.08	0.10	0.10	0.10
14303	Wooden or padded chairs or seats (per item) in m^2	0.08	0.08	0.00	0.15	0.00	0.18	0.20	0.20
14309	Raised computer floor, steel faced 45 mm chipboard, 800 mm above, no carpet	0.08	0.08	0.07	0.06	0.07	0.08	0.08	0.08
14310	Suspended ceiling tiles	0.05	0.15	0.23	0.22	0.30	0.25	0.18	0.13

Odeon simulation results and measured values are compared in Fig. 3.16 between 63 Hz to 8000 Hz at octave band frequencies.

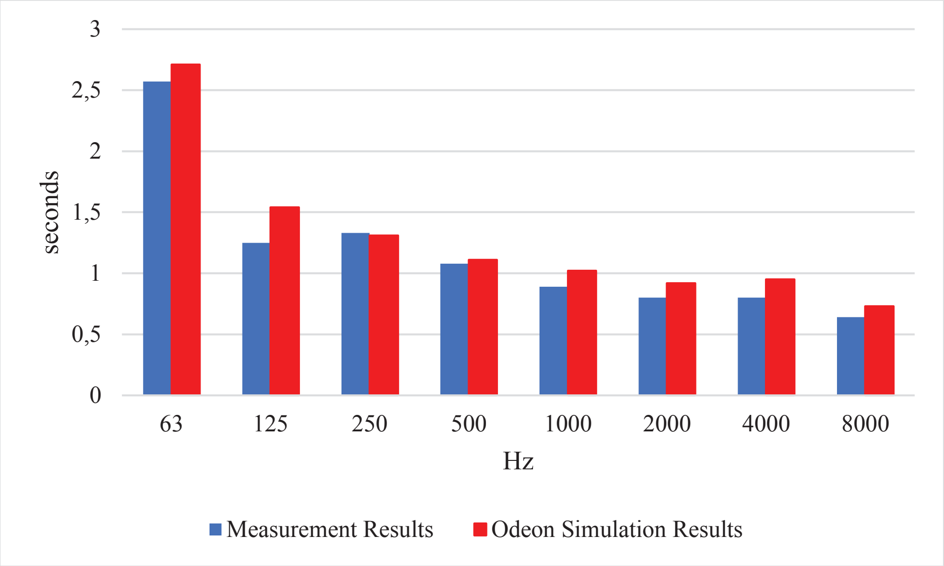


Figure 3.16. Comparison of acoustic field measurements and simulation for T20 average

Results are closer at mid frequencies which is concentrated on speech and the coefficient of determination (R^2) values is calculated as 97% (Fig. 3.17). Their correlation shows us measured and simulated outputs perfectly match, while the latter has slightly higher values than the former. T20 averages were ranged from 0.6 to 2.6 seconds in measurements; while they vary approx. from 0.75 to 2.75 seconds in Odeon model.

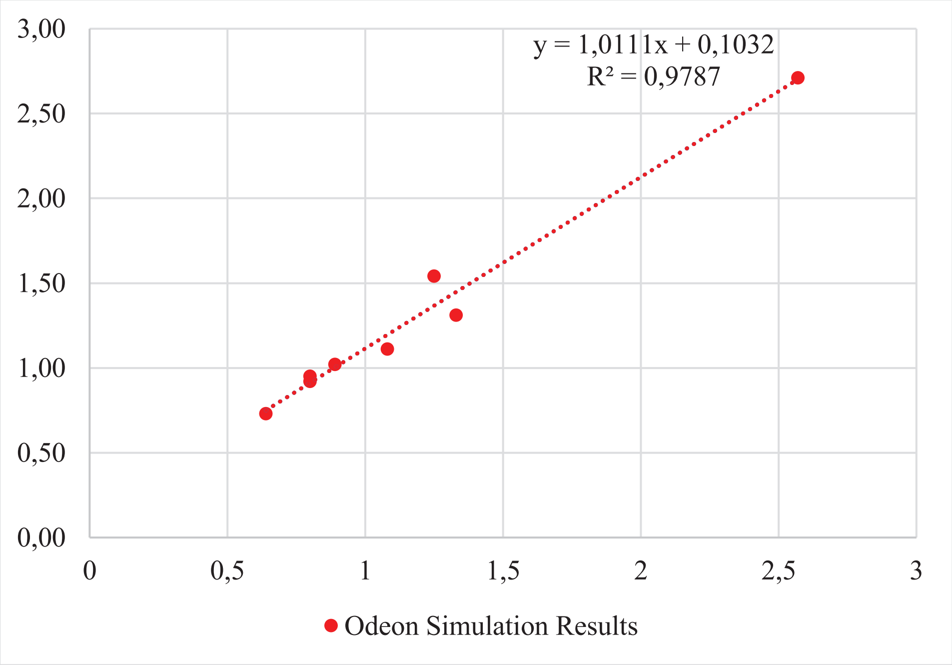


Figure 3.17. Scatter plot diagram for validation

CHAPTER 4

PROPOSING DESIGN COMPONENTS

This chapter involves information about proposed common design components, namely, ceiling geometry, seating layout and material combinations to figure out their effects in design and the ways to improve acoustic and visual performance simultaneously.

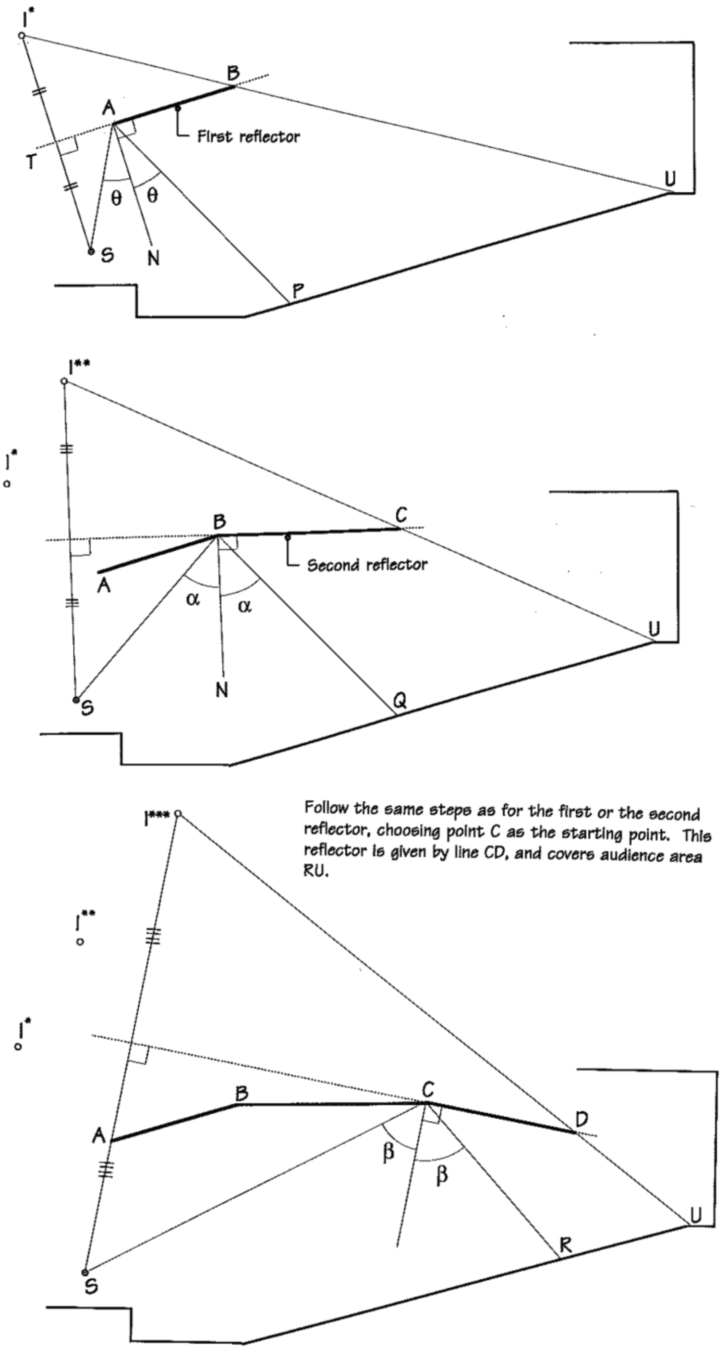
4.1. Common Design Components

Sample room, the lecture hall is evaluated depending on the visual and acoustic performance parameters mentioned above. To achieve this, their illuminance, luminance uniformity and reflectance values were specified, their visual performance were determined and the ways for improving the daylight performance were studied. In the same way, existing room's reverberation time, speech transmission index and clarity values' improvement ways are studied and common components that both effect the design performance were detected. Although there are many design components which can affect the visual and acoustic performances, three of them, namely ceiling geometry, seating layout and material combination are selected since it is possible to retrofit such an existing lecture hall by modifying these design components.

4.1.1. Ceiling Geometry

A series of studies were examined to find out how to arrange ceiling profile for a well-designed acoustic environment. At first, Mehta, Johnson and Rocafort mentioned at their book that, room shape and ceiling design need to be considered in an acoustic design process (Mehta, Johnson, & Rocafort, 1999). That includes a study on speaker-listener distance, room shape, room volume and ceiling reflector profiles. Since the scope of the study includes interior interventions, designing a ceiling reflector is chosen to be applied.

The design of a ceiling surface is prepared in three steps (Fig. 4.1) as recommended:



1st step: Placement of the first reflector surface

2nd step: Placement of the second reflector surface

3rd step: Placement of the third reflector surface

Follow the same steps as for the first or the second reflector, choosing point C as the starting point. This reflector is given by line CD, and covers audience area RU.

Figure 4.1. Reflector acoustic panel design strategies
(Source:(Mehta et al., 1999)

Ceiling geometry components are also to be improved according to the lighting needs of the lecture hall to provide a simultaneous improvement. So, since point S (source- lecturer), P and U is stable, point A is chosen up to the lighting conditions. To understand the effects of ceiling design in daylighting, ceiling design for daylighting is studied in depth. As Freewan and colleagues studied at their research, louvers and ceiling geometry effects the daylight distribution to the interiors (Freewan, Shao, & Riffat, 2009).

Regarding this study, lighting distribution characteristics is found to be similar. If the designed reflector surface is also in light reflective quality – that means its reflectivity degree is high- this surface may distribute the daylight coming from the windows.

Ceiling geometry is modified considering the existing locations and sizes of beam and columns. Conducting ceiling design strategies, it is possible to generate two ceiling alternatives. First one is to prepare one reflective panel – to test the impact of adding only one single surface- for acoustics. Second one is preparing an additional second reflector surface to the first one and applying that reflector panels to both acoustic and visual performance studies.

4.1.2. Seating Layout

A lecture hall may be used during reading, presentation and listening activities. Since each of them requires different amount and orientation of light, a seating layout of the lecture hall is to be considered up to the change of sun position (Köknel Yener, Kutlu Güvenkaya, & Şener, 2009).

To begin, alternatives of seating layouts are determined as below. Since it is desired to keep the current physical elements as much as possible and to obtain improved results, audience area and rows are kept in original dimensions and they are simply rotated to east, west and north. At each scenario, white board placement and entrance ways were analyzed and north facing alternative was eliminated since it was not appropriate to place the white board and there were problems in arranging entrance. So, seating layout variations were determined as the east and west facing alternatives. Distribution of the light can be observed from field measurements of a sunny and overcast days. Since current plan of the lecture hall facing nearly southwest, the white board and lecturer's position becomes darker than needed at the morning lecture meetings while its sunny. At the afternoon, sun position directly effects the front desks close to the west windows (A5-C5, A6-C6, A7-C7 measurement points). So, glare problem occurs at that area and rest of the lecture hall still be darker than needed. This is an issue causes non-uniform distribution of the daylight. Seating layout may be changed and raised floor may be placed facing west and east. Then presentation area, illumination level on white board and light distribution quality is to be compared with current position.

On the other hand, seating layout is also effective on distribution of the sound (Yang, Becerik-Gerber, & Mino, 2013). as seen Yang's studies on audience area and source relationships, it is understood that, surfaces that are close to the sound source (the lecturer) become the surfaces that reflect first reflection. These surfaces' material and placement are essential to determine the way of sound distributed to the hall. So, changing the seating layout may be essential to find the best material combination and placement that exist at the presentation area.

4.1.3. Material Selection

Material properties are classified as absorptive or reflective for both acoustic and lighting analysis (Briggs & Kolosov, 2009; CIBSE, 2014). Materials are grouped up to their light reflective degrees (%) in lighting and this is related with surface color, transparency, roughness and its mirror effect. However, in acoustic analysis, surface quality and material's own characteristics and density is also essential. For instance, a plasterboard surface may become less light reflective by changing its color and roughness and by adding chemicals into its ingredient, it may be acoustically absorptive.

During lighting design, it is desired to provide a uniform light distribution (Chraibi, Crommentuijn, Loenen, & Rosemann, 2017). By the help of light color selection, the space may look bright and well-lit since those colors provide additional reflectance to enlighten the interior. Surface colors are also having effect on the perception including dimension and users' mood.

The reverberation is higher than expected in high ceiling and reflective surface covered lecture halls. Increasing the reverberation reduces the intelligibility of speech. A student receives both his or her direct voices and reflected voice from walls and other surrounding surfaces.

Factors affecting the reverberation time are the absorbing surfaces at interior finishing and dimensions of the lecture hall. The reverberation time can be shortened by decreasing lecture hall sizes or by converting surfaces (floor, walls, ceiling) into high sound absorbing surfaces especially using sound-absorbing materials on the back wall of the lecture hall (Toksoy, 2015). The use of materials like carpet reduces the reverberation time. Material selection for the lecture hall is a key to determine the recommended levels of reverberation.

4.2. Design Component 1 – Proposing two ceiling geometries

Sloped ceiling panels are proposed as design component. To evaluate each ceiling panel's effect, one and two reflector panel placements is added to the current conditions of simulation model. These are identified as CG1 and CG2 respectively.

First reflector panel "AB line" is designed according to the directions mentioned in Fig. 4.2. Its axial placement is given below in section view.

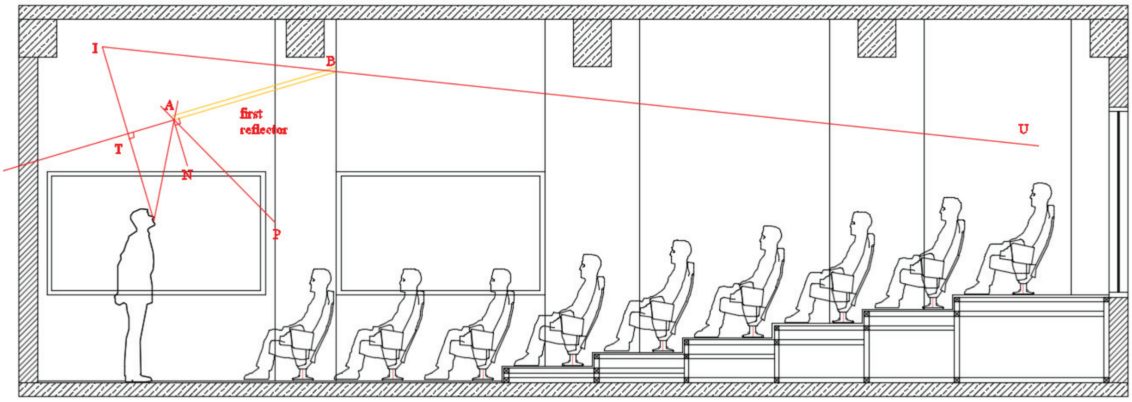


Figure 4.2. Design of first reflector in lecture hall (CG1).

Placement of the first reflector (Fig. 4.2) is also simulated at ODEON and expected reflection results are seen in acoustic simulation model (Figure 4.3).

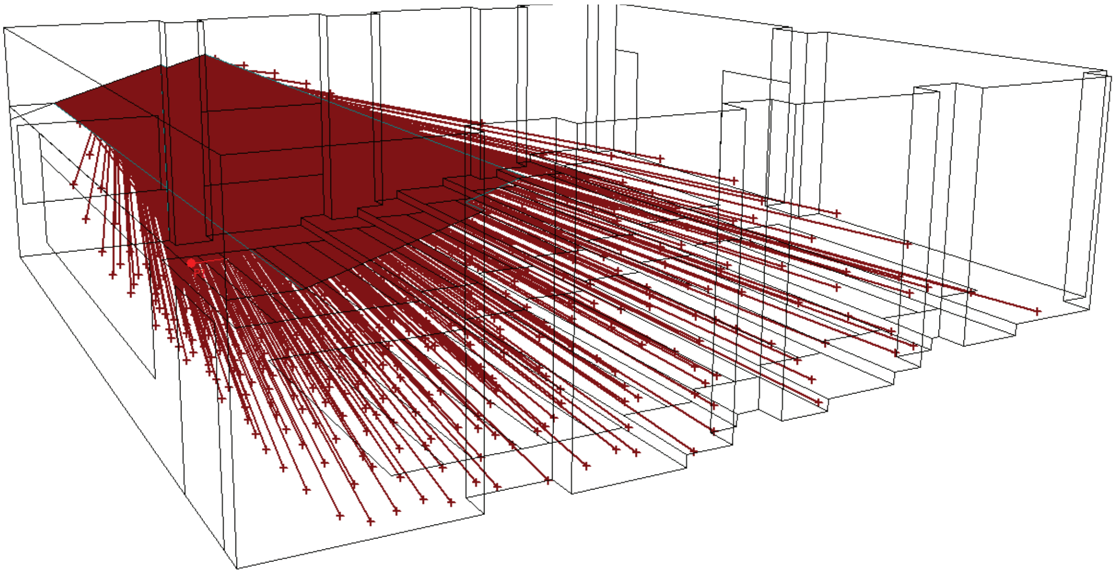


Figure 4.3. Reflection coverage in ODEON model

Following that, that reflector panel is reviewed to get the best daylight reflectance. At this step, its material quality is determined as "reflective panel" since it is needed to reflect sound (which is obtained with hard smooth surface) and daylight (which is at the lightest color and smooth surface). At the below, the placement of first reflector is seen with reflectance paths in Fig. 4.4. Interior surrounding is presented in Figure 4.5 which is a view from daylighting model.

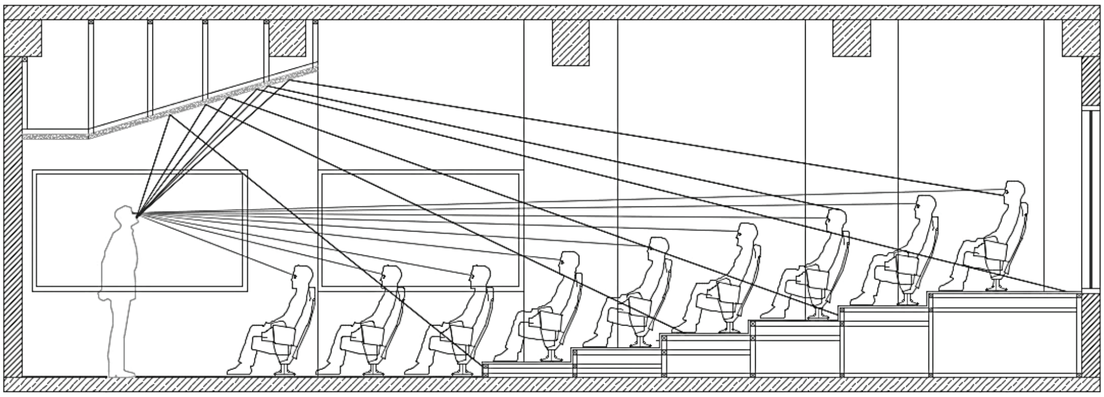


Figure 4.4. Placement of the first reflector panel (CG1)

Figure 4.5. Interior surrounding with one reflector panel, view obtained from DIALux model

After placing the first reflector panel, the second one is also added to the design to see the differences of each panel application. Details of placing the second reflector-BC line is illustrated in Figure 4.6.

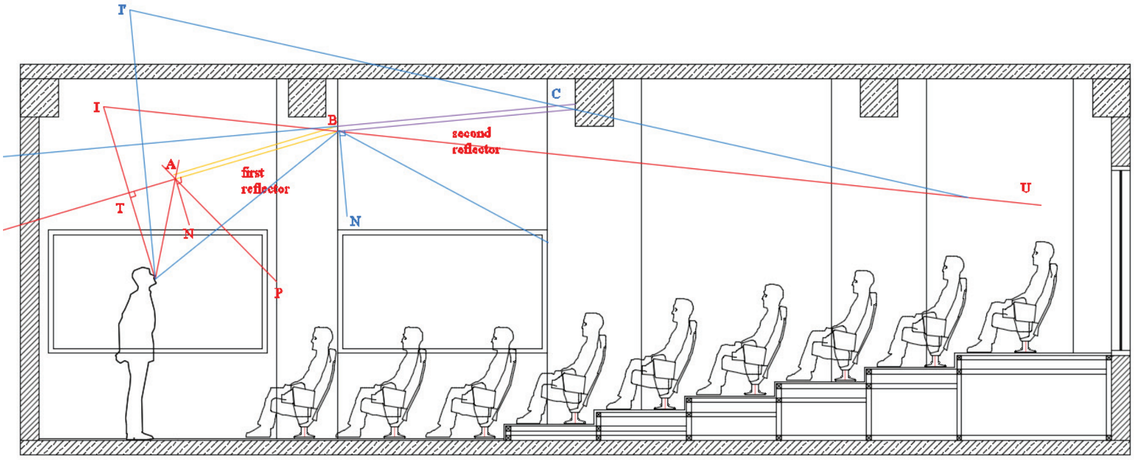


Figure 4.6. Design of second reflector panel (CG2)

Second panel is placed to the addition of the first panel and it had to fixed to the existing beams. Then it's placement is determined and illustrated in Fig. 4.8. Its acoustic model is also prepared in ODEON and reflectors are defined in simulation (Fig. 4.7 and Fig. 4.9).

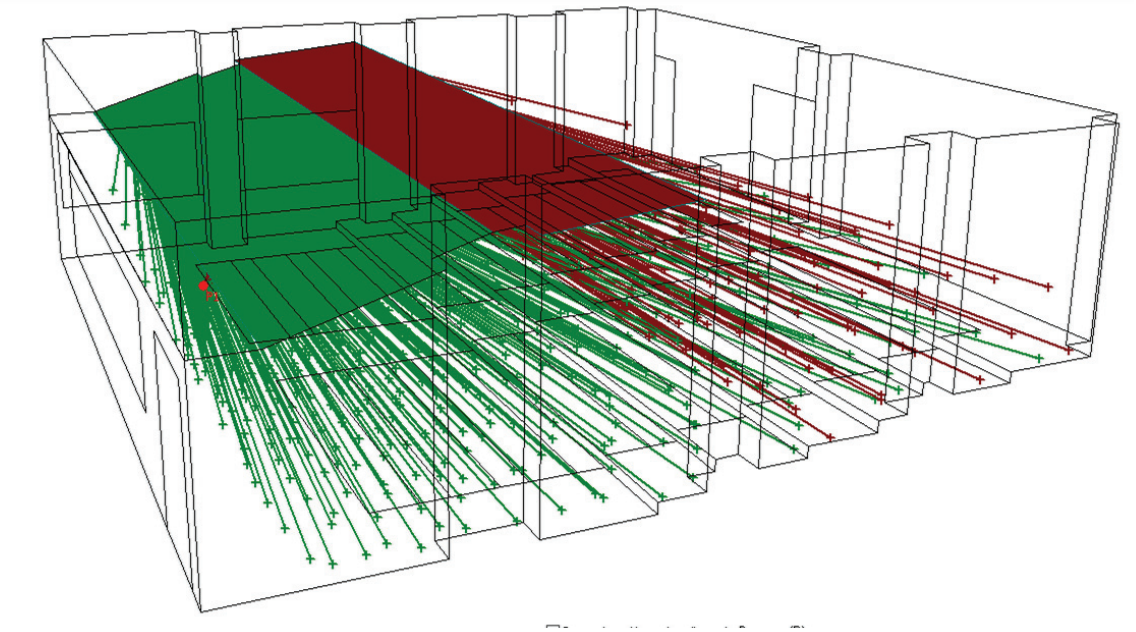


Figure 4.7. Reflection coverage of two reflectors in ODEON model

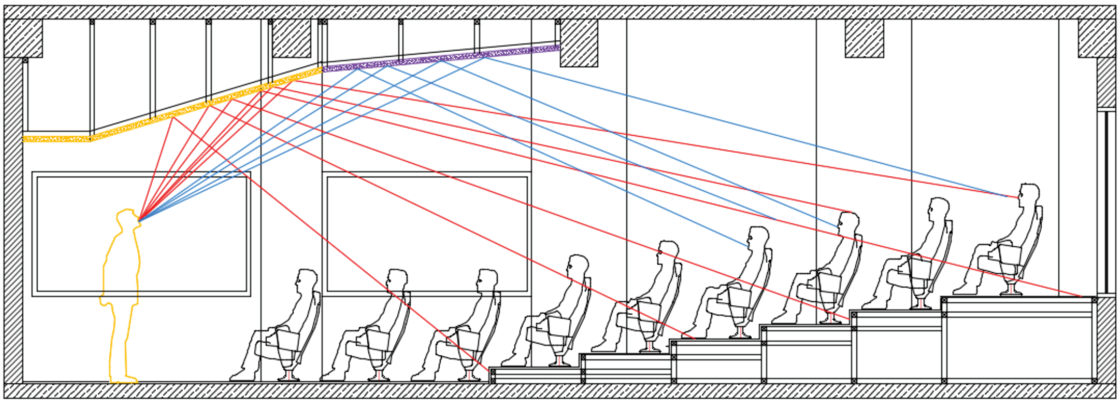


Figure 4.8. Placement of the second reflector panel

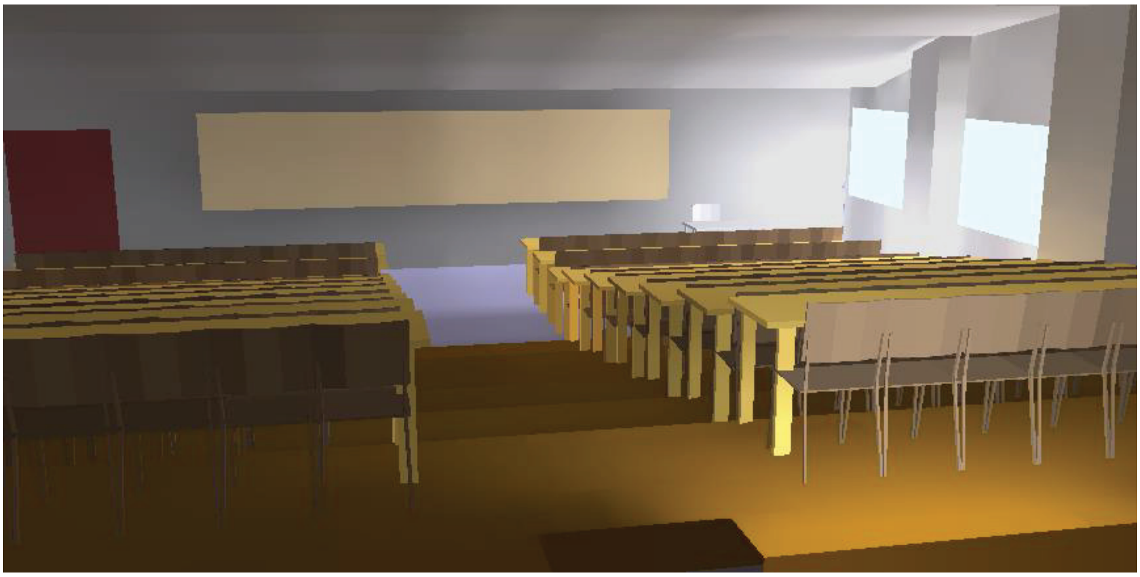


Figure 4.9. Interior surrounding with two reflector panels, view from DIALUX model

While placing two panel application types, it is desired the find out each panel's effects on the interior environment. Regarding Fig. 4.4 and 4.7, it is understood that, second panel is essential to the reach further audiences to reflect sound. Front desk audiences are able to hear both direct sound and reflected sound comes from panels. At that point, the critical distance was achieved and potential problems about acoustics are prevented. Then, lighting characteristics of applying angled reflector panels are criticized while placing them. Adding reflective finishing close to the windows' higher points is creating a potential to reflect light, however, the study is limited only with interior details, so only a part of daylighting strategies excluding window apertures is conducted to the study. Yet, slight change at some of the lighting reference values are observed.

4.3. Design Component 2 – Proposing two seating layouts

Seating layouts are effective on getting daylight from desired directions (Loe et al., 1999). So, current seating layout of the lecture hall is turned to facing west and east directions which is also appropriate to place white board. They are designated as SL1 and SL2 respectively.

Material placements and their variation when changing the seating layout is other aspect. Materials like glazing are generally remembered at sound insulation process, however, they are also existing part of room acoustics (Yılmaz Demirkale, 2007). As seen in Sirel's study, different finishing materials for instance a carpet, a window glass, a curtain or any wall covering, any suspended ceiling plate can be a significant absorber for certain frequencies, and a strong reflector for certain frequencies (Sirel, 2000).

Painted plaster surfaces on the walls and glazing are located at the windows become side part reflective surfaces in the existing case. But, glazing's and plaster surfaces' sound absorption properties has a slight difference per frequencies (Table 2.11). Glazing becomes a bit absorber at lower frequencies and has a perfect smooth surface than walls. For this reason and quality differences, placing sound source closer to the glazing area may affect sound distribution since it has reflective panel characteristics at each frequency.

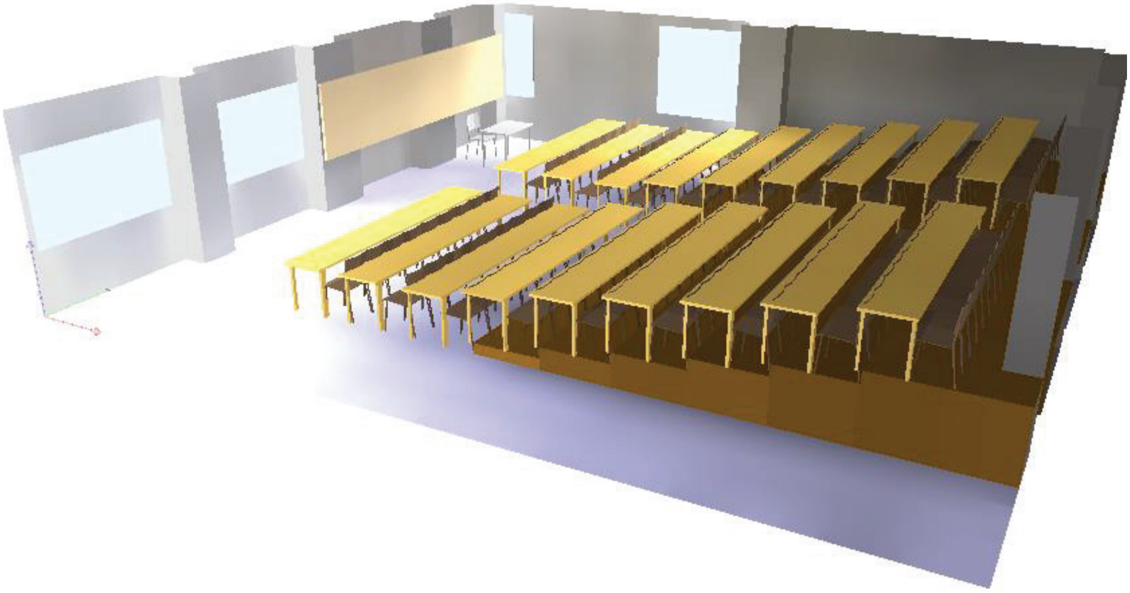


Figure 4.10. DIALux model of west facing seating layout (SL1).

At the west facing model, white board is placed on to the right part attaching to the columns (Figure 4.10). In this way, two of the daylight source paths are gathered at the presentation area. Additionally, raised floor placed to the east wall and this became an advantage to get the sunlight with the least obstacle Similarly, audience area is turned to the east facing position. At this model, daylight comes from back walls (Fig. 4.11).

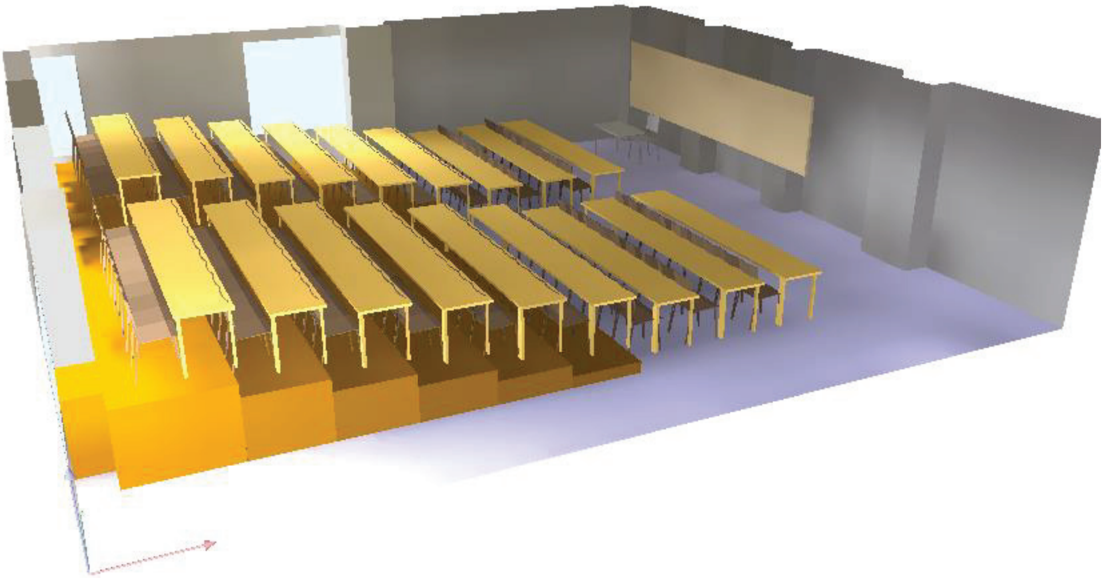


Figure 4.11. DIALux model of east facing seating layout (SL2).

Those models are chosen at opposite directional ways and prepared to see the effects of orientation of the audience area. In this way, it become possible to see either placing the light source to the sides or back part of the lecture hall.

4.4. Design Component 3 – Proposing material combinations

The third design component is fully focused on replacing materials method. At this process, existing conditions' material characteristics are criticized. As acoustic environment, lots of them can be defined as reflective areas since most of them painted plaster surfaces, marble, glazing and wood coverings. Additionally, since there are not enough surfaces that are able to absorb lower frequencies, existing conditions' T20 graph become at the higher level between 63-250 frequencies. Such clues are evaluated at the material selection phase. So, walls are totally and partly changed to be the absorptive materials and that material's absorption coefficients are selected for the acoustical needs to reach the optimum reverberation levels and speech intelligibility.

Following that, the existing conditions' lighting results are also evaluated. According to the standards, optimum illumination levels during oral communication for the lecture hall is around 300 lux, and when teacher is writing on board, it is 500 lux. However, average illumination is 308 lux, 640 lux and 281 lux respectively in field measurement days which is at closer values yet not well distributed (See Chapter 5). Walls were normally at the high reflectance degree, but their finishing surface is not smooth enough. Then while replacing the wall coverings, the sound absorber material is chosen among absorber qualified perforated wood panels at desired color. In this way, absorber defined wall covering surfaces become reflective in lighting design.

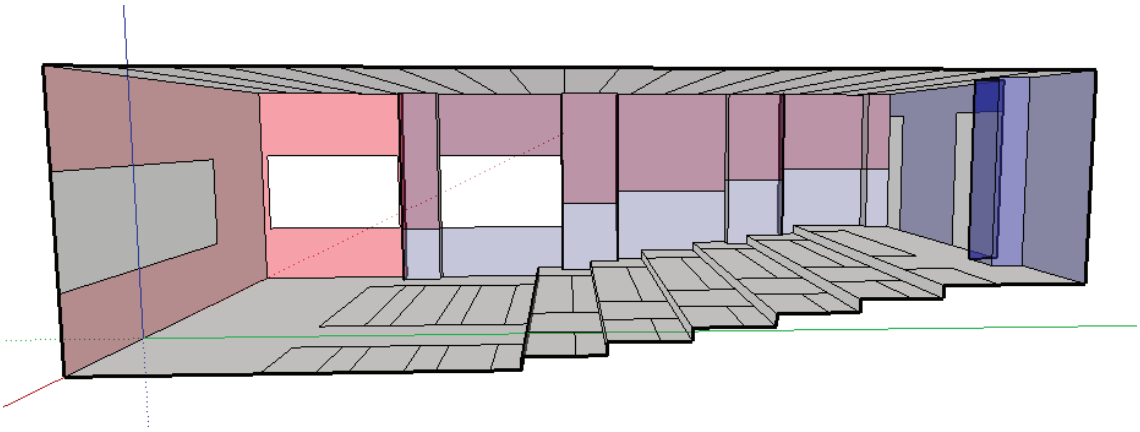


Figure 4.12. Placing three different acoustic characteristic materials on divided wall panels (MC1)

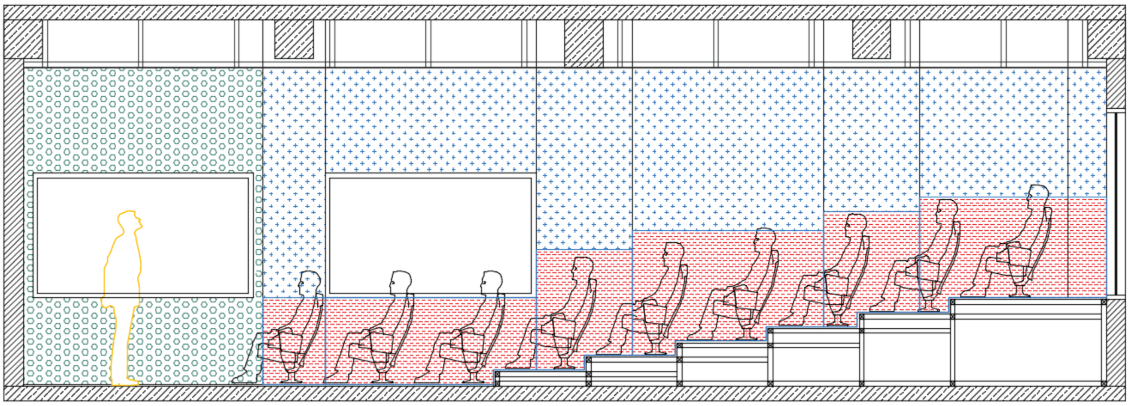


Figure 4.13. Section of MC1 application

Regarding the material placement and characteristics, two models are prepared, one is considered changes only at walls (Fig. 4.12 and Fig. 4.13) and the other one is considered changes only at ceiling materials (Fig. 4.14) and they are named MC1 and MC2 respectively.

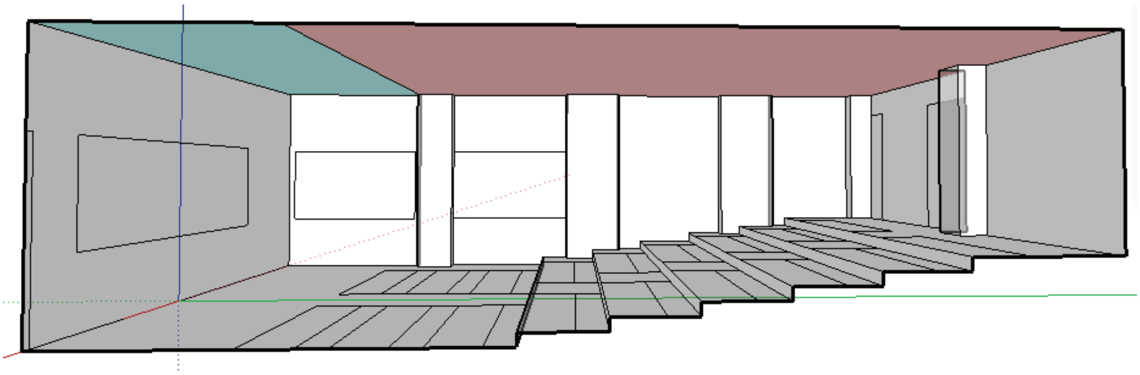


Figure 4.14. Placing two different acoustic characteristic materials on total surface of ceiling (MC2)

Additional materials are designated according to the lighting and acoustic needs. At this process, materials are examined to perform desired quality for acoustic absorption quality and light reflectance. Acoustic wood wall and ceiling panels are determined to design for the requirements. Because, it is possible to design perforated panels at desired absorption distribution by changing the hole diameter, slot dimensions and density of backfill material and thickness of backfill material that is placed to the back surface of the perforated and slotted wood acoustic panels (Table 4.1).

Table 4.1. Additional materials' acoustic characteristics

Material definition	Absorption coefficients							
	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
Material 1	0.55	0.55	0.30	0.10	0.05	0.05	0.05	0.05
Material 2	0.35	0.33	0.45	0.53	0.58	0.50	0.45	0.40
Material 3	0.55	0.60	0.63	0.65	0.65	0.55	0.45	0.30

At the same time, those panels may be smoothed and colored up to the lighting reflectance needs. At the proposing step, there was a need for smoother surface like well varnished wood panels, since reflectance values of the walls are already high thanks to the color choice of the walls at lighting design. So, Material 1 and 2 is optimized up to that needs. Simultaneously, Material 1 is chosen to absorb lower frequencies, which is defined bass absorber acoustic panel, Material 2 is chosen as light colored and able to absorb mid frequencies. Material 3 is chosen as mainly mid-frequency absorber acoustic ceiling panel. All of them are prepared with smooth and light colored surface to reflect the light to the interior areas (see Table 4.2).

Table 4.2. Additional materials' lighting characteristics

Material definition	Material Description	Smoothness (%)	Reflectance (%)	Visible Transmittance (%)
Material 1	Bass absorber acoustic wall panel	0	90	0
Material 2	Mid frequency absorber acoustic wall panel	0	90	0
Material 3	Absorber acoustic ceiling panel	0	90	0

CHAPTER 5

RESULTS

5.1. Findings Regarding Field Measurements

Current daylighting and acoustic conditions of the lecture hall was examined and they were found to be poor in general according to daylight measurement findings as below.

5.1.1. Daylight Measurement Results

On-site measurements were done in the lecture hall on three specific time stamps, first, on September 30th, 2016 at 10.30, second, on September 30th at 15.00 and finally, on November 4th at 12.00 under clear and overcast sky conditions. During the analysis phase of current conditions, September 30th, 2016- 15:00-16:00 measurements are chosen for determining the effects of design components since the coefficient of determination is founded at the highest level among other measurements.

Here, to inform about the overall daylight conditions, minimum, maximum and average values of illuminance values are presented in bar charts in Figure 5.1. The days are quite near to the autumn equinox. The reason why the illuminance on November 4th is lower than the daylight levels on September 30th at nearly similar day time is the sky condition. The former is under the overcast sky while the latter is under clear sky. Due to the orientation of this room facing west and north, illuminance readings are at the lowest level in the morning on September. Although the shape of the room is rectangle whose edge lengths close to each other, the inadequate illuminance below 100 lx near the two rear walls is caused mainly because of the insufficient value of window to wall ratio which is approx. 20 %; the high value of depth which is 12 m; and the arbitrarily located windows.

When we examine the illuminance at points in detail, almost 40 % of the room satisfies the daylight requirement of a lecture hall on September 30th in the morning, 70% in the afternoon and 30 % on November 4th at noon.

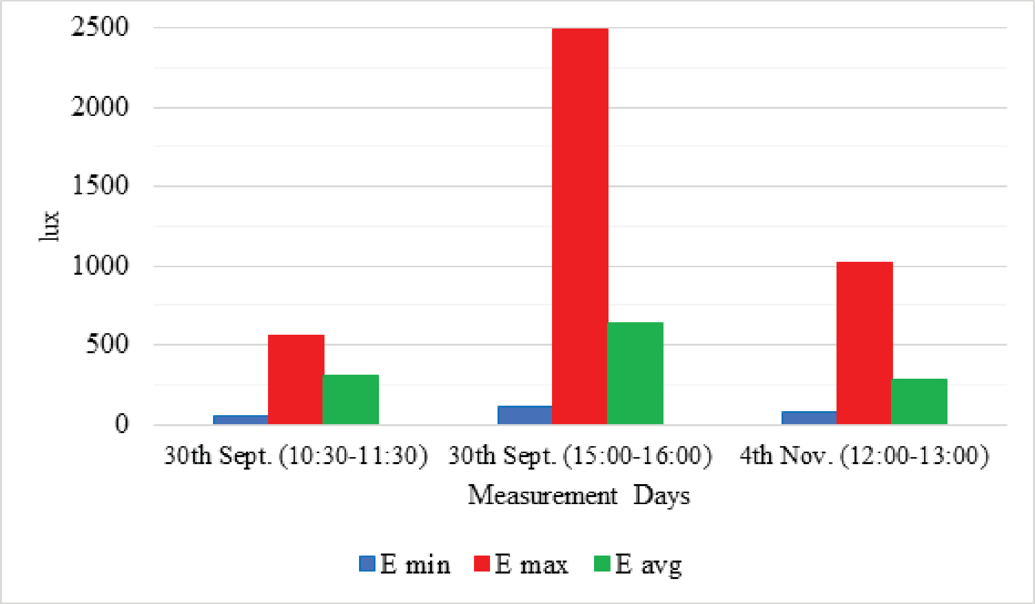


Figure 5.1. Min., max. and average illumination levels on field measurement days

The external and internal illumination levels are presented in Fig. 5.2. Windows located at the side wall named as W1 and W2, and windows located at the back wall are W3 and W4. Highest illuminations in interior surrounding are observed (509 lux in avg.) at Sept. 30th ,15:00-16:00 measurement set, where they are at the lowest level (454 lux in avg.) at Nov. 4th, 12:00-13:00.

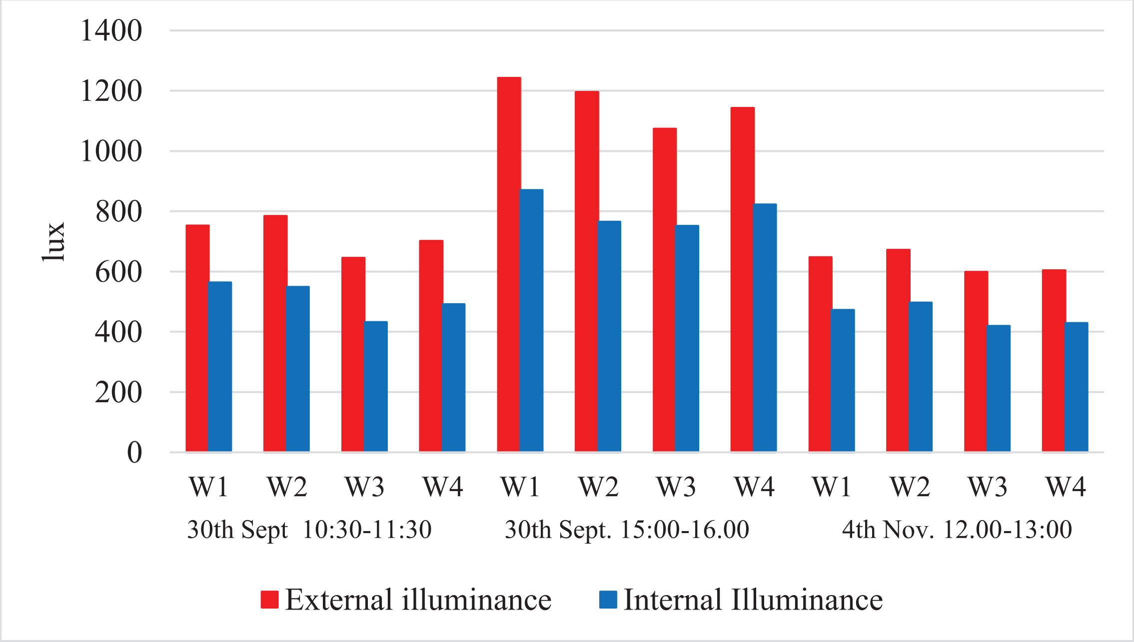


Figure 5.2. External and internal illumination levels on field measurement days

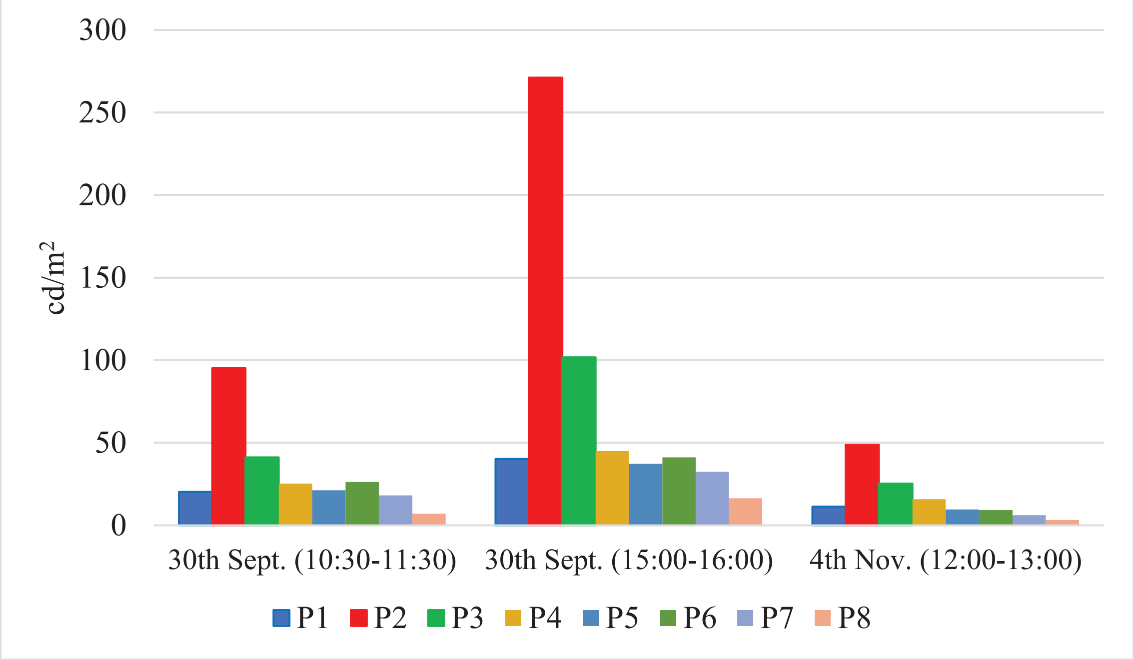


Figure 5.3. Luminance levels at selected points on field measurement days

Fig. 5.3 represents the value of luminance levels at determined eight points (Fig. 3.6) that are selected up to the possible white board locations. P3, P4 and P5 are located at the surface of white board at existing seating layout. P1 is the location of luminance measurement of SL1 layout -white board placement and P6 and P7 points are the location of luminance measurement of SL2 layout. As seen in Fig. 5.3, luminance values are respectively higher at September 30th, 15:00-16:00 field measurement set. P2 location which is close to the glazing are has the highest value with 271.2 cd/m^2 where the P8 has the lowest value 16.5 cd/m^2 which is located at the back part of the lecture hall. While considering the two types of seating layout, P1 and P6-P7 points are evaluated. Both are around 40 cd/m^2 at September 30th , 15:00-16:00 field measurement set and that value is higher than P8 averages. So, west and east faced white board locations are worth to consider because of their luminance values and two seating layouts are arranged up to the luminance measurements.

5.1.2. Acoustic Parameters' Results

During the evaluation process of acoustic field measurements, average of four receiver points is used to obtain reverberation time of the lecture hall. (Fig. 5.4). Four points of microphones T20 results are changing between 2.23 and 2.87 at low frequencies, 1.06 and 1.33 at mid frequencies and 0.64 and 0.8 at high frequencies.

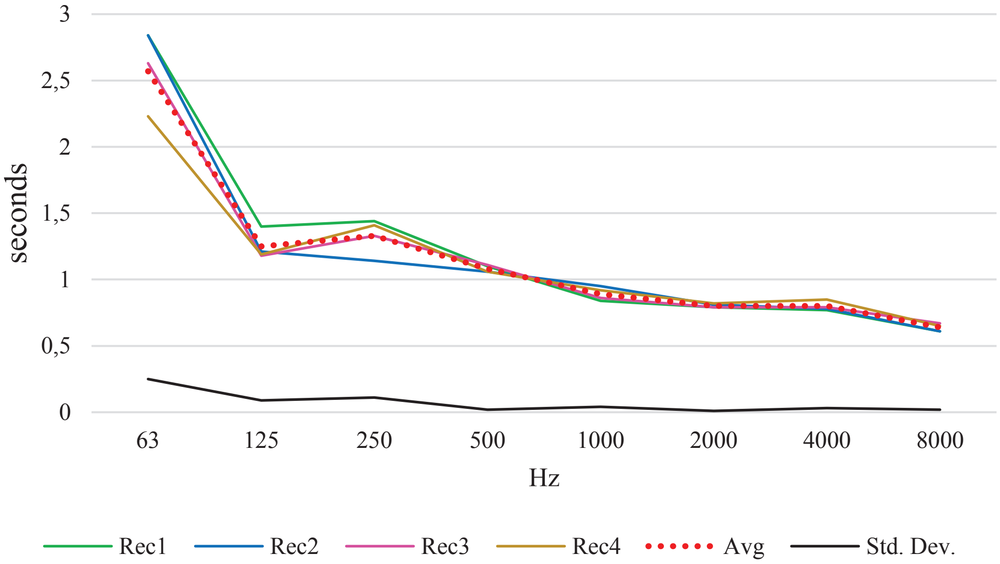


Figure 5.4. Existing conditions' T20 average from acoustic field measurement

As seen, red dotted line illustrates the average distribution of T20. This average is higher at low frequencies (63-125 Hz) which is 2.5 sec and relatively lower at mid frequencies (500-1000 Hz) which is 1.1 sec.

Since the lecture hall is used with speech and presentation purpose, it is desired to fit the reverberation times at mid frequencies (500-1000 Hz) to the recommended values. So, the most considerable part of the field measurements was the mid frequency reverberations. Lastly, the averages at high frequencies (4000-8000 Hz) is calculated as 0.8 sec, which is also the lowest value of reverberation times.

From these averages, it is understood that, this lecture hall is quite reflective at low frequencies since there is almost none of surface is able to absorb lower frequencies. There is a higher degree of reverberation for speech and that distribution is needed to be decreased to the recommended value, which is around 0.7 sec (Fig. 2.5).

5.2. Findings Regarding Simulation

At this part of study, three field measurements for lighting conditions and results of acoustic field measurements are presented.

5.2.1. Daylight Simulation Results

To simulate design components and their effects, Sept 30th, 15:00-16:00 conditions are used. At this evaluation, minimum illumination is calculated 29 lux at the rear areas of the lecture hall, 584 lux at the areas that are close to the west side glazing and average illumination levels are observed as 148 lux, which is under the recommended values.

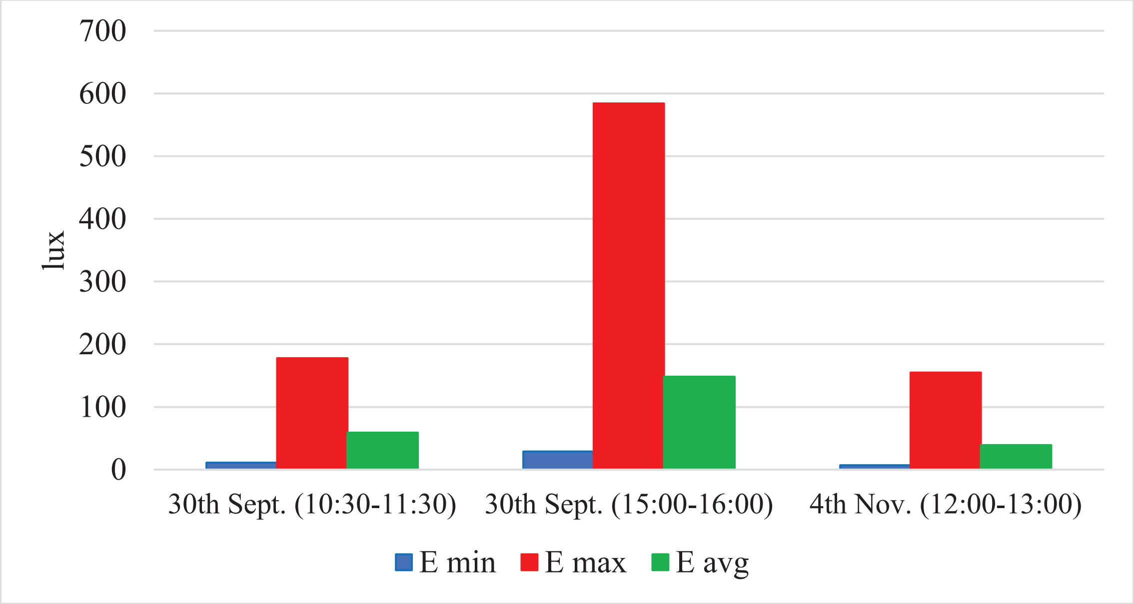


Figure 5.5. DIALux results for the existing condition

Existing condition's illuminance distribution means that, 50 lux line covers almost half of the seating area, which is extremely low at the recommended levels. The highest values of around 500 lux is apparent near the window region. The recommended illuminance 300 lux cannot be satisfied on the majority of the work plane which is the seating area. The illuminance on the white board fluctuates from more than 500 lux to lower values of 50 lux. Similarly, luminance distribution covers a wide range from 400 cd/m^2 to values below 50 cd/m^2. Lower luminance values cover more than the half of the wall area and the brightness ratio is around 1/10 on this vertical surface. That is acceptable for a comfortable vision. Although the one third of the area has the highest illuminance value, the brightest area is less than the one tenth of the wall.

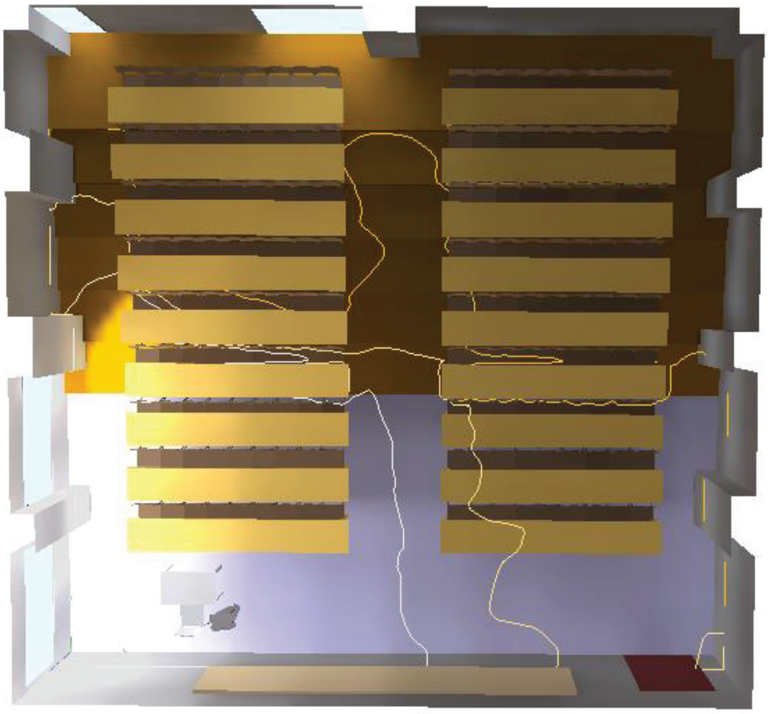


Figure 5.6. Illumination level distribution

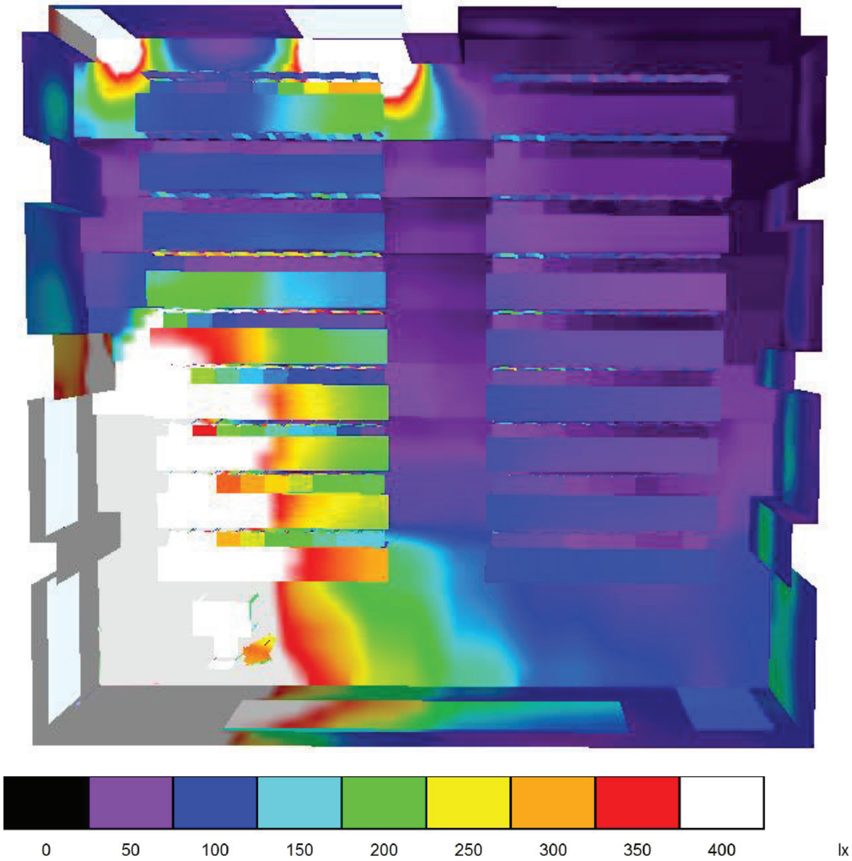


Figure 5.7. False color distribution (unit: lux)

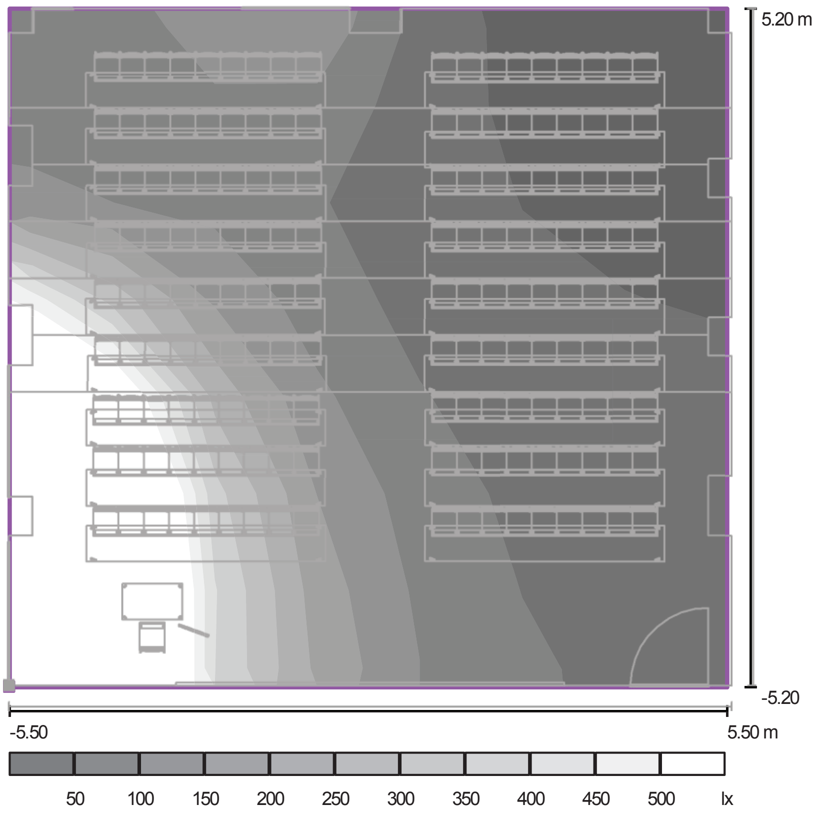


Figure 5.8. Illuminance distribution on work plane (unit: lux)

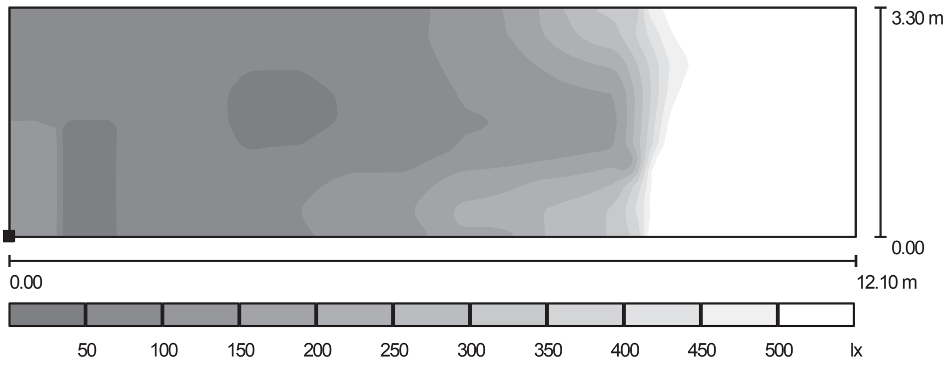


Figure 5.9. Illuminance value distribution on white board’s wall (unit: lux)

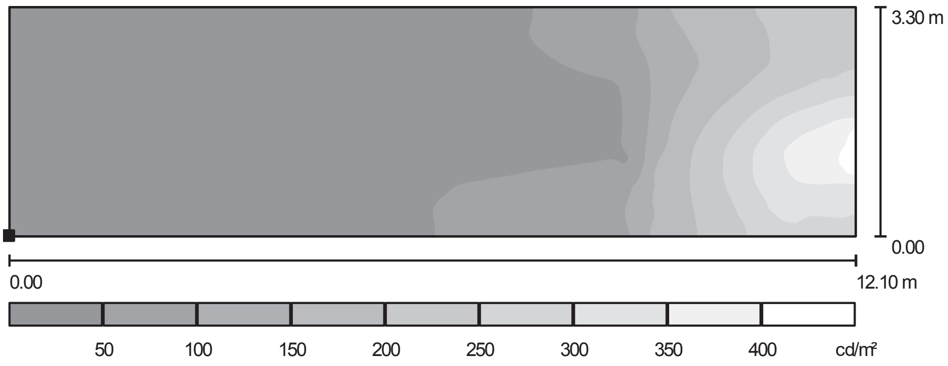


Figure 5.10. Luminance value distribution on white board’s wall (unit: cd/m^2)

5.2.2. Acoustic Simulation Results

The selected lecture hall was examined in terms of acoustical requirements and the architectural and seating layout relationships shown in the following drawings were examined.

For acoustical investigation, firstly, the seating arrangement and the hall geometry in the existing conditions are evaluated and modeled. The volume of the hall was calculated as 393.4 m^3. Then, current conditions materials are assigned and related background noise settings are assigned to the model. Acoustic parameters obtained as containing existing ceiling form, wall coverings and other materials at the site are as follows.

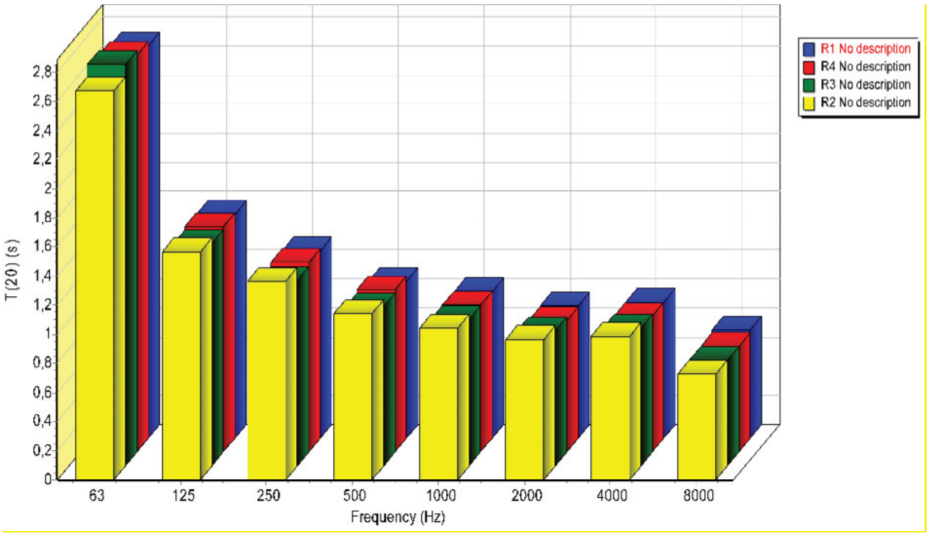


Figure 5.11. T20 results of receiver points for existing model

The time required for a decrease of 20 dB after sound source switched off is called T20. Above, the T20 values obtained at the four different receiver points described in Figure 5.11 are given. Blue bar corresponds to Receiver 1 (R1), yellow bar is for R2, green bar is for R3 and red bar is for R4. Below, T20 parameters are given in terms of grid calculations at 500-1000 Hz (Fig 5.12). In mid frequencies (500 – 1000 Hz), receivers obtain T20 values around 1.2 – 1.4 s. For this volume and aim of speech, when the target reverberation time value specified in international standards for the hall are examined (Fig. 2.4), it should be in the range of 0.7-0.8 sec while considering T20 averages at 500 Hz- 1000 Hz frequencies. Yet, simulated values are higher than recommended values and they need to be lowered to reach higher speech intelligibility levels since there is more than required reverberation time.

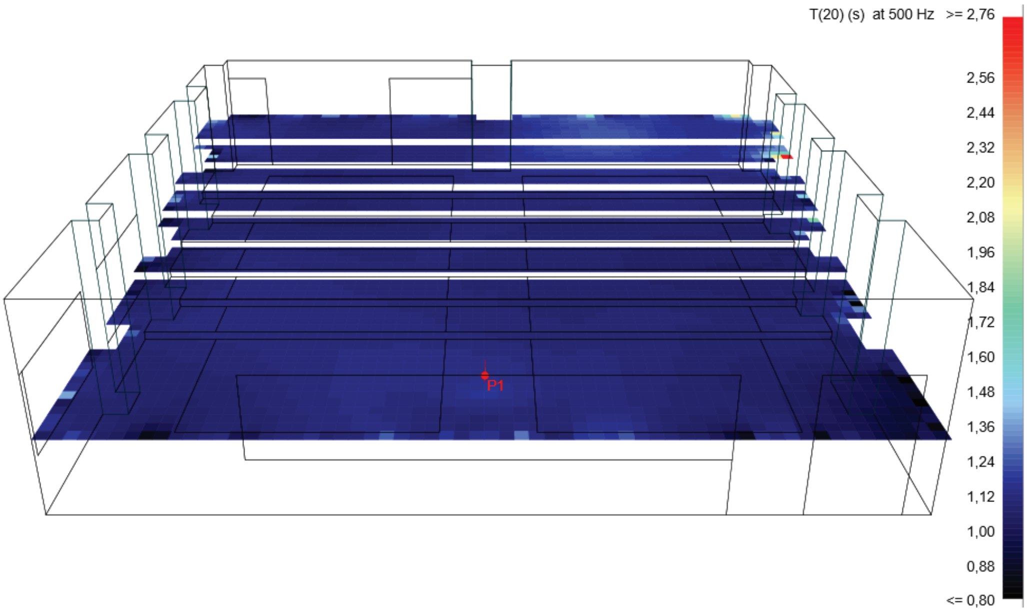


Figure 5.12. T20 results of grid calculation at 500 Hz for existing model

The distribution of T20 parameter at frequencies of 500 Hz is calculated as 1.10 sec where the recommended level for that volume is around 0.7 sec for speech oriented lecture halls. It is related to reverberation time. When the figures are examined, the distributions of T20 parameters are higher than recommended values but uniform in the whole audience. That means, the lecture hall is uniformly covered with reflective surfaces. Yet, reverberation levels are higher and longer than recommendations (Fig.2.4). So, there is a need of solution that distributes or effects the whole hall uniformly, not locally to decrease the reflection at each area of the hall.

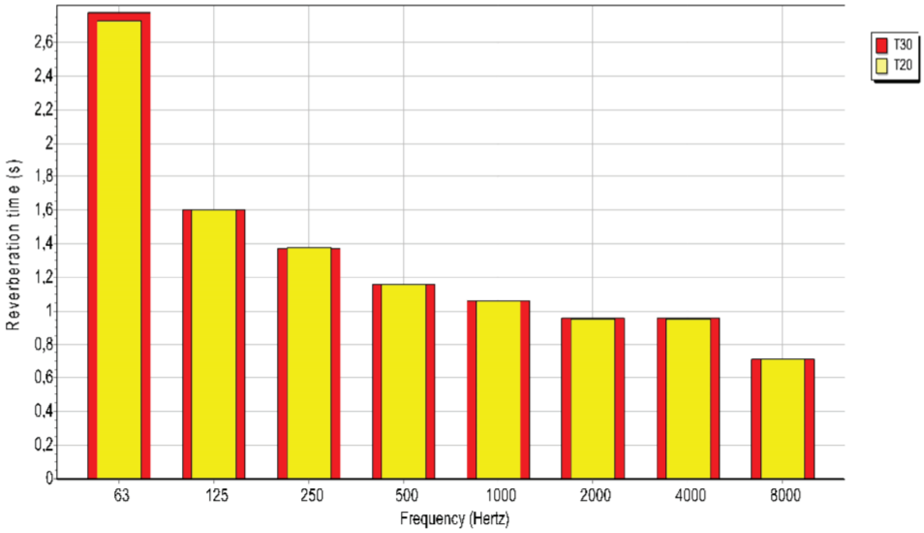


Figure 5.13. Reverberation time results of existing model

Reverberation time is advised to be between 0.7 and 0.8 sec according to the standards (Moore, 1978).When Fig.5.13 examined, existing conditions reverberation time distribution is higher at low frequencies and a bit lower at mid frequencies. However, since the lecture hall is proposed to be used with speech and presentation, it is essential to cover between 250 Hz to 2000 Hz and that area is between 1.00-1.1 sec.

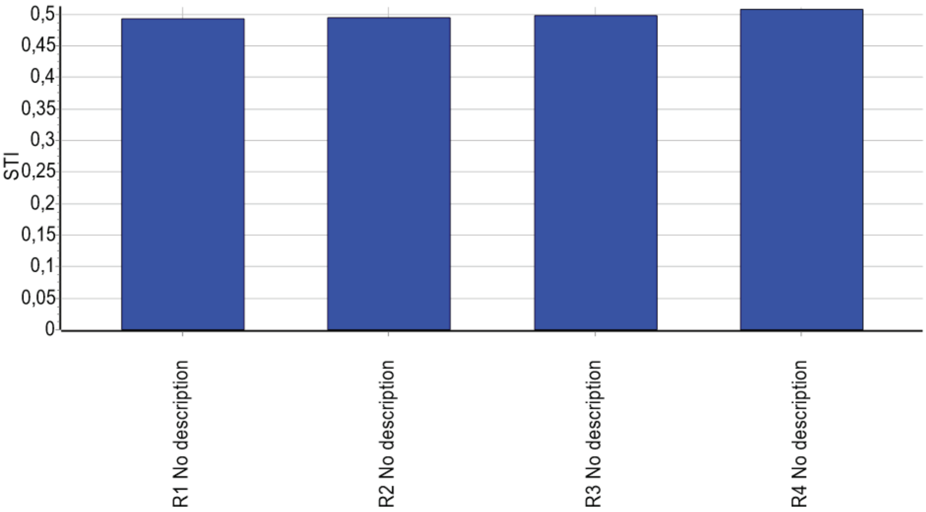


Figure 5.14. STI averages of receiver points for existing model

The STI value, which is the speech intelligibility parameter, is one of the basic design parameters of the lecture halls. the average STI values of 4 receiving points is calculated as 0.50 (Fig. 5.14), it indicates that the room is not suitable for speaking purposes since 0.60 and over in the 'good' category in the literature.

Below, STI parameters are given in terms of grid calculations (Fig. 5.15). As seen, only the parts covered with red are around 0.57-0.59 STI level that are close to the 0.60 - good STI limit. However, only the first line of audiences is able to hear with that quality, rest of the lecture hall is calculated around 0.50 STI value, which is found to be in fair level and those audiences are not able to hear the presenter.

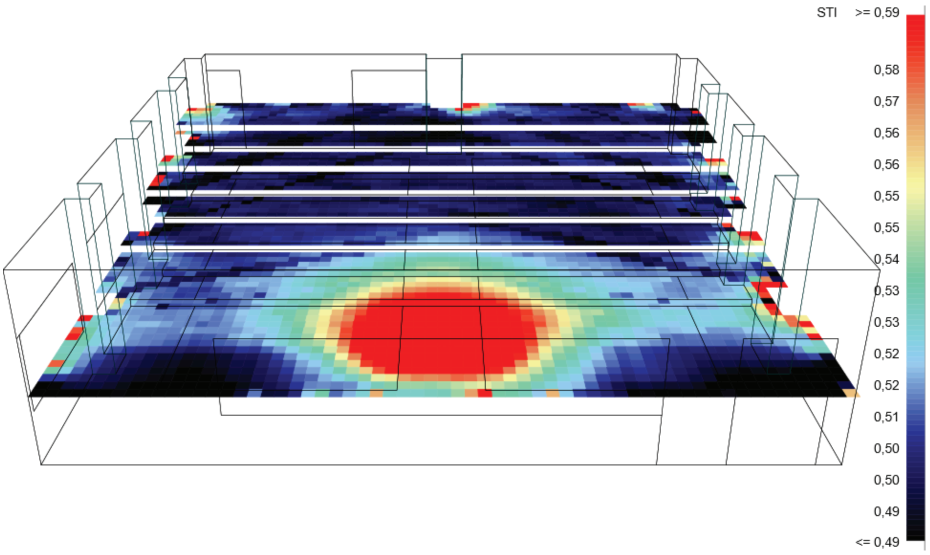


Figure 5.15. STI results of grid calculation for existing model

C50 parameter, which specifies the ratio of the sounds before and after 50 ms in dB in the C impulse response, is required to be positive values as a measure of speech clarity of the room.

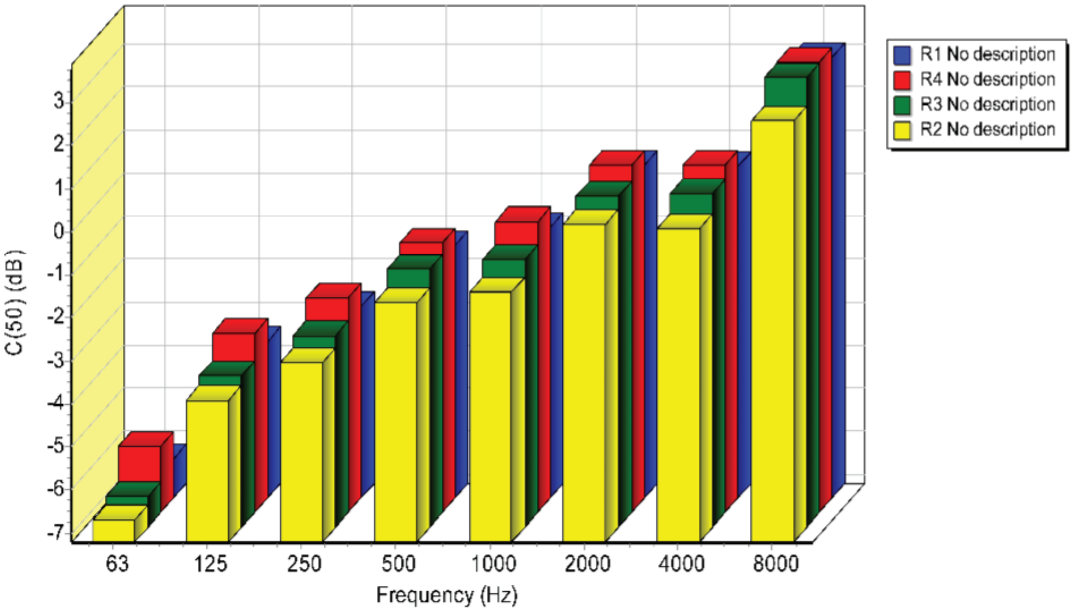
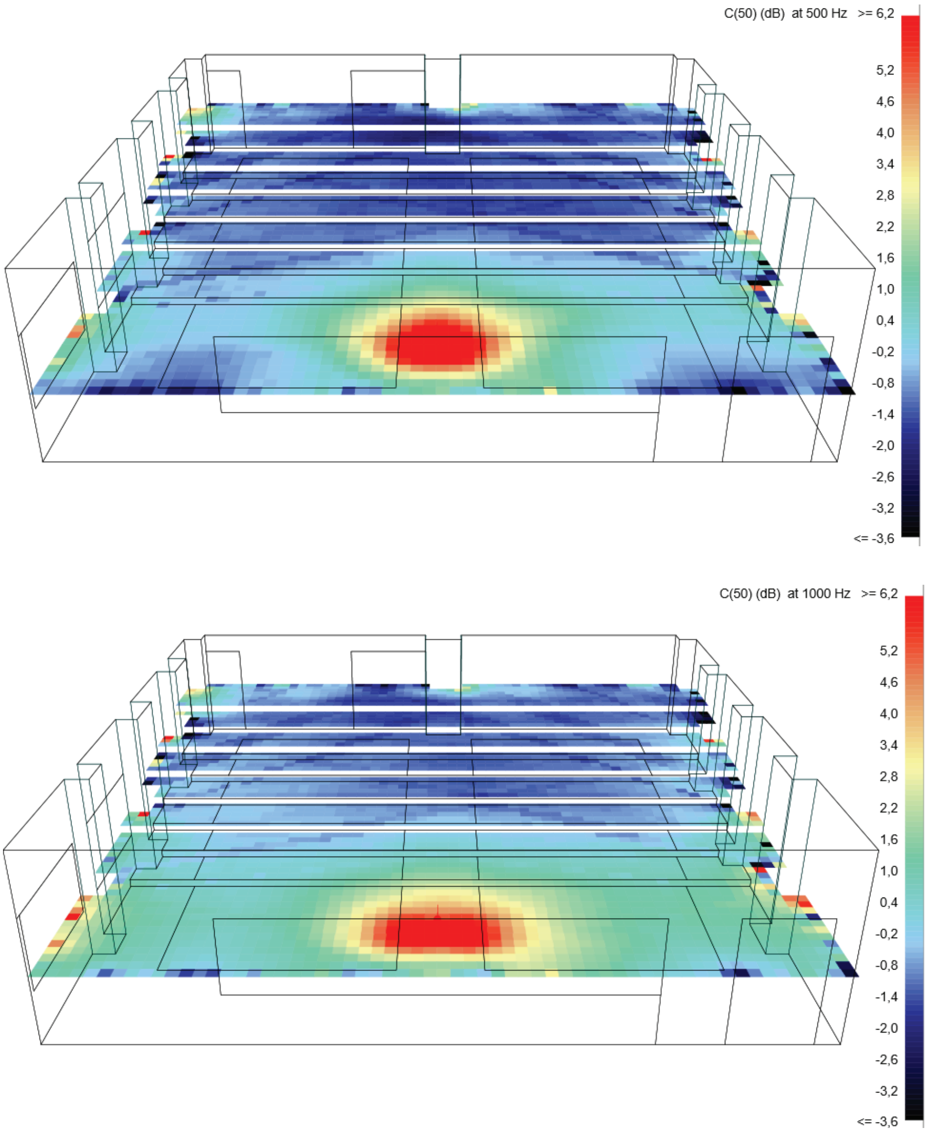


Figure 5.16. C50 averages of receiver points for existing model

According to Figure 5.16, an average value of -1.2 dB at 500-1000 Hz was obtained. The negative value of this value is an indication of insufficient clarity evaluation of the place. The recommendations for C50 are in positive values between 500-1000 Hz, but the distribution of C50 values is only can be reach to that level at 2000 Hz and higher. Since the room needs to be fit to the recommendations of speech, it is required to reach to the values at least at 500 Hz. Below, C50 parameters are given in terms of grid calculations at 500-1000 Hz (Fig. 5.17).



(a)

(b)

Figure 5.17. C50 results of grid calculation at 500 Hz and 1000 Hz for existing model

As seen in Fig. 5.17., areas covered with light green, yellow and red illustrates the positive C50 values. Almost all the lecture hall excluding the first line is negative and their speech clarity is under the recommended level and poor quality.

5.3. Application of the Proposed Systems

As can be acquired from the result maps of field measurements and DIALux simulations, the existing daylighting condition of the lecture hall was insufficient considering the norms of lecture halls and teaching areas. Existing condition's daylight distribution was not uniform and inner parts of the hall was not satisfying the minimum illumination levels and reference points concluding A5-C5, A6-C6, and A7-C7 which are close to the west side glazing areas were too bright to sit at that area. The measured values of luminance were noticeably differing from each other. Glazing ratio, which is the ratio between glazing and floor square meters, need to be calculated to determine the existing rooms' glare problems. So, depth of the lecture hall was 12 m and glazing ratio is calculated around % 20 for the lecture hall. That value is highly lower than minimum limits for the learning spaces and this was one of the elements that creates a nonuniform distribution of the light.

Considering field measurements for room acoustics, reverberation distribution of the lecture hall is found ununiformly distributed. Reverberation was too high (2.5 sec) at lower frequencies, relatively lower (1.1 sec) but still much more than recommended values at mid frequencies and closer to the recommendations at high frequencies (0.8 sec). So, it was determined to lower the mid frequency reverberation and increase the absorption with material combination was decided. Seating layout is analyzed and variations are evaluated.

With those determinations, this thesis stated proposed design component which cover internal changes to improve the daylight and room acoustic performances in this lecture hall. In regard of those design components, each application should provide a more uniform distribution of light and speech intelligibility level at the inner parts of the room and become a guide to perform better design schemes. To achieve this, ceiling geometries are shapes up both to the reflection of the daylight to the interior as much as possible and directing the sound to the back part of audiences. Seating layouts are changed for the daylight capabilities and existing material placements. Material combinations are selected to perform a better reflective-absorber panel placement that influences both light and sound distribution.

Daylight and acoustic simulations are carried on in regard of those statements with three design components; ceiling geometry, seating layout and material combination to perform a simultaneous change in daylight and acoustic performances. For the examinations, existing conditions are analyzed in depth at the first section of results. Thus, it was aimed to compare each design component with existing conditions and between each other. Results of existing conditions and proposed design components are presented in mappings at following parts.

5.3.1. Design Component 1 – Ceiling Geometry

Two type of ceiling geometry, one and two reflector panel placements is conducted to the existing conditions of the lecture hall respectively CG1 and CG2. The first design component, ceiling geometry, is mainly a study of the removal of the existing suspended ceiling application and the addition of reflective panels to the ceiling.

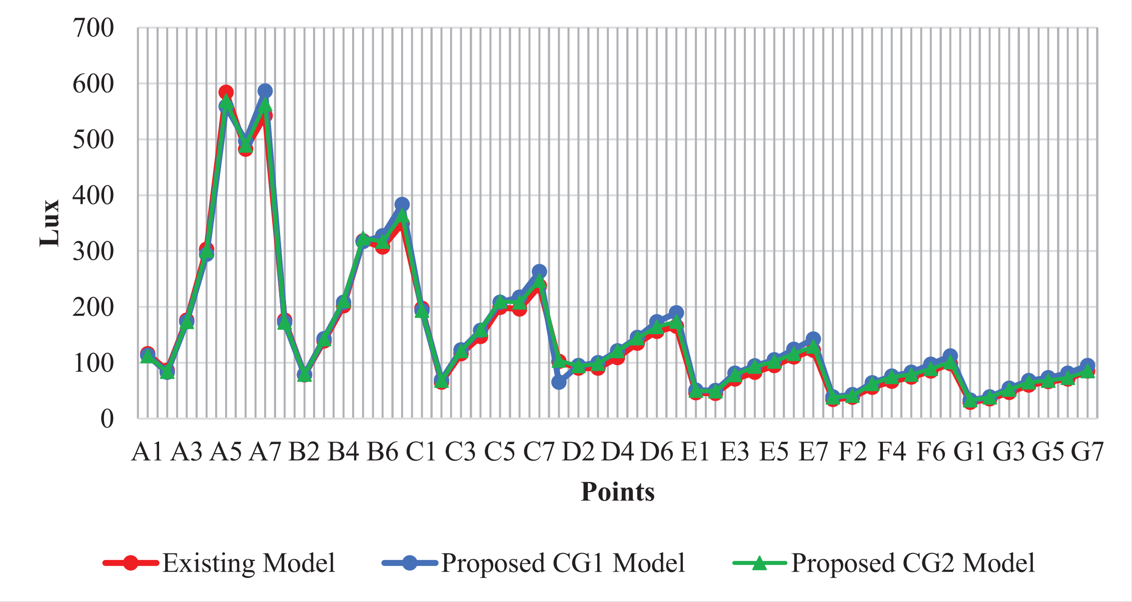


Figure 5.18. Comparison of ceiling geometry conducted study CG1 and CG2 with existing model for date: 30.09.2016 time: 15.00-16.00 (sunny day)

The single reflector panel (CG1) and two reflector panels (CG2) are designed and tested in accordance with the lighting and acoustical conditions, at appropriate angles and with suitable materials, to determine the influence percentages by each panel. Regarding the findings, E max in CG1 was obtained as 586 lux, while E min was 33 lux. E max is lower in CG2, as 569 lux, while E min is the same. Compared to the current situation and CG1 values, the illuminance values did not show any significant increase in general. Only the first row A7-G7 was affected slightly. Illuminance on the row increased relatively. (Fig. 5.18). Figures 5.19 illustrates the distribution in detail. The window region has the brightest area and the uniformity which around 0.21 did not change much. The average illuminance in CG1 (156 lux) is very slightly higher than the value in CG2 (153 lux), while the minimum illuminance remained the same as 33 lux. In this way, a very tiny development achieved with the application of lecture hall CG1 have been observed.

Figure 5.20 shows us the illuminance distribution on work plane. It is inclined because of the inclined seating area. Almost one fourth of the seating area receives adequate illuminance which above 300 lux. However, half of the seating area has got inadequate daylight level which is below 100 lux. Interestingly, CG2 leads to a slightly larger bright area near the windows than CG1 does.

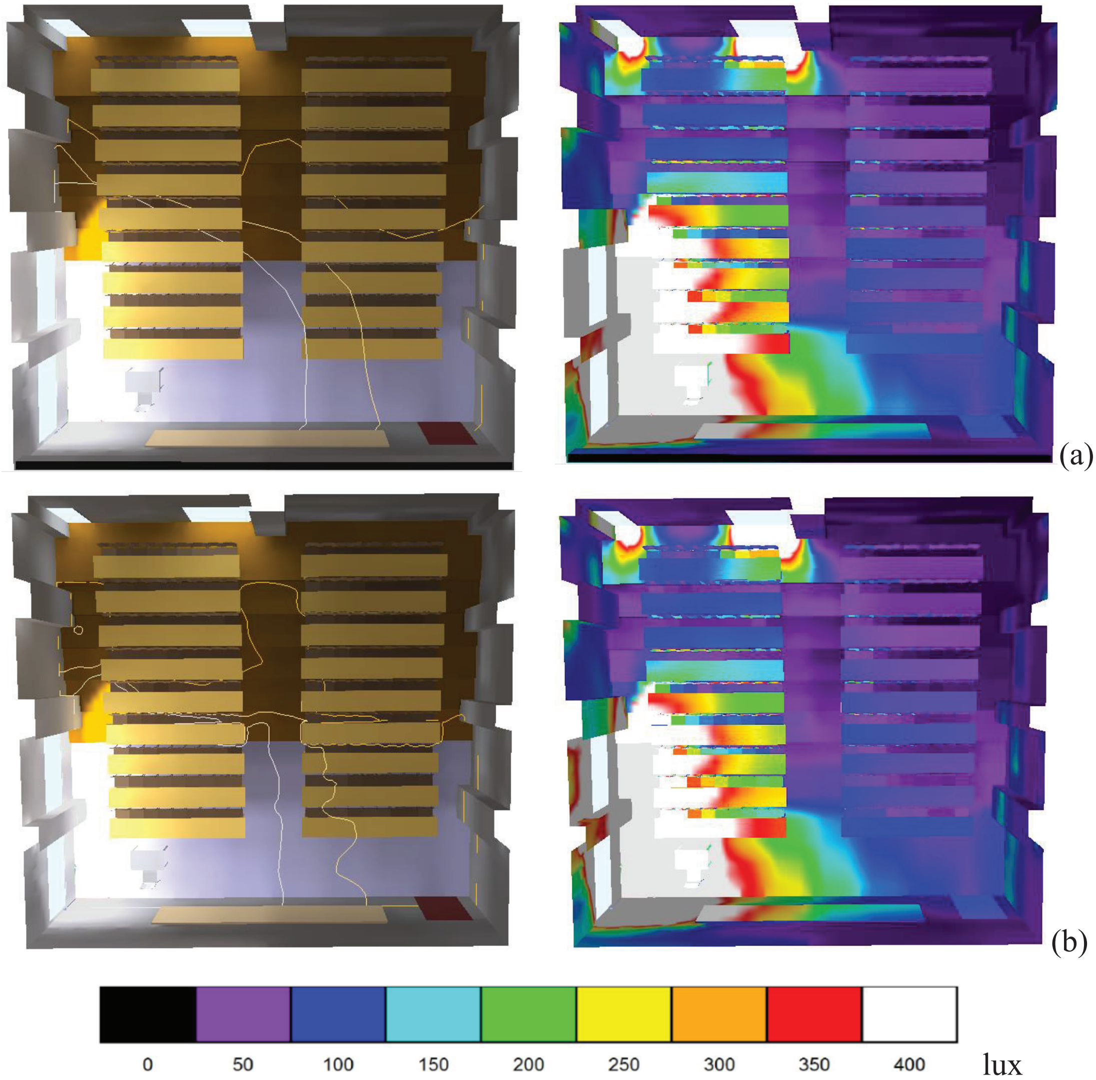


Figure 5.19. Illuminance (left) and false color (right) distribution for CG1(a) and CG2 (b).

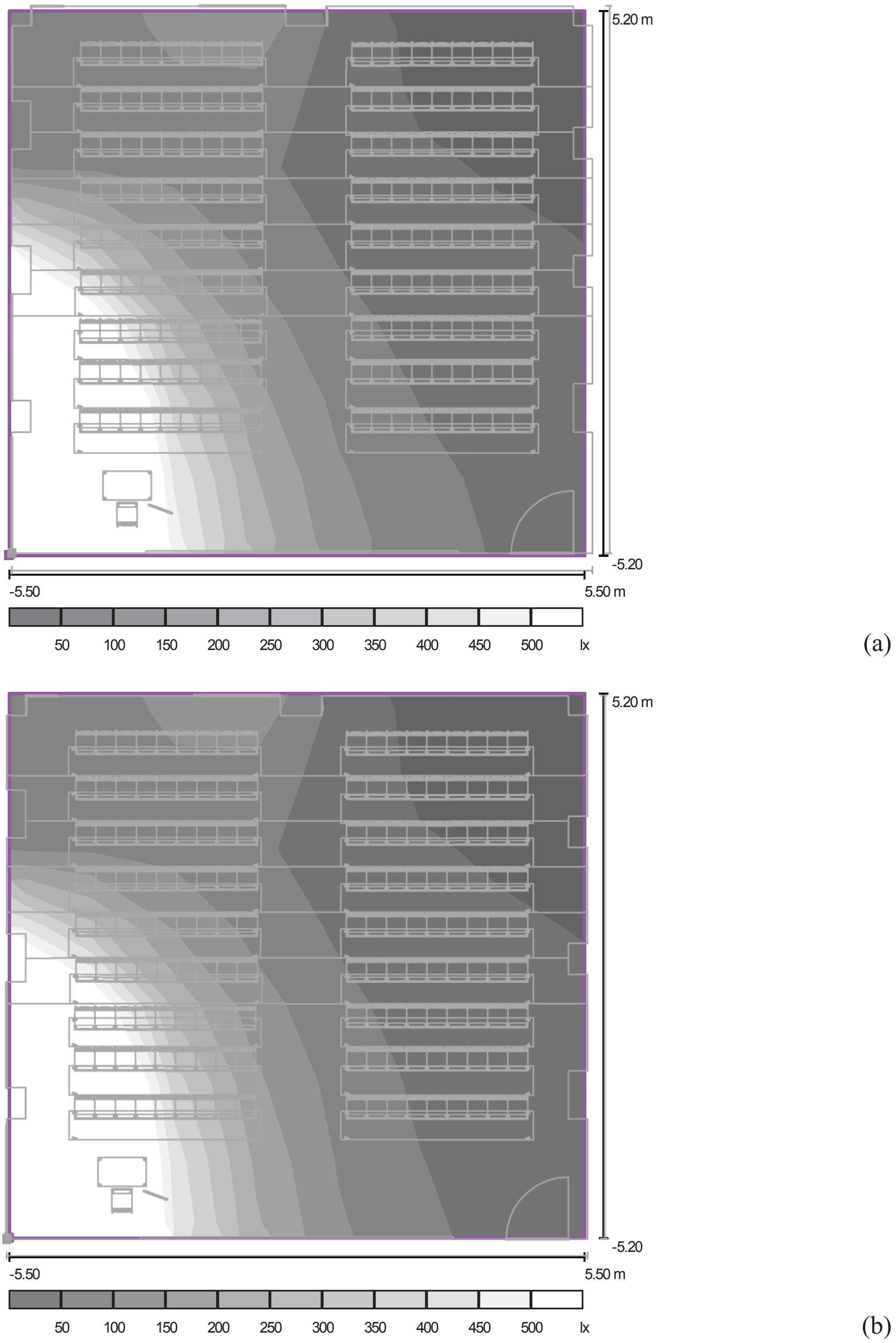


Figure 5.20. Illuminance distribution on work plane for CG1 (a) and CG2 (b) (unit: lux)

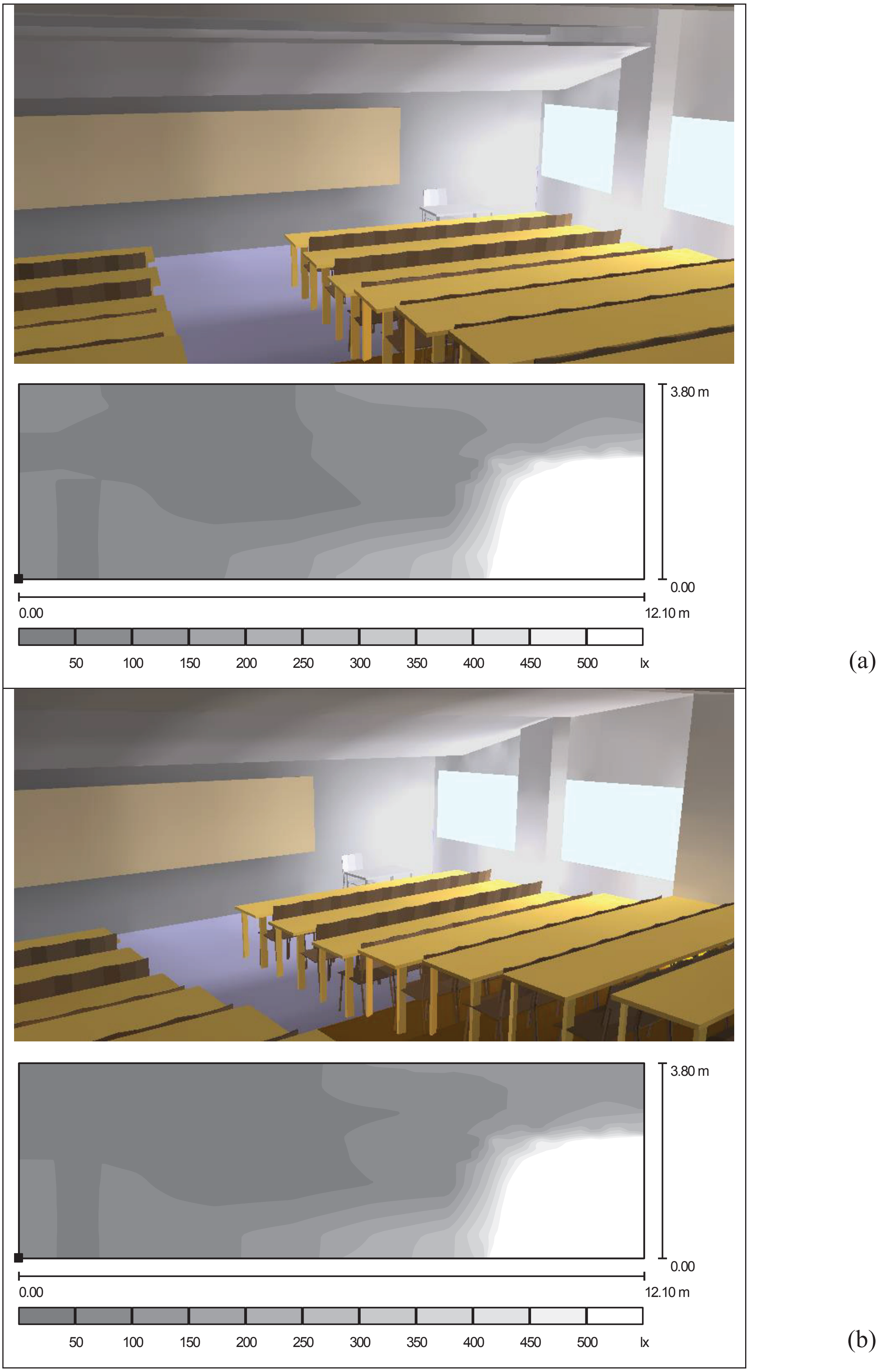


Figure 5.21. Illuminance distribution on white board's wall for CG1 (a) and CG2 (unit: lux)

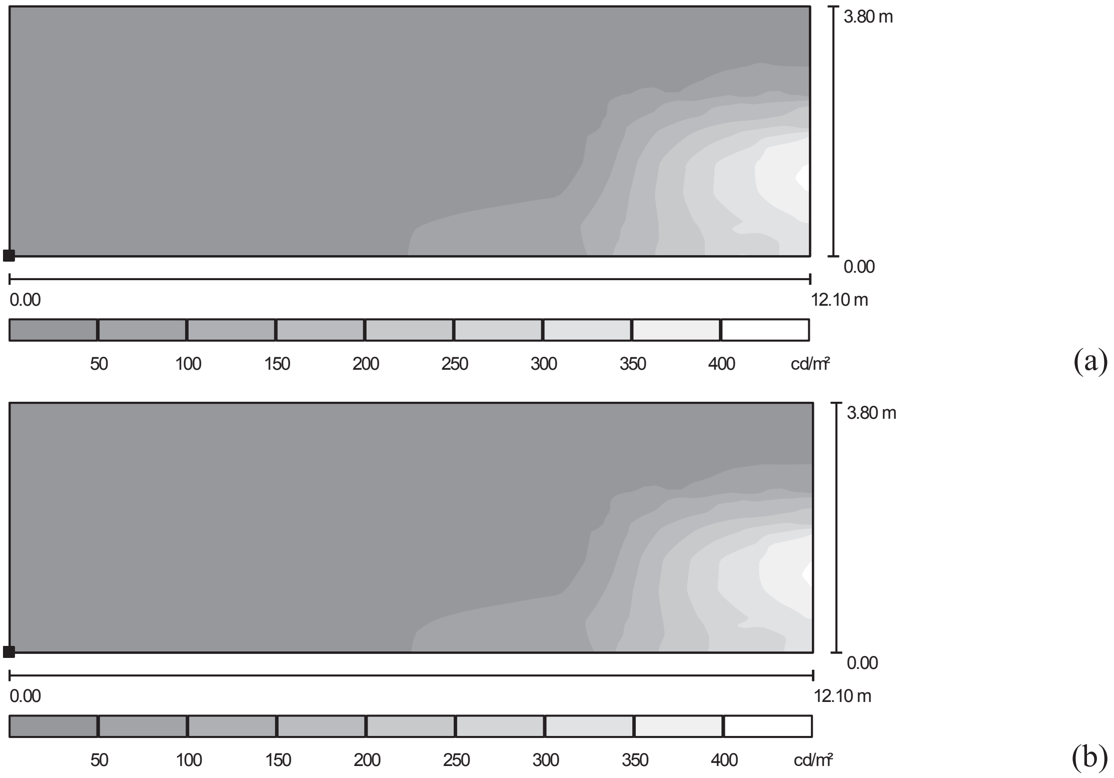


Figure 5.22. Luminance distribution on white board's wall for CG1 (a) and CG2 (unit: cd/m^2)

Fig. 5.21 and 5.22 present the illuminance and luminance distribution on vertical surface on which the white board is attached. Although similar distributions are attained, CG2 results in a brighter area to some extent. The brightness ratio is more than 0.12 and is improved with the application of these two ceiling components. When compared to the existing situation, the luminance distribution is much balanced at this time.

Simultaneously, CG1 and CG2 applications were evaluated in acoustic simulations. The first application for this is the removal of the suspended ceiling. This causes an increase in volume (RT formula). A typical material has been assigned to the rest of the ceiling to reduce the impact of this volume increase on existing conditions. That material is metal perforated sheet at least 80% porosity ratio with 50 mm thick wool backfill and has a smooth and light-colored surface that's lighting reflectance is equivalent to the current ceiling material.

When T20 (500 Hz) and reverberation time for CG1 and CG2 are considered, a parallel distribution per frequencies is observed. First, the current situation is compared with the CG1 application. As calculated at the existing model, average of reverberation time value was 1.1 at the existing model simulation, while it is 0.70 sec in empty occupancy and 0.6 sec in full occupancy condition with the CG1 application. This value is very close to the recommended reverberation time values. Then the CG2 application is evaluated and compared to the existing model and the CG1 model. As seen in illumination distributions, CG2 application which consist an additional panel was comparatively determined in a lightly lower to get recommended values. Yet, the reverberation time averages of CG1 and CG2 values was around 0.70 and 0.90 sec in empty occupancy and 0.65 and 0.82 sec in full occupancy condition respectively and so close to each other while reverberation time average was higher than recommendations with CG2 application.

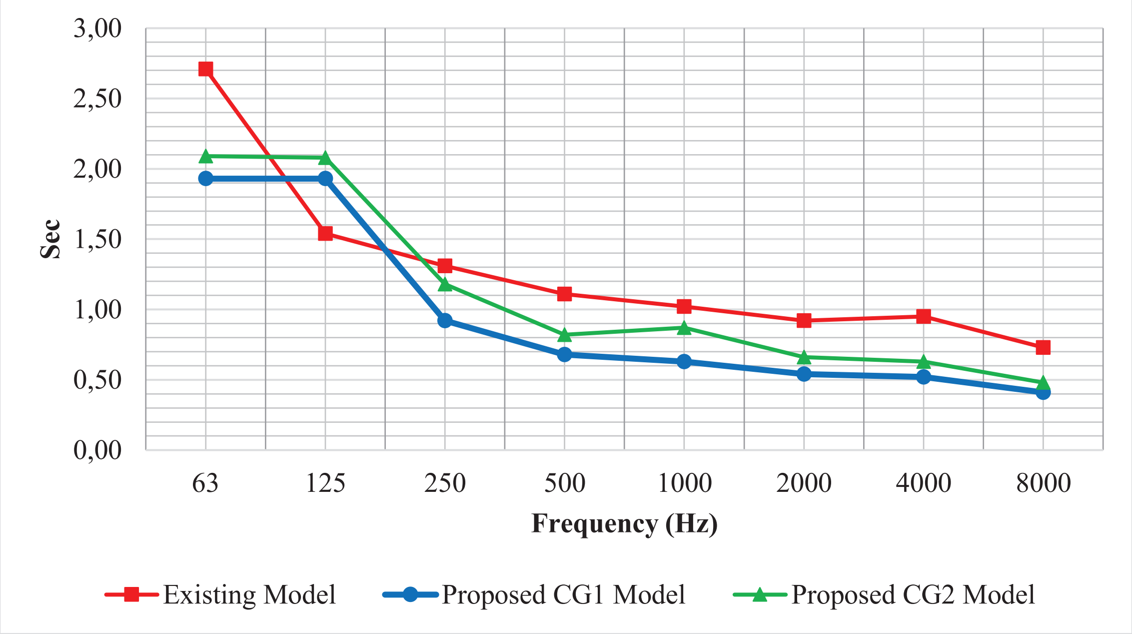


Figure 5.23. Comparison of CG1 and CG2 with existing model according to reverberation time in full occupancy condition (unit: s)

When the target reverberation time international standards are examined for this volume and for a hall to be used for speech, it appears that it should be in the range of 0.7-0.8 seconds at mid frequencies (between 500Hz - 1000Hz). As the second step, CG1 and CG2 design components proposed for the hall are added, and the reverberation time about 0.65 and 0.82 seconds are obtained respectively at the mid frequencies (Fig. 5.23). Those values are close to the recommended range for lecture halls, however CG1 application perfectly match with recommendations.

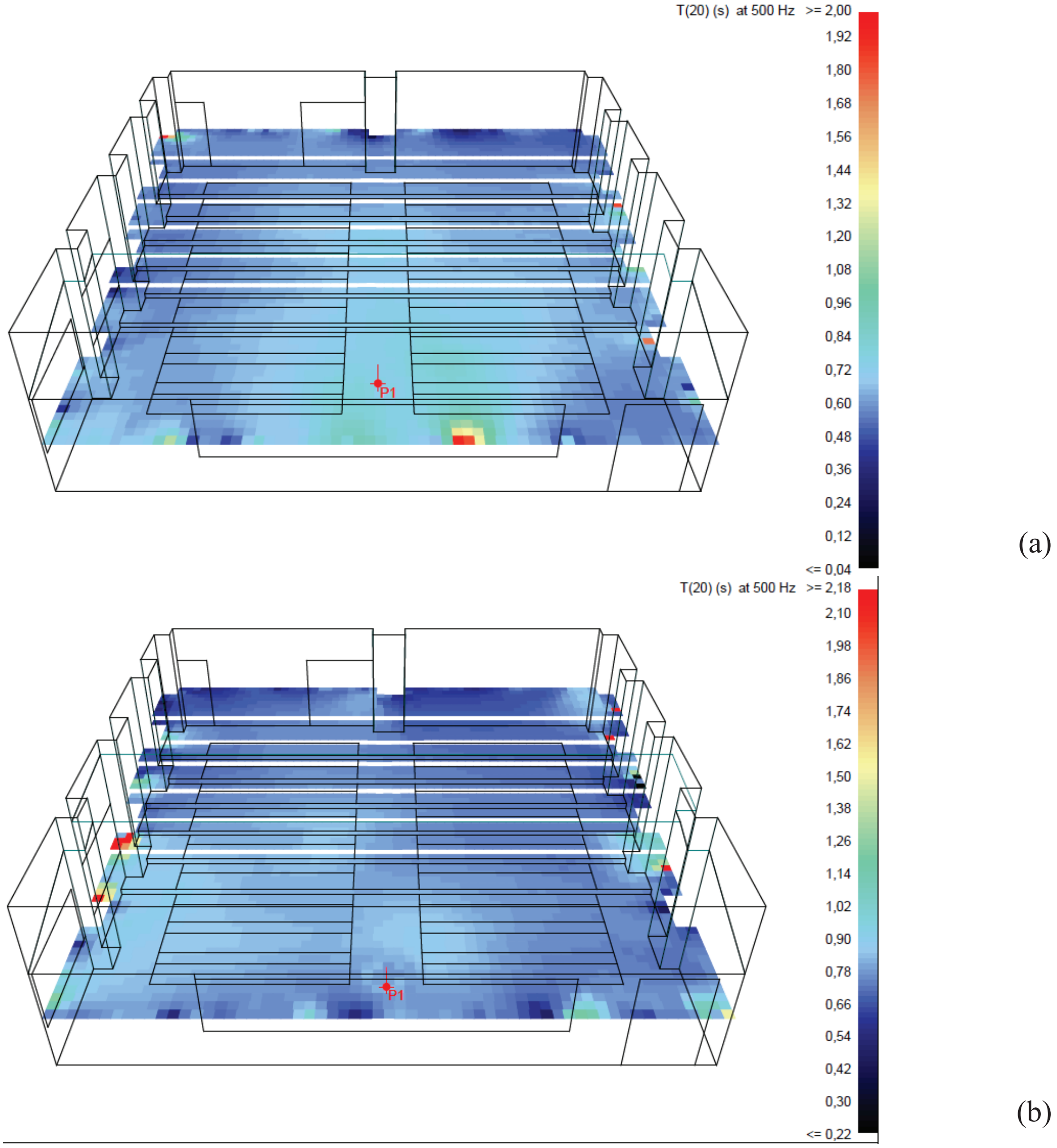


Figure 5.24. T20 results of grid calculation at 500 Hz for CG1 (a) and CG2 (b) in full occupancy condition (unit: s)

Above, T20 value distribution on grid calculation is illustrated (Fig. 5.24). As seen there is a uniform distribution of values at whole lecture hall. Comparing with existing model, both of the applications are able to lower the reflections uniformly and that is a sign to apply design component strategy same at each area of the hall and not decrease the audience's hearing quality.

While comparing speech transmission index results of CG1 and CG2 applications, existing model's qualities are reminded. STI averages of existing conditions are varying between 0,49 and 0,51 at four receiver points. With CG1 application, that distribution raises to 0,58 - 0,61 value range in empty occupancy and 0.59 – 0.61 range in full occupancy condition and has a remarkable change and defined in good quality of speech intelligibility index limit. With the CG2 application, STI value is still higher than existing conditions (0.53-0.55 range in empty occupancy and 0.58-0.59 range in full occupancy condition) but it is not as much as achieved with CG1 model. Additionally, there is a well-defined area marked with red in grid distribution and that is over 0.60 STI level, where, rest of the hall is marked with blue and that means STI is below 0.60 good quality limit, yet still close to that limit, which is 0.56-0.60 at both CG1 and relatively CG2(Fig. 5.26).

Figure 5.26 presents the STI distribution over the grid calculation area. As seen, red covered areas are around 0.60-0.66 values of STI and may be defined in good quality. Then, rest of the lecture hall is generally covered with blue color which corresponds to 0.56-0.60 values and that distribution means the lecture hall able to have a well speech transmission index evaluation.

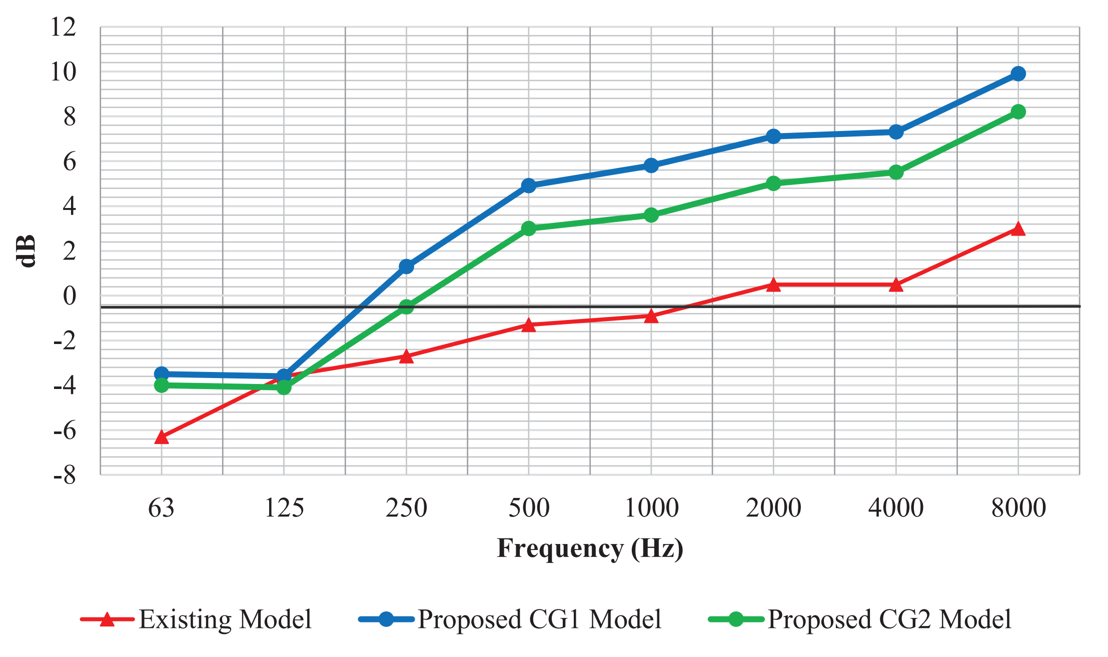


Figure 5.25. C50 results for CG1 and CG2 with existing model in full occupancy ………….. condition (unit: dB)

Figure 5.25 presents the C50 distribution of existing and proposed models. As seen, the average C50 value of CG1 is +4.2 dB in empty occupancy and +5.3 dB in full occupancy condition, where average C50 of CG2 is +1.3 dB in empty occupancy and +3 dB in full occupancy condition. Both are able to reach positive values as recommended, yet there is a better result obtained from CG1 comparing with CG2. CG1's C50 distribution in overall area is uniform in general and reaching to the positive values starting from 250 Hz, where it is only become positive 500 Hz and higher frequencies at existing model. That means, existing model is inadequate while considering clarity at speech and so at mid-frequencies, where CG1 model results in better quality and even quite better that two-reflector application, CG2 model.

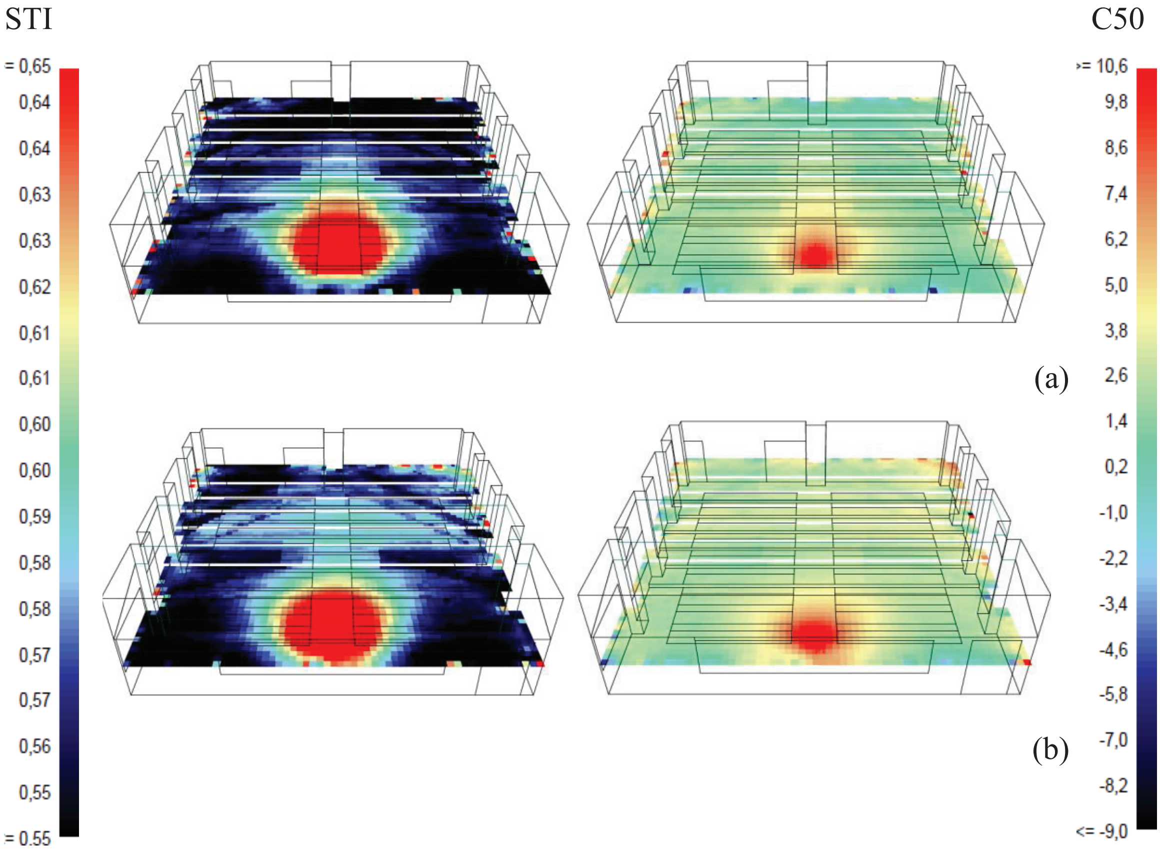


Figure 5.26.STI of grid calculation (left) and C50 of grid calculation at 500 Hz (right) for CG1 (a) and CG2 (b) in full occupancy condition (unit: s)

5.3.2. Design Component 2 – Seating Layout

The second design component is the seating layout. SL1 and SL2 layouts were designed, according to whiteboard locations, facing west and facing east. SL1 results in 406 lux of E max on Sept. 30th at 15:00 in simulations, while SL2 leads to 254 lux of E max which is the half of the former (Fig. 5.27). In general, the daylight level cannot satisfy the required 300 lux lighting level in this hall. On the other hand, uniformity is improved from 0.15 to 0.36 as the illuminance values decreased on the overall work plane. It was also observed that with the light source came closer to the presentation area in SL1, the uniform light distribution ratio in the lecture hall is increased, when we compare to the existing situation.

Since luminance values on the white board were low, it was seen that SL2 layout not lead to a glare and provides a better-lighted surrounding. In the SL2 layout, where the light source is in the back area of the lecture hall, raised platform prevents the light coming from windows and illuminance level is reduced to 76 lux in average, and the whiteboard and presentation area are also not well illuminated.

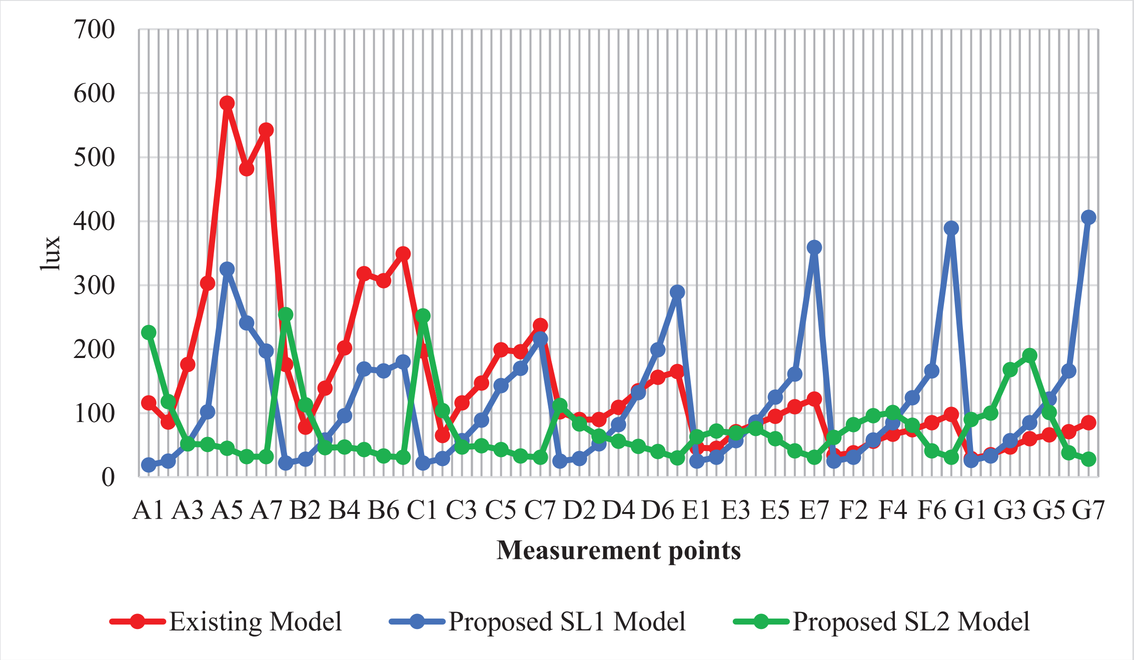


Figure 5.27. Comparison of seating layout changed studies SL1 and SL2 with existing …………… model for date: 30.09.2016, time: 15.00-16.00 (sunny day)

Figure 5.28 displays the illuminance and false color renderings of distribution, while Figure 5.29 explains the illuminance distribution on work plane in detail. Although both in SL1 and SL2 half of the work plane area is below 100 lux, the front desks can receive adequately very high daylight in SL1, while almost the overall desk area maintains the daylight level below 300 lux, receiving light from their back.

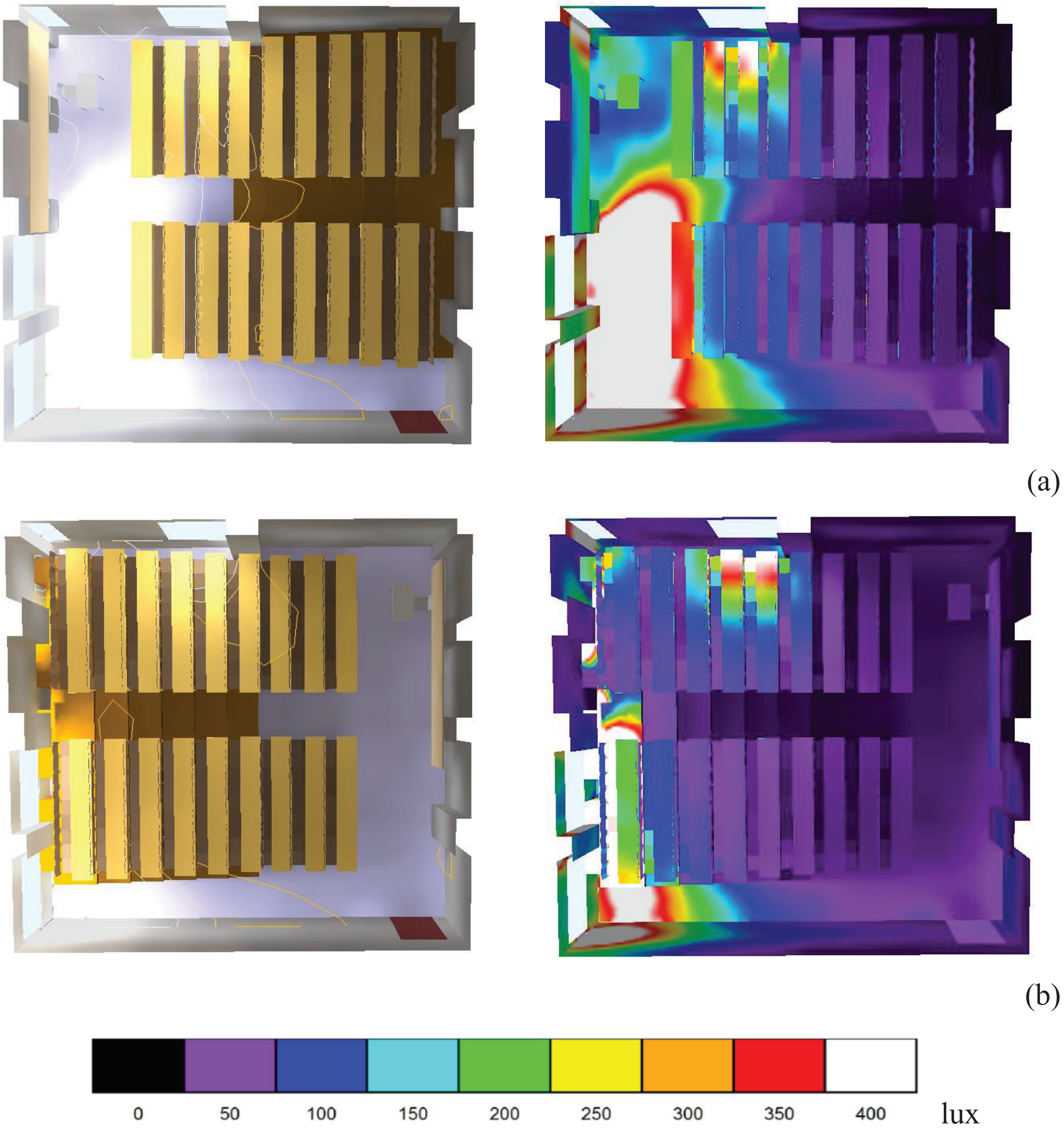


Figure 5.28. Illuminance (left) and false color (right) distribution for SL1(a) and SL2 (b).

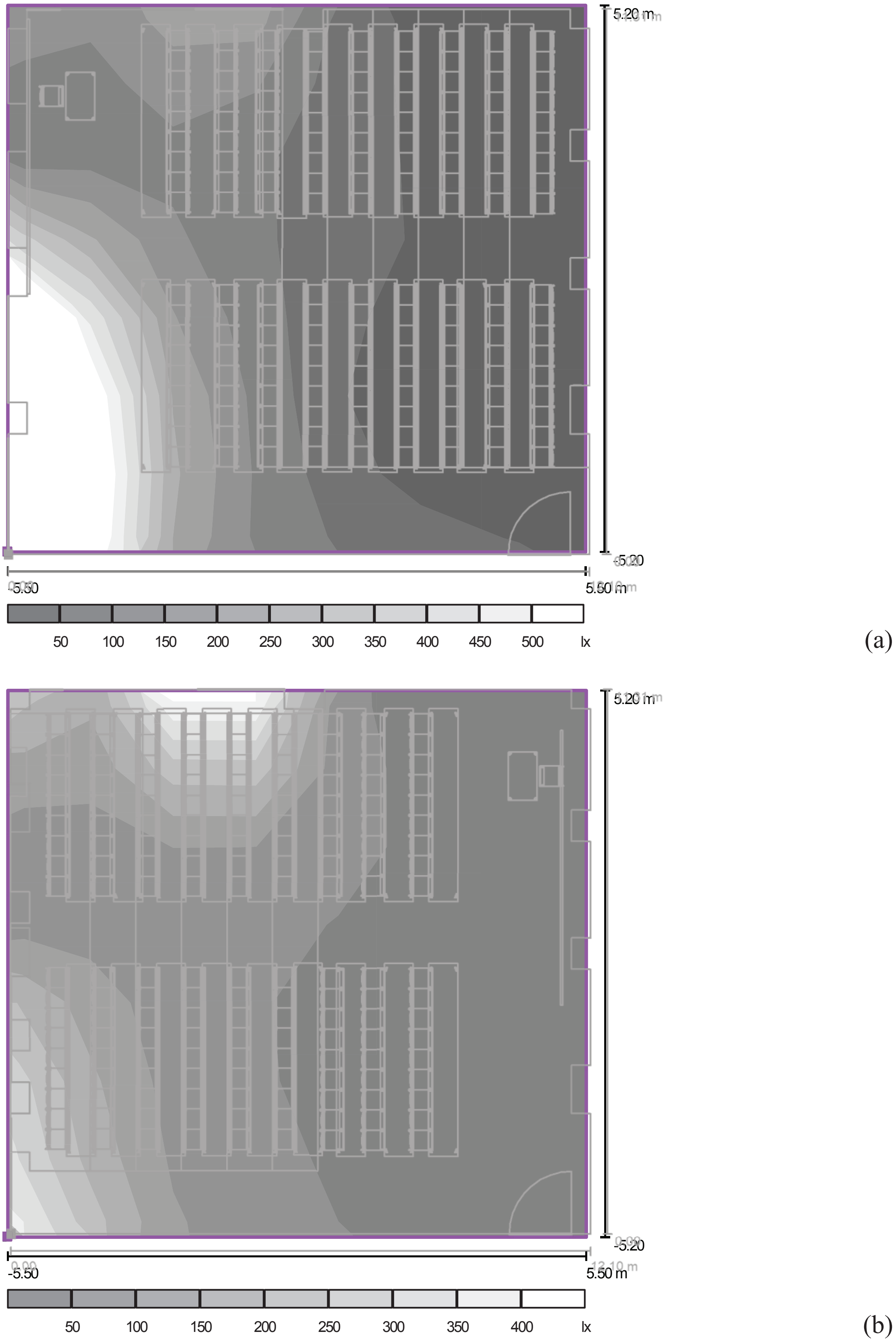


Figure 5.29. Illuminance value distribution on working level for SL1 (a) and SL2 (unit: lux)

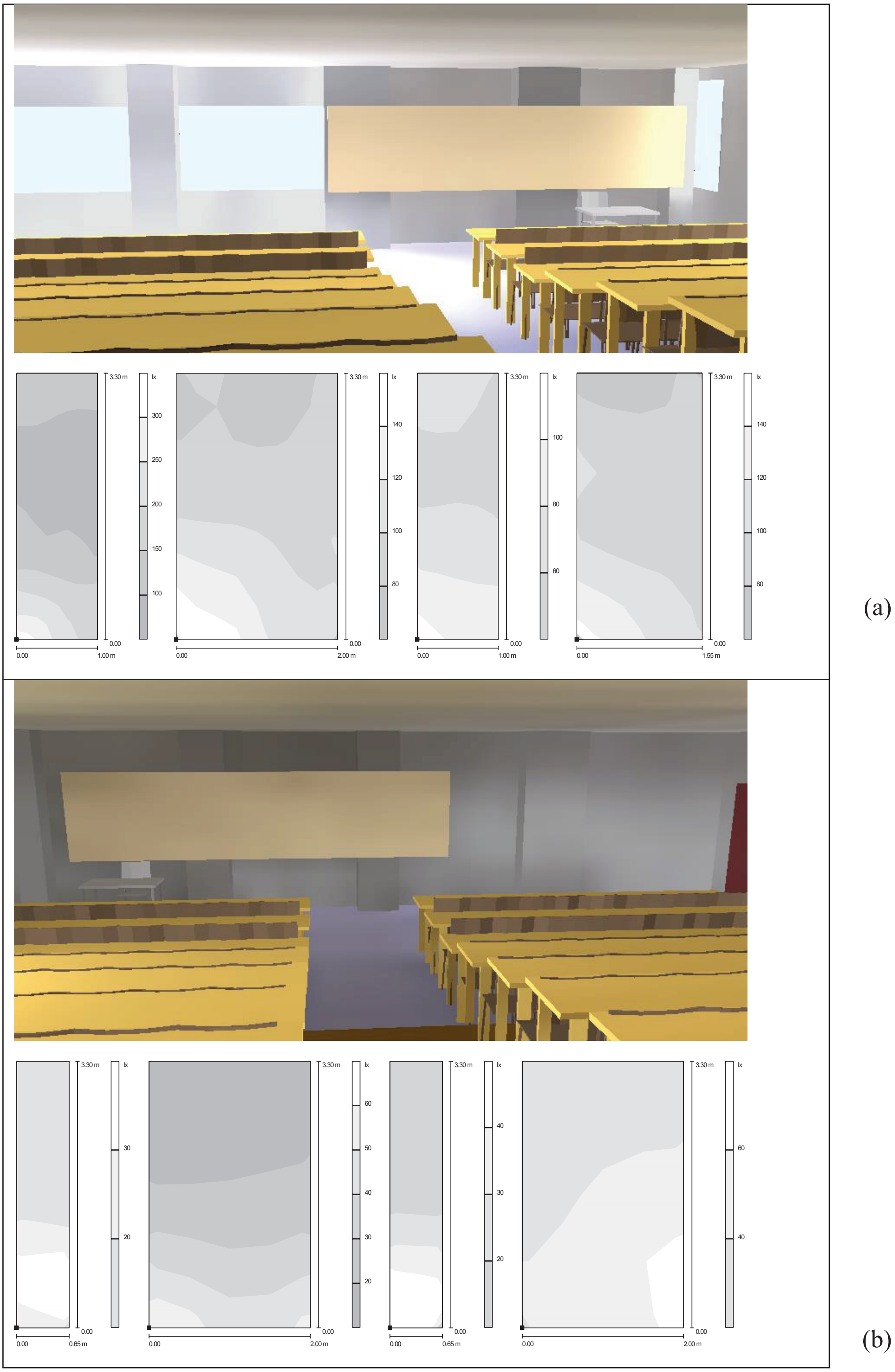


Figure 5.30. Illuminance distribution on white board's wall for SL1 (a) and SL2 (unit: lux)

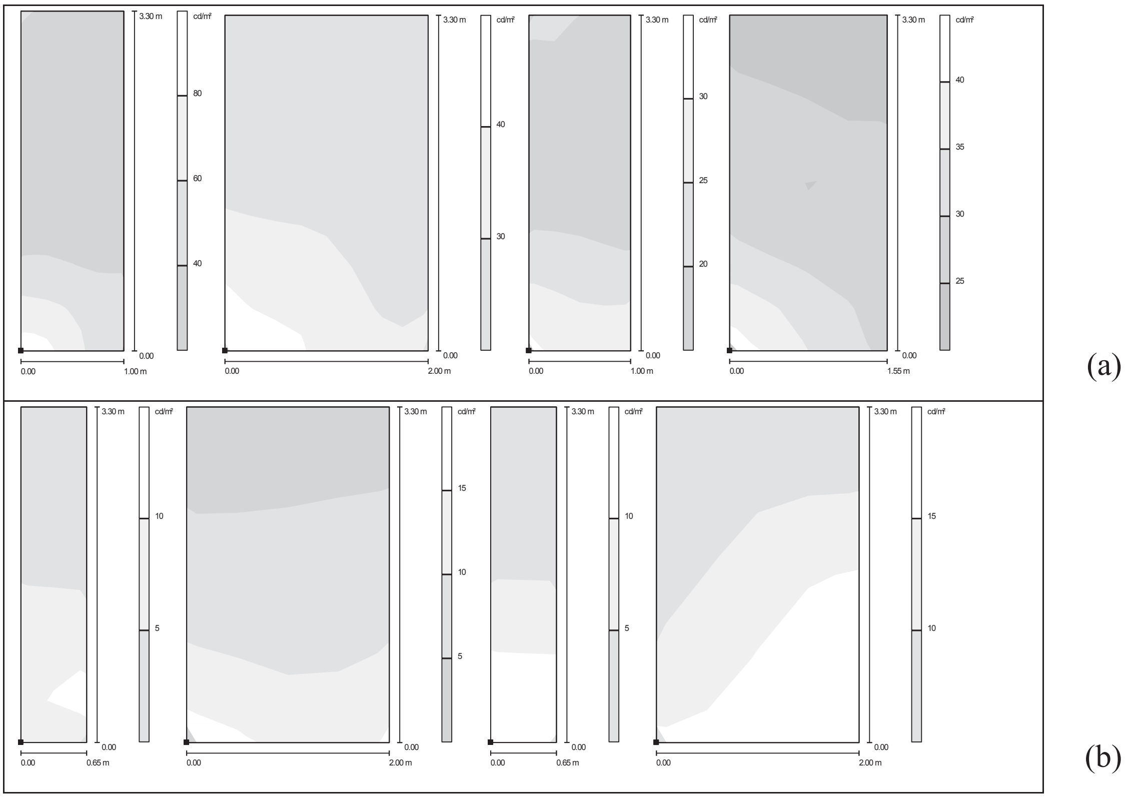


Figure 5.31. Luminance distribution on white board's wall for SL1 (a) and SL2 (unit: cd/m^2)

Figure 5.30 and 5.31 provide information about illuminance and luminance distribution on vertical surface for whiteboard. As comparison examined in detail, average illuminations on SL1 layout are around 119 lux, while it is just 76 lux at SL2 layout. Apparently, SL1 has a better illuminance distribution on work plane and white board surfaces compared to SL2. Because, SL1 layout let the daylight comes to the inner area of the lecture hall and raised platform is not preventing the reflections around glazing which is an element to light the rear areas. Glazing areas are at the closest position at SL1 layout and that creates a well illuminated white board location where there is no glare problem since the daylight not falls directly on to the white board and brightness ratio is over 0.20. However, SL2 is not reaching to any of those advantages since the white board is on dark area and raised platform prevents the daylight.

In terms of illuminance values, SL1 design component has a higher uniformity level which is improvement from 0.15 to 0.36, 77 lux average illuminance distribution, which is also higher than existing conditions (59 lux) and higher than SL2 (56 lux). Therefore, when SL1 and SL2 have been compared in terms of illumination, SL1 was observed to be preferred.

At the same time, acoustic modelling of the SL1 and SL2 models are prepared. At the SL1, windows' glazing areas come closer to the sound sources and their effects are searched for distribution of the sound. Similarly, the sound source (the lecturer) in the SL1 layout is closest to the glazing, which is the smoothest and bass frequency absorber surface in the lecture hall. It is expected that these glazing will absorb the low-frequency values of the sound and reflect the mid frequency values into the lecture hall. However, such a small square meter glazing area causes insufficient levels to reach a significant increase in acoustic performance in the lecture hall.

Similarly, SL2 is expected to have lower acoustic quality as compared to the existing conditions, but insufficient glazing surface area causes an ignorable change. So, the volume of the lecture hall and the small size of the material surfaces make it difficult to see the effects of the seating layout.

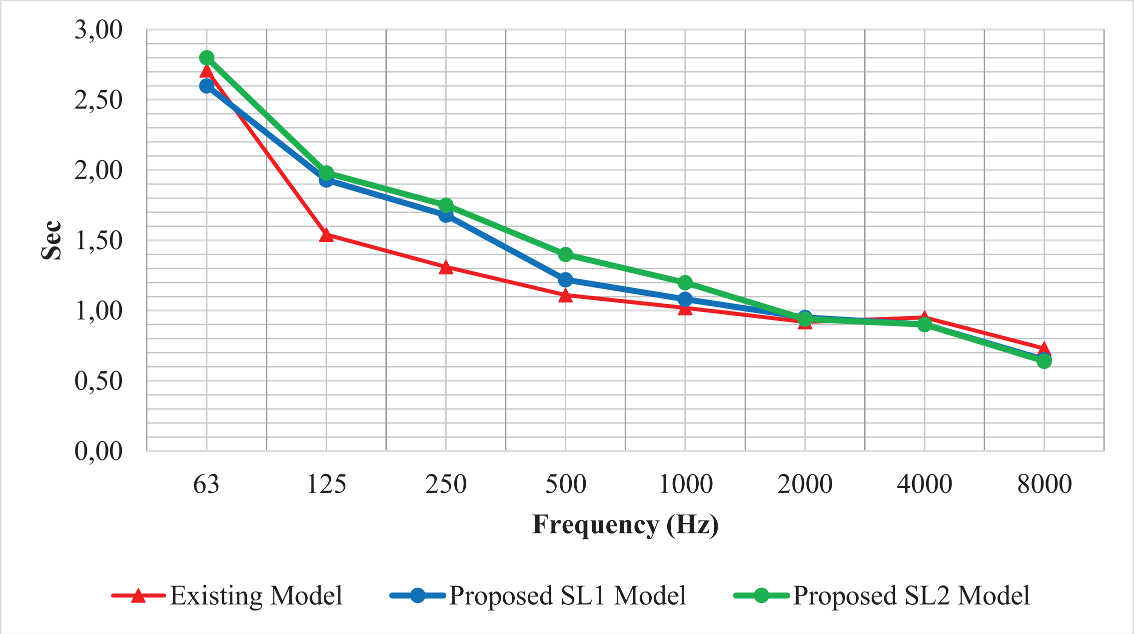


Figure 5.32. Reverberation time results for SL1 and SL2 with existing model in full ………….. occupancy condition (unit: s)

Fig 5.32 presents the reverberation times comparing SL1 and SL2 layouts with existing model. As seen, reverberation time averages at existing model was around 1.1 sec while it is 1.2 and 1.6 sec in empty occupancy condition and 1.15 and 1.38 sec in full occupancy condition at SL1 and SL2 respectively. That shows us there is no improvement reverberations to near up to the recommended values. Still there is a high but uniform distribution of reverberation at both of the design components (Fig. 5.33).

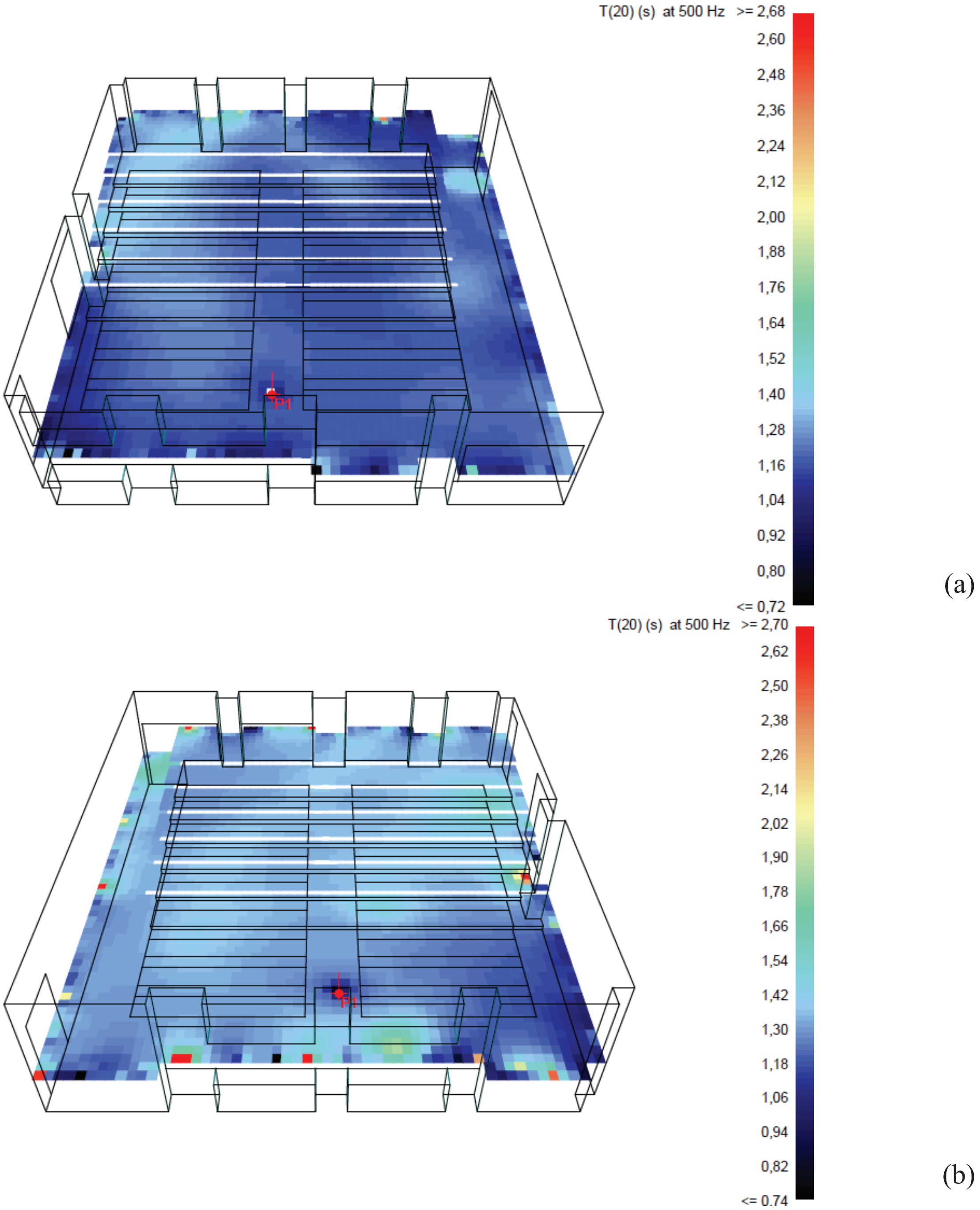


Figure 5.33. T20 results of grid calculation at 500 Hz for SL1 (a) and SL2 (b) in full …………… occupancy condition (unit: s)

STI results of proposed SL1 model is 0.51, 0.50, 0.50 and 0.52 respectively to the four receiver points in empty occupancy and 0.52, 0.49, 0.50 and 0.54 respectively to the four receiver points in full occupancy conditions. However, SL2 results are calculated oppositely and has a negative distribution that existing conditions. They are varying between 0.46 and 0.48 at receiver points in empty occupancy and average 0.52 in full occupancy conditions. As observed, they are at lower values than existing conditions.

That shows us there is no significant improvement at STI values and SL1 results are defined as poor STI category like existing model and SL2 results are in the lower limit of poor STI quality.

Figure 5.34. C50 results for SL1 and SL2 with existing model in full occupancy ………….. condition (unit: dB)

Fig 5.34 shows the C50 parameter averages obtained from four receiver points in existing model, proposed SL1 and SL2 model. Average C50 value is calculated between 500 Hz and 1000 Hz as -1.3 and -0.9 dB in existing model. Since the recommendations are obtaining positive values from C50 results (Table 2.9) reaching to the positive values at least at mid and high frequencies was the target. Then, SL1 results are analyzed and -0.8 and -0.2 dB in empty occupancy and 1.22 and 1.08 dB in full occupancy is obtained at 500 Hz – 1000 Hz, and positive values are obtained at 1000 Hz and higher. That means, SL1 model is improved clarity values compared to existing model, and come closer to the positive values. Yet it is still in negative part and defined in the poor quality (Table 2.9). Average C50 clarity values of SL2 is -2.40 and -2.60 in empty occupancy and -0.9 and -0.3 in full occupancy at 500 Hz and 1000 Hz. So, the average speech clarity is below the existing model and results are not improved with SL2 model. Similar to the STI value examinations, SL1 model was found in improvement of existing model, while SL2 reaches lower acoustic performances.

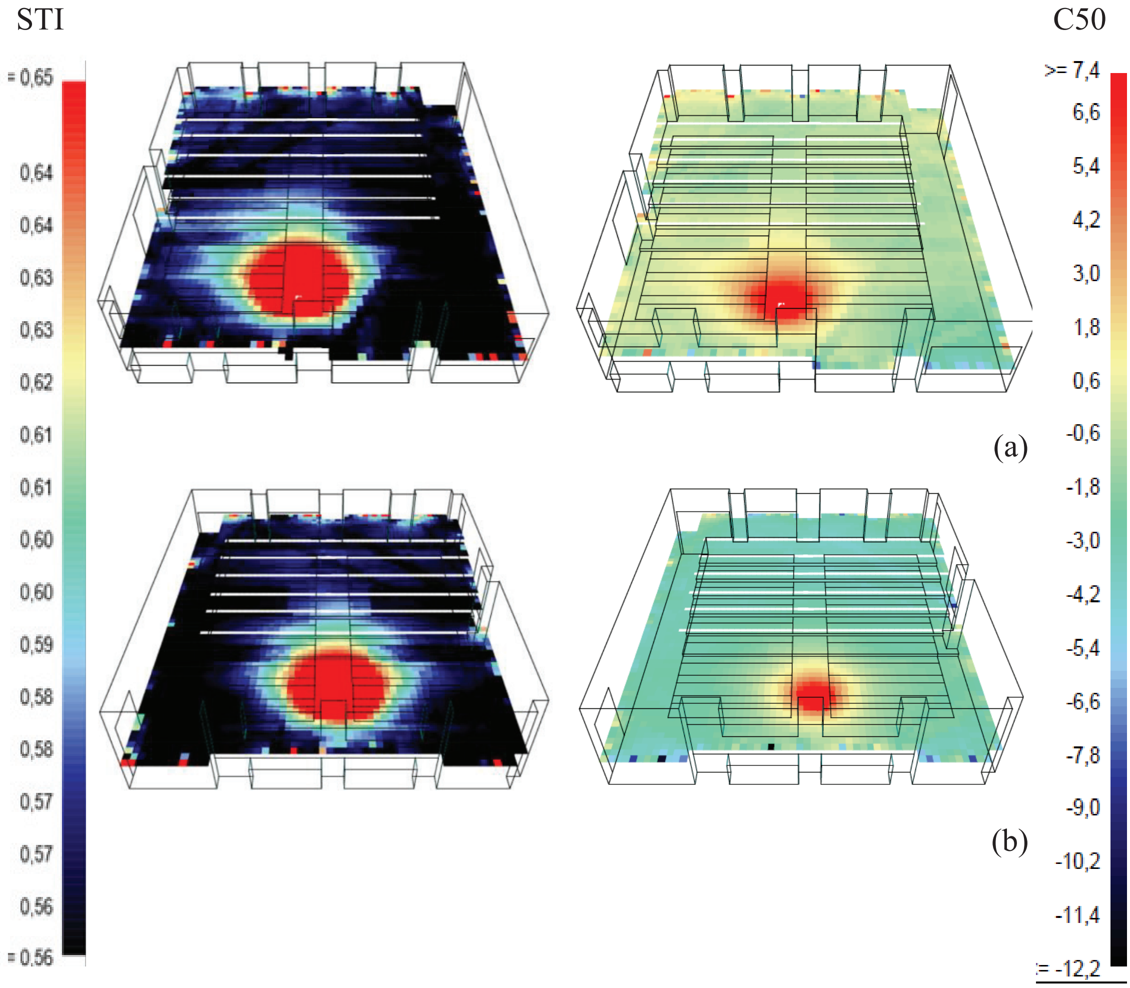


Figure 5.35. STI of grid calculation (Left) and C50 at 500 Hz (right) for SL1 (a) and SL2 (b) in full occupancy condition (unit: s)

Fig 5.35 is the grid calculations of SL1 and SL2 models respecting to the STI values and C50 clarity at 500 Hz. At the left (a) part, STI values at over 0.60 is marked with red area which covers only first row of audience like existing model, but rest of the audience's STI values are around 0.57 and it is better than existing conditions. Left (b) part covers slightly less red area than SL1 model grid calculation. Similarly, right (a) part is able to cover audience rows between first and fifth in positive clarity values while right (b) model only covers first and second row with positive clarity distribution. That means, SL1 model performs slightly better that existing model and at least nears to the recommendations but not reaches the exact acoustic quality limits.

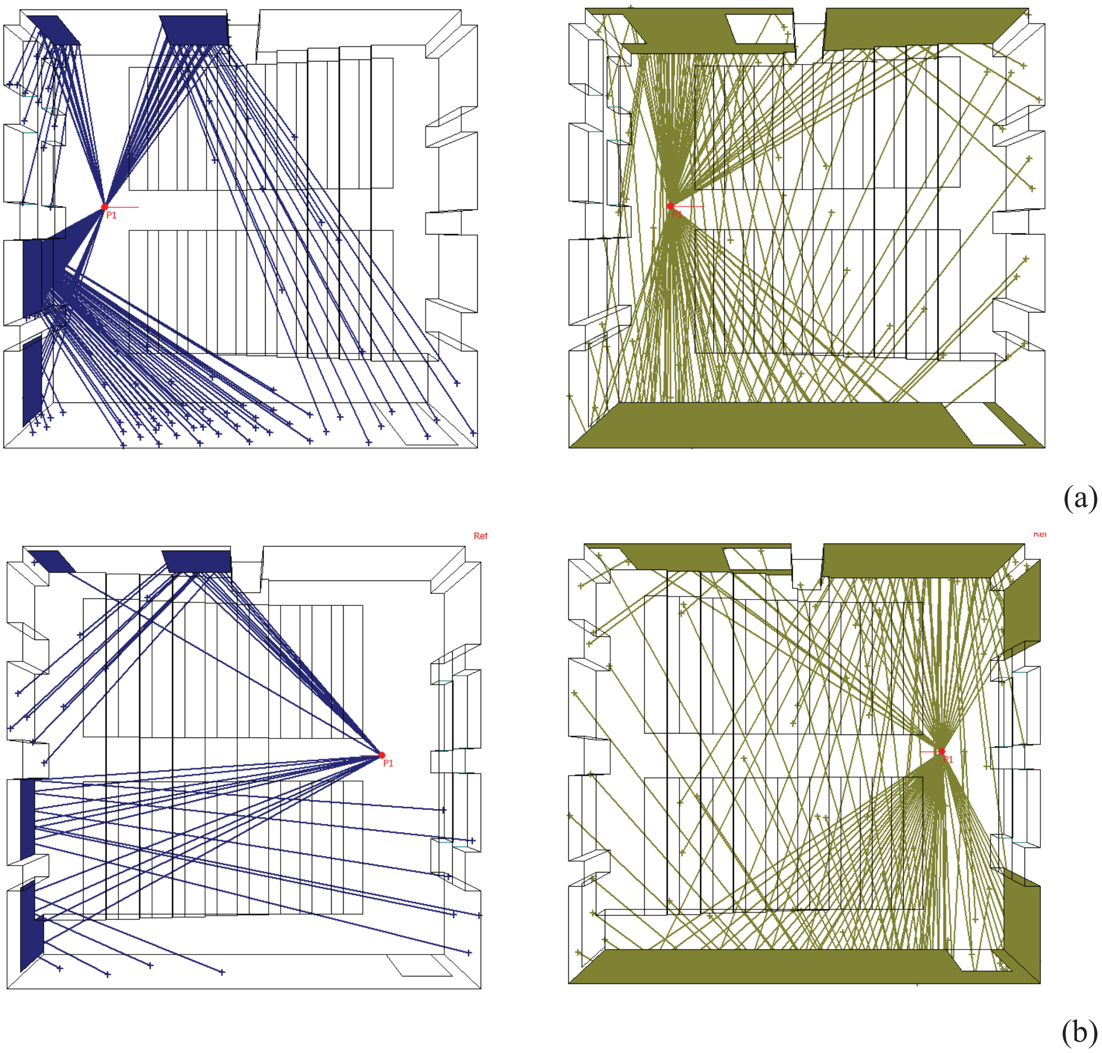


Figure 5.36. Side reflective surfaces for windows (Left) walls (Right) and for in SL1 (a) and SL2 (b), when they are accepted as totally reflective areas

Similarly, side walls and glazing are considered as totally reflective surface at reflective coverages to see their effects on interior reflections. As seen in Figure 5.36, windows are not a big part of sound distribution from sides and their low frequency absorber quality is not effective. So, expected results obtained from material absorption qualities are not observed at any of acoustic performance parameters.

5.3.3. Design Component 3 – Material Combination

The third design component, the material combination, is based on only evaluating the surface finishing selections. Accordingly, if the finishing surfaces on the walls and ceiling are changed according to the principles of reflective-absorptive surface placement in lighting and acoustic design strategies, how the results are affected is assessed. The first application, MC1, involves modifications made on the walls. On the side walls, the over-the-ear level and all the back walls are covered with material 2 with the aim of absorbing the mid-frequencies. The back wall of the lecturer and the side walls of presentation area are covered with material 1 because of the need for low-frequency absorption in the lecture hall. These materials were designed as lighting reflective quality surface finishing as much as possible since the lighting distribution in lecture hall was low.

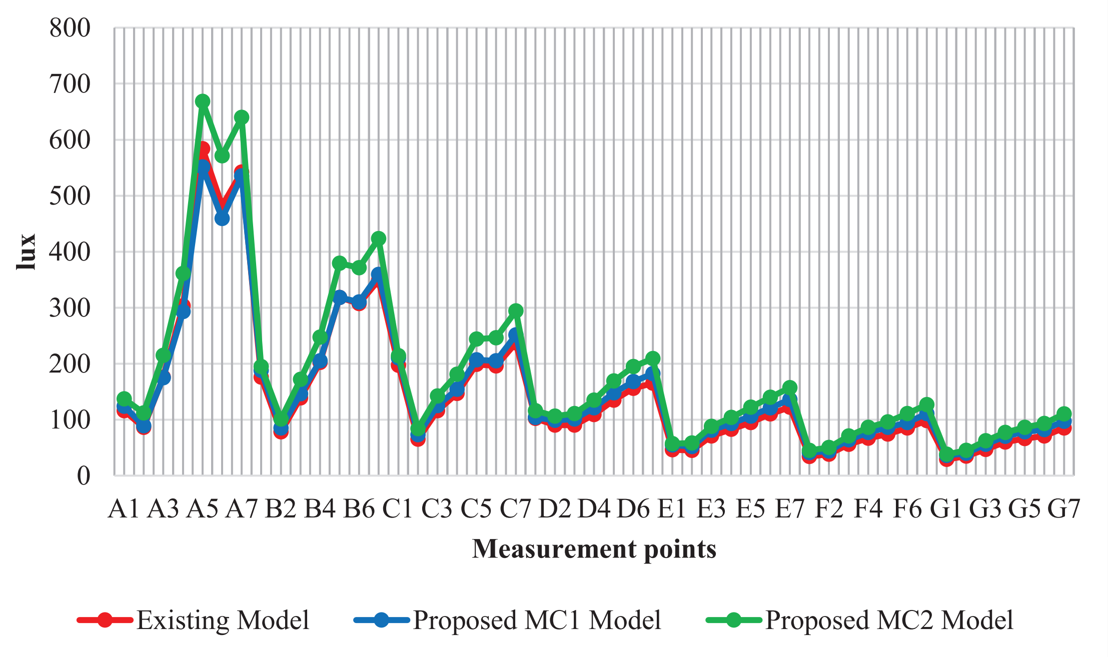


Figure 5.37. Comparison of material combination changed study MC1 and MC2 with …………… existing model for date: 30.09.2016 time: 15.00-16.00 (sunny day)

Figure 5.37 displays the illuminance values at measurement points after the implementation of MC1 and MC2 simulations. Though the distributions overlap each other precisely, very slight rises at some specific points (A5-7, B5-7, C5-7, D5-7, E5-7, F5-7) are observed. Average illumination values are 155 lux in MC1 and 181 lux in MC2 model, while it was 156 lux in existing model. Minimum values of illumination observed as in similar values at both MC1 and MC2, 36 and 38 lux. However, maximum values are higher in MC2 application, 668 lux, where it is 551 lux in MC1 model. That means, a design component applied from ceiling which is MC2 is slightly resulted better in terms of illumination since it reaches a bit higher than MC1 values.

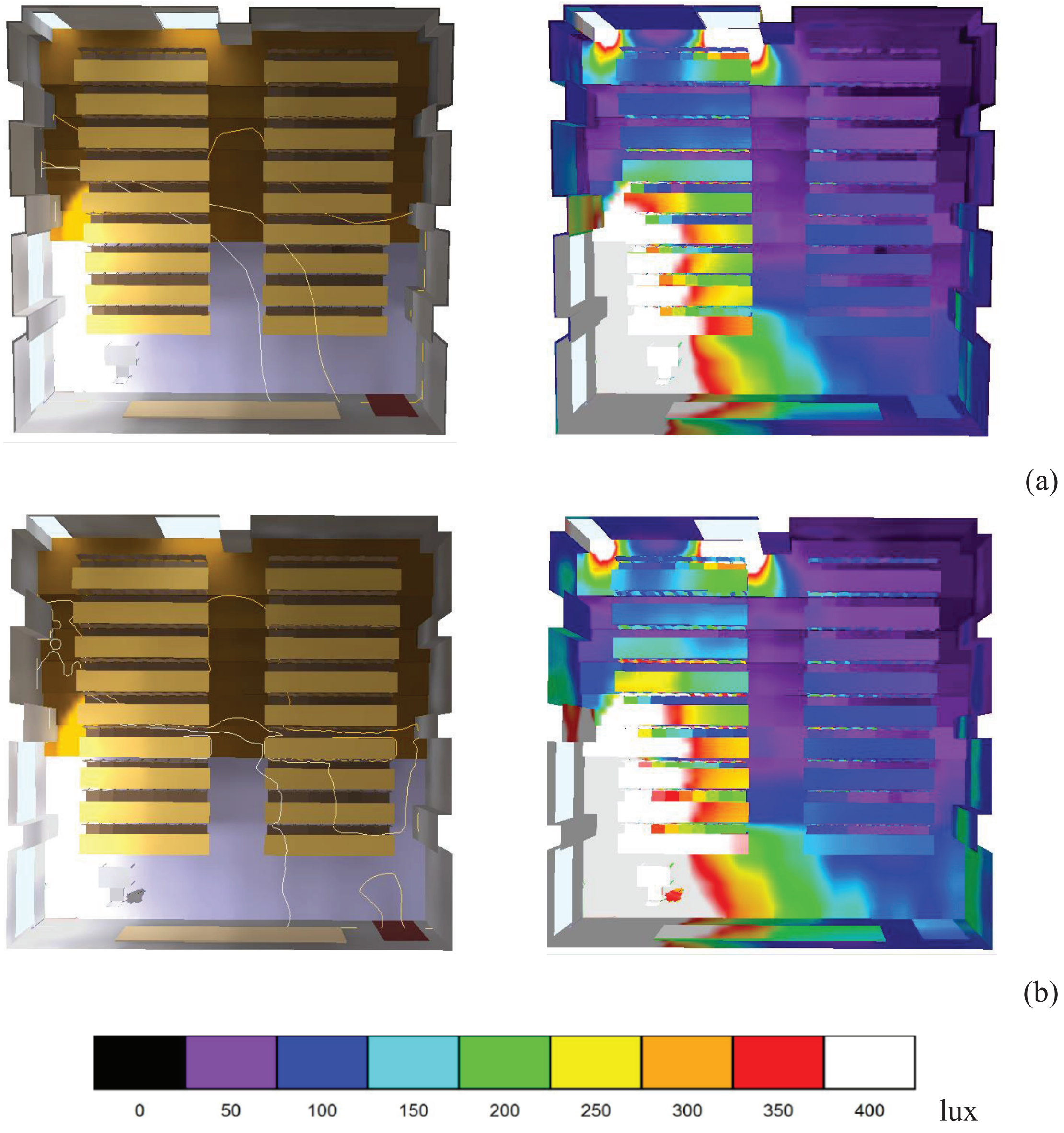
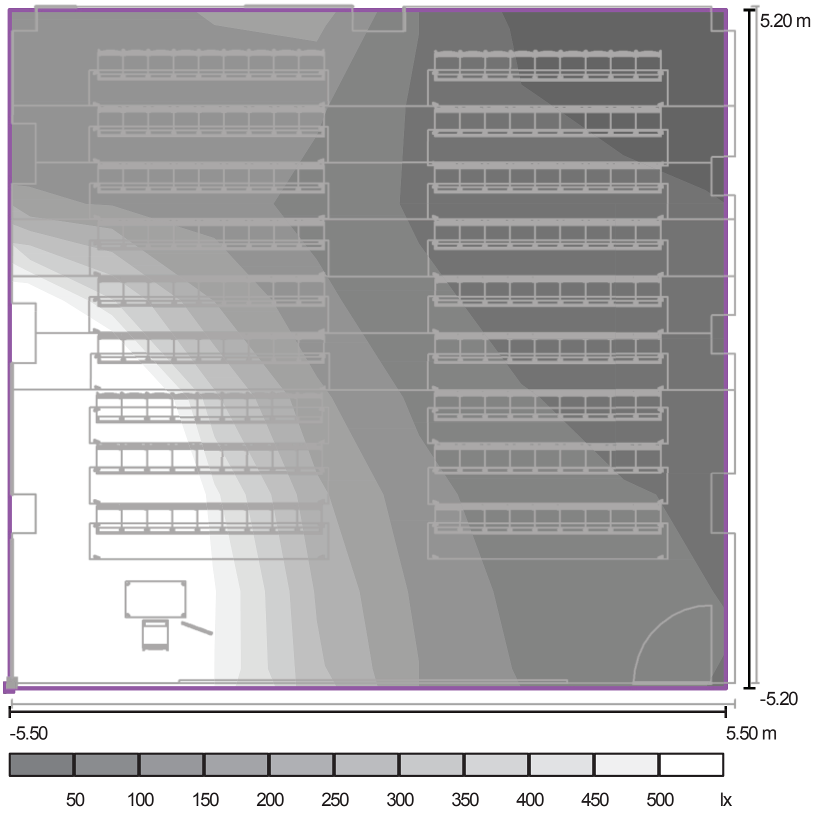
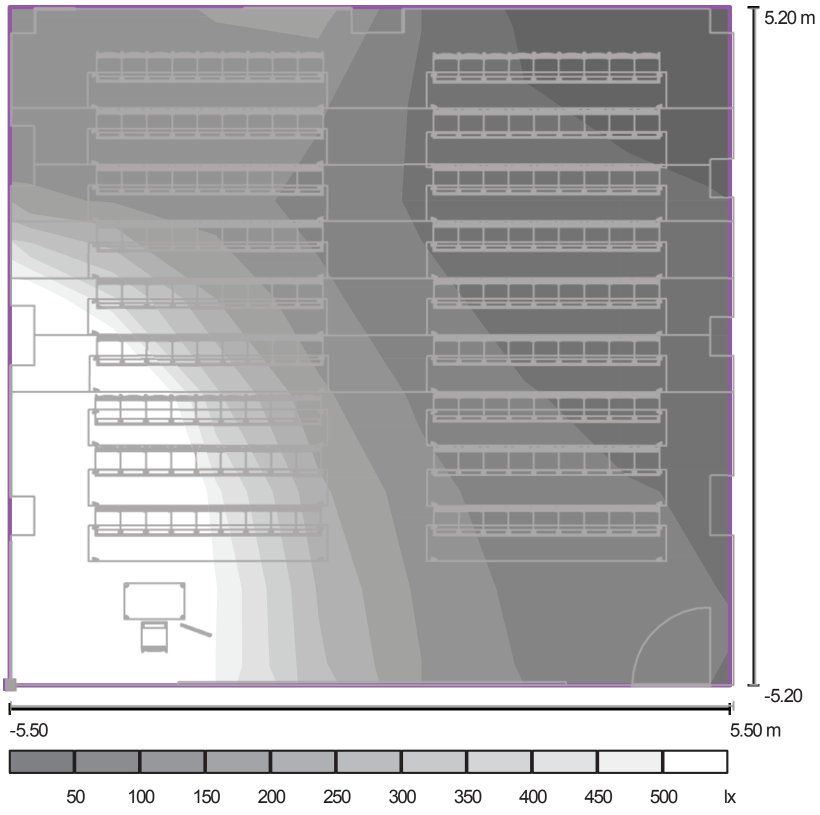


Figure 5.38. Illuminance (left) and false color (right) distribution for MC1(a) and MC2(b)

Figure 5.38 also shows the comparison of illuminance mapping on the interior space. The brightest region near the window was enlarged with the application of new materials remaining the half of the space in darker region (which is below 100 lux). MC1 model has a lightly well illuminance than existing model but still at the same average of illumination, in 155-156 lux. MC2 model has a wider distribution of well illuminated areas and almost one third of the lecture hall is at recommended illumination levels and rest of it is in 50-100 lux.



(a)



(b)

Figure 5.39. Illuminance distribution on floor level for MC1 (a) and MC2 (b) (unit: lux)

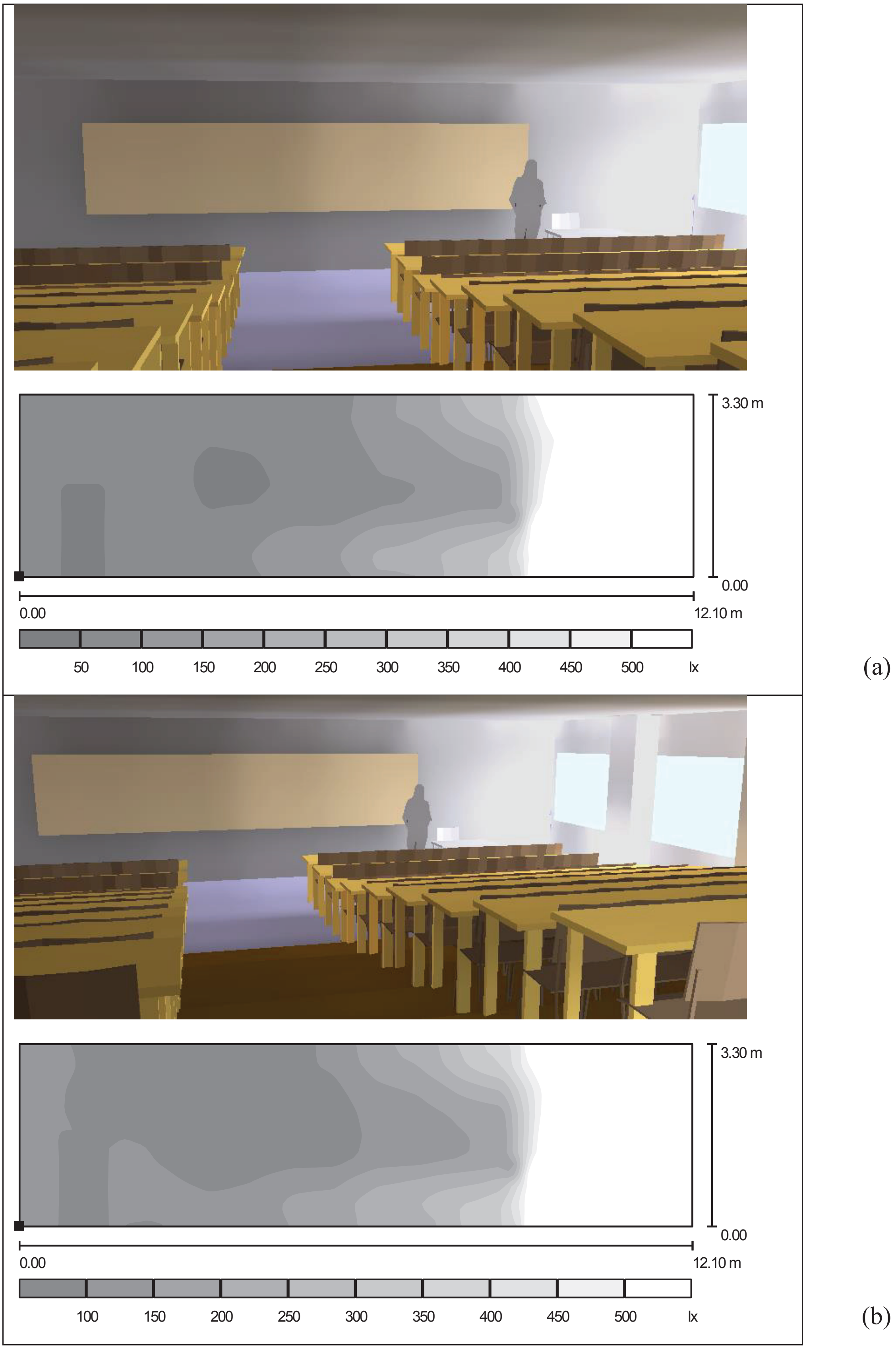


Figure 5.40. Grey value distribution on floor level for MC1 (a) and MC2 (b) (unit: lux)

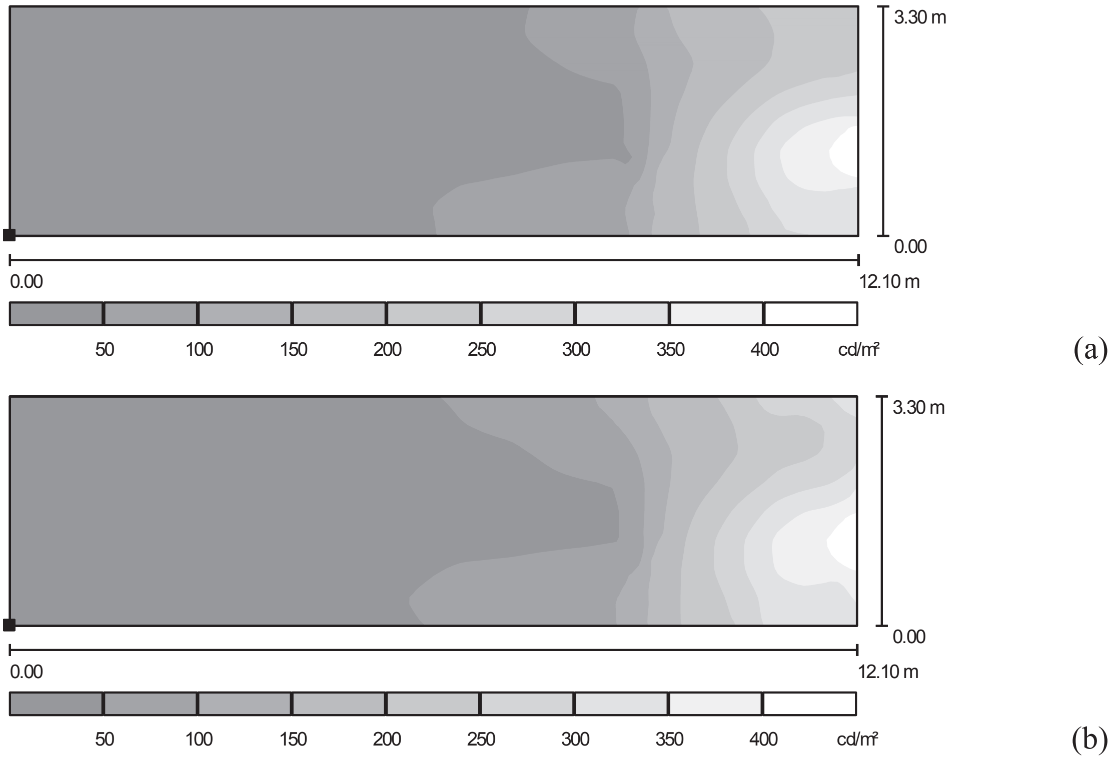


Figure 5.41. Luminance distribution on floor level for MC1 (a) and MC2 (b) (unit: cd/m^2)

Illuminance values on work plane is given in Fig 5.39 and at vertical surfaces are given in Fig. 5.40 according to the white board placements. As seen, MC1 and MC2 models are almost acted in the same way in illuminations and 80% of the work plane is above 100 lux at the work plane. Similar to the illuminances, luminance distributions are varying between 50 cd/m^2 and 400 cd/m^2 at the white board placed wall (Fig. 5.41). When board area is considered, two of them have luminance ratio around 0.25 and it is well distributed and not caused to glare at both MC1 and MC2 model.

With these determinations, room acoustic models of two material combinations are prepared and evaluated according to the acoustic performance expectations. As mentioned in Chapter 4, three types of materials are designed for the acoustic needs. The details of the selected acoustic panels are shown in Table 4.1 and Table 4.2, which are presented up to the lighting and acoustic needs Material 1 and 2 are placed on parts of the walls at MC1 model and Material 3 is placed to the part of MC2 model. Fig. 5.42 represents the reverberation time distribution of existing and proposed models. As seen, reverberation time averages of MC1 is 0.76 sec and 0.71 sec in empty occupancy and 0.67 sec and 0.62 sec in full occupancy condition at 500 Hz – 1000 Hz, while reverberation time averages of MC2 is 0.73 sec and 0.71 sec in empty occupancy and

0.69 sec and 0.66 sec in full occupancy condition at 500 Hz – 1000 Hz. Those results are almost the same and they both are in the recommended levels. The reverberation time averages of existing model were around 1.1 sec, that means there is an equivalent improvement at both of those design components.

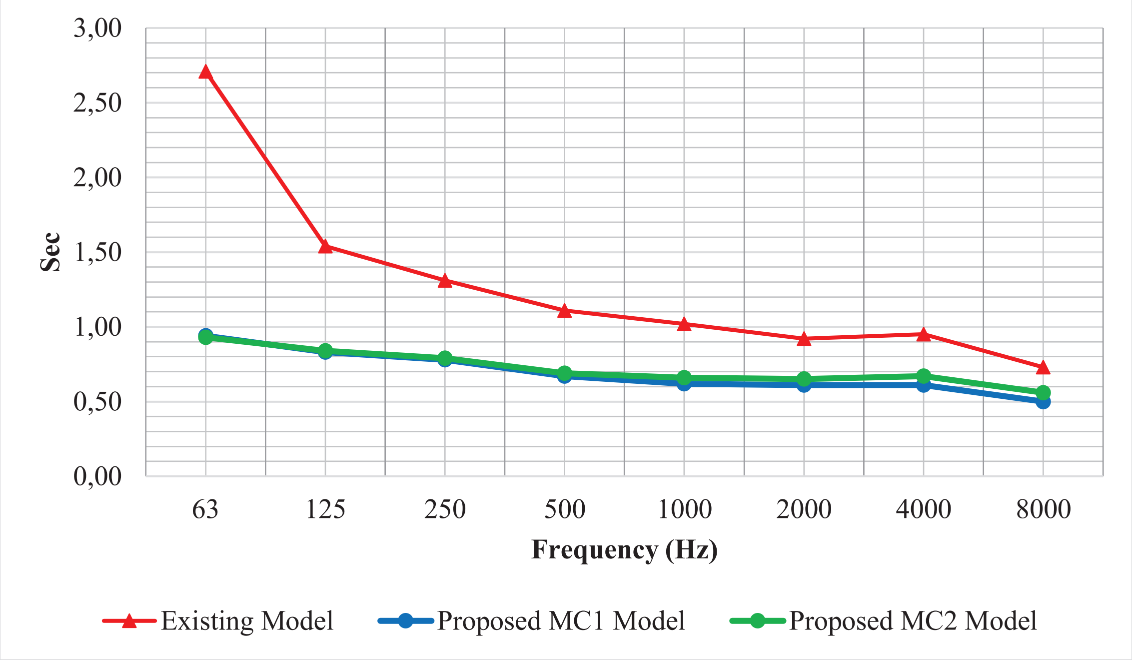


Figure 5.42. Comparison of material combination changed study MC1 and MC2 with ………… .existing model according to reverberation time in full occupancy condition ………… (unit: s)

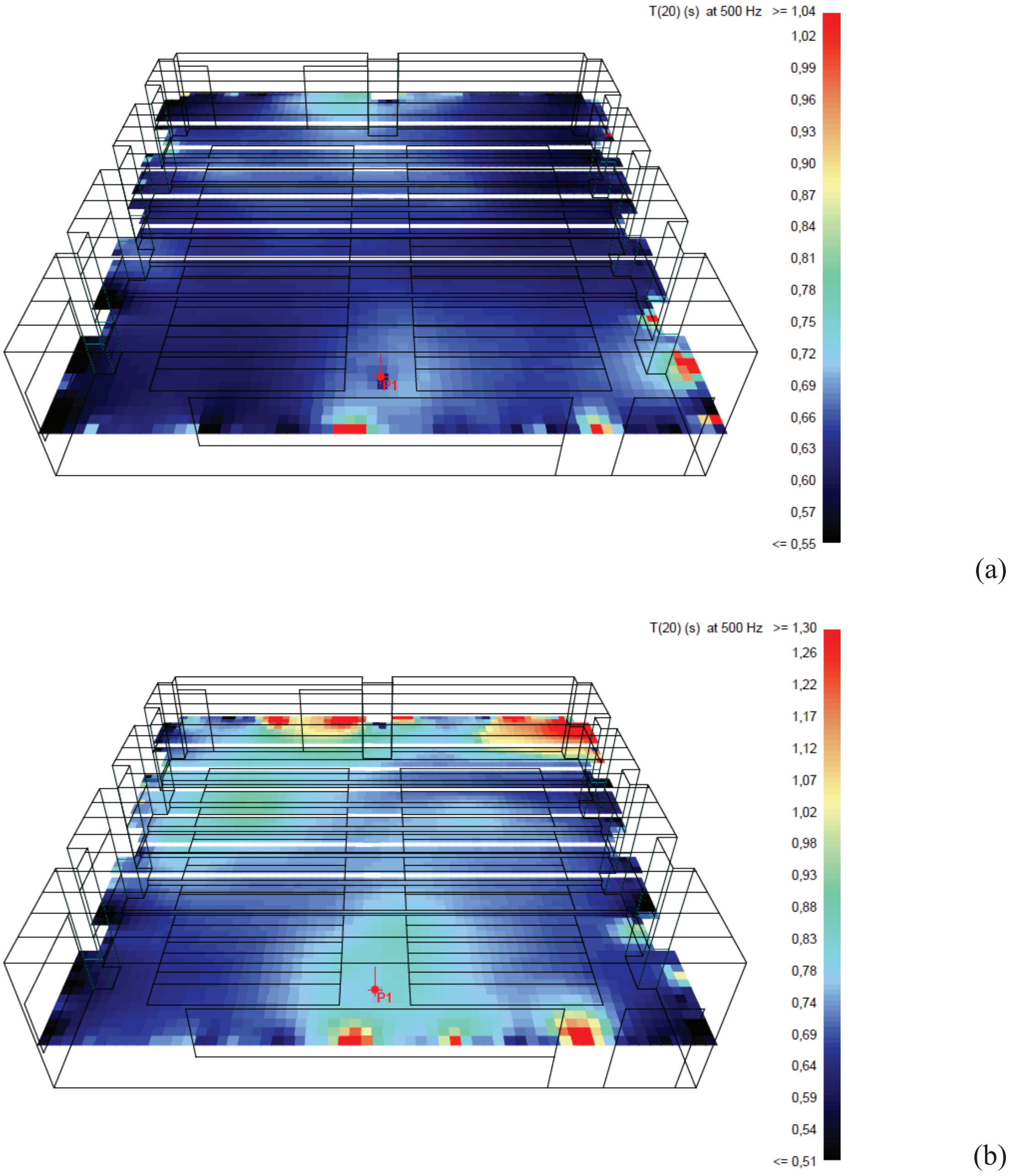


Figure 5.43. T20 results of grid calculation at 500 Hz for MC1 (a) and MC2 (b) in full occupancy condition (unit: s)

Fig 5.43 is the grid distribution of T20 averages at 500 Hz for MC1 and MC2. Those illustrations bring the slight difference on acoustic performance between MC1 and MC2. As seen, grid calculation of MC1 is almost equal and covered in blue tones which corresponds to 0.66-0.72 dB. Yet, MC2 model is covered with blue and green which is 0.69-0.88 dB but just not as uniform as MC1.

STI distribution of MC1 is 0.58, 0.57, 0.58 and 0.55 in empty occupancy and 0.60, 0.58, 0.61 and 0.57 in full occupancy condition respectively to the four receiver points. That means receivers closer to the lecturer are able to reach slightly higher values than back area but that difference is at the ignorable level. Similarly, STI results of MC2 distribution 0.58, 0.57, 0.58 and 0.55 in empty occupancy and 0.60, 0.57, 0.60 and 0.56 in full occupancy condition respectively to the receivers and still both of design components are in higher level than existing conditions. Subsequently, MC1 and MC2 applications were compared, both of them are found at 0.59 STI averages which is almost at good quality limit and higher than existing model.

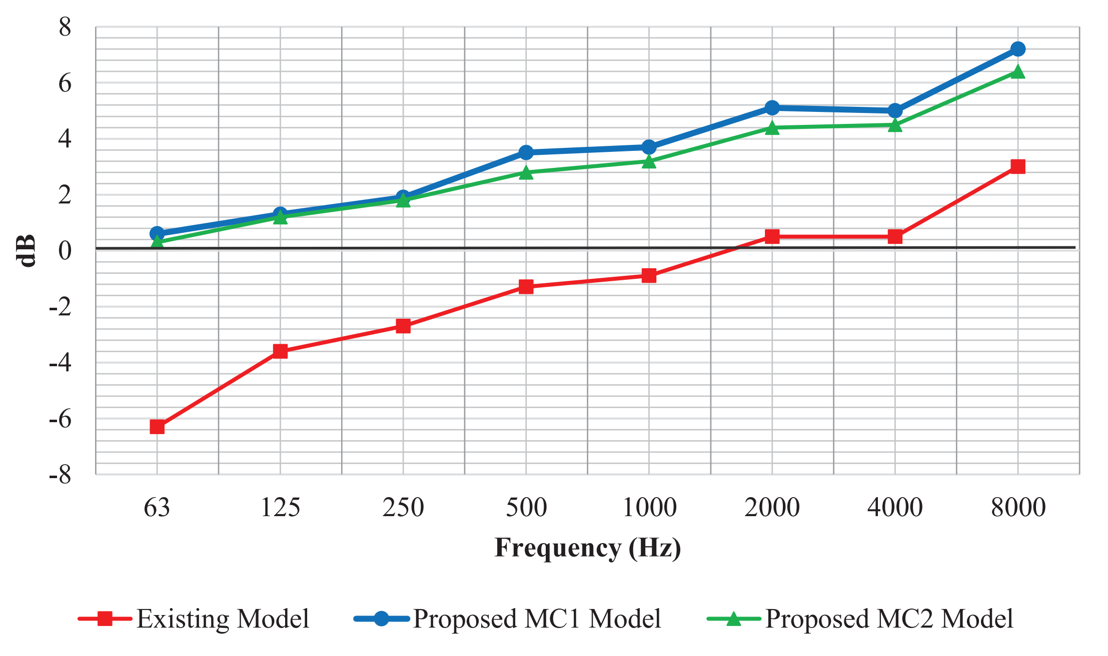


Figure 5.44. C50 results for MC1 and MC2 in full occupancy condition (unit: dB)

When speech clarities are compared, the C50 clarity value is -1.3 and -0.9 dB at 500 Hz- 1000 Hz in the existing condition, while it is +2.2 dB in empty occupancy and 3.5 dB and 3.7 dB in full occupancy condition at both 500 Hz and 1000 Hz in the MC1 application (Fig. 5.44). The choice of second material made in MC2 is involving the absorption and reflective panel placement onto the ceiling. Accordingly, like in CG1, the area in the lecturer section is covered with reflective ceiling panel in terms of acoustics and illumination, while the rest of the ceiling is covered with acoustical absorber but light reflective panel, Material 3. The MC2 results also showed an increase in C50 averages comparing to the current situation.

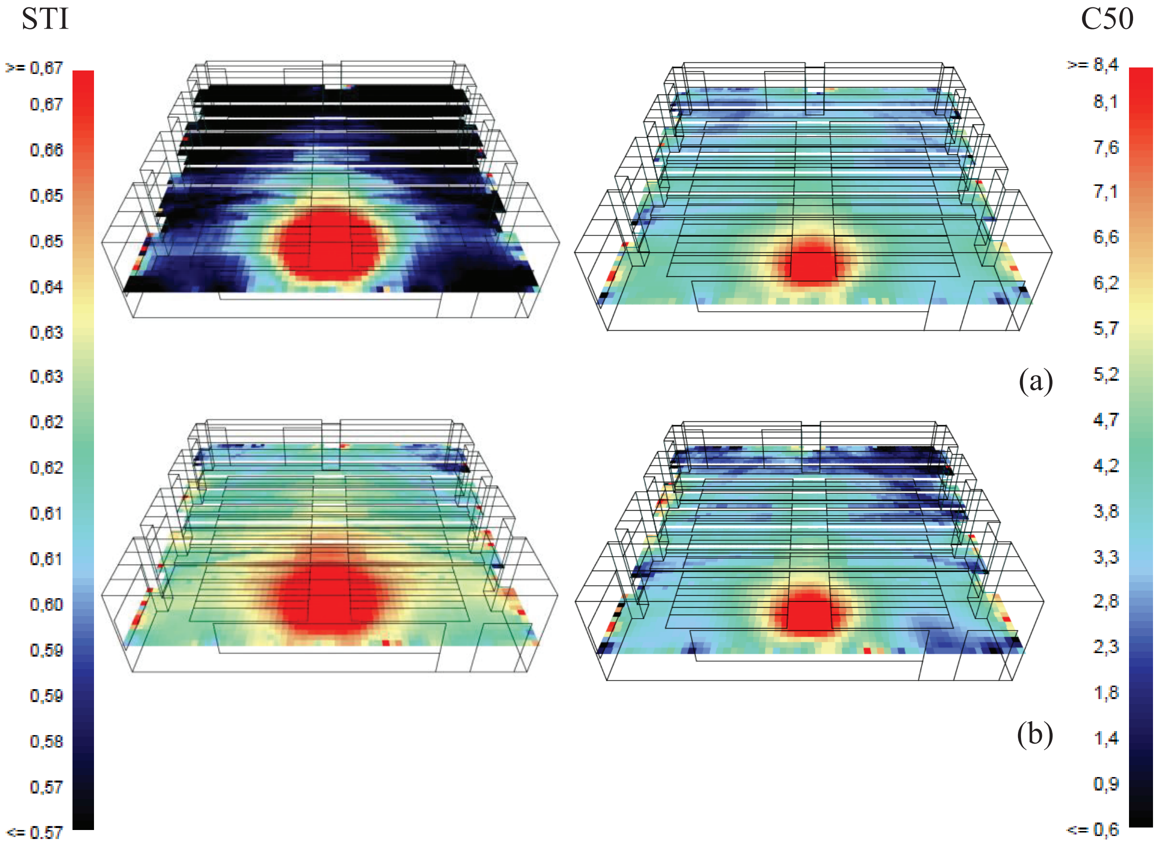


Figure 5.45. STI of grid calculation (left) and C50 of grid calculation at 500 Hz (right) for MC1 (a) and MC2 (b) in full occupancy condition (unit: s)

Figure 5.45 presents the STI and C50 grid calculation of proposed material combination models. As indicated in figures, the average C50 value of MC1 is +2.2 dB in empty occupancy and +3.5 dB in full occupancy condition, where average C50 of CG2 is +1.3 dB in empty occupancy and +2.8 dB in full occupancy condition. Two of them are reaching to recommendations starting from 500 Hz and 2000 Hz in empty and 250 Hz in full occupancy condition respectively, however there is a higher result obtained at MC1 comparing with MC2. C50 distribution of MC1 in grid calculation is generally uniform, colored green and around +4.6 dB except the red area which is so close to the lecturer position and around +8 dB. That means, both MC1 and MC2 are reaching to the positive values and their distribution are better than existing model.

5.4. Summary

At this section of the study, the summary of all simulations is presented below with comparison between design components in Table 5.1.

Table 5.1. Comparison of daylighting and room acoustics performances

Model Type	**Daylighting Performances**				**Room Acoustics Performances**			
	Illumination	**Sept. 30th 10:30-11.30**	**Sept. 30th 15:00-16.00**	**Nov. 4th 12:00-13.00**	**Reverberation Time**	**STI**	**C50 Clarity**	*Frequencies*
Existing Model	E_{min}	11	29	59	1.11 1.02	0.50	-1.3 -1.02	*500 Hz* *1000 Hz*
	E_{max}	178	584	148				
	E_{avg}	59	155	39				
CG1	E_{min}	18	33	10	0.68 0.63	0.60	+4.9 +5.8	*500 Hz* *1000 Hz*
	E_{max}	168	586	148				
	E_{avg}	59	156	41				
CG2	E_{min}	19	33	10	0.82 0.87	0.58	+3.0 +3.6	*500 Hz* *1000 Hz*
	E_{max}	164	569	150				
	E_{avg}	59	153	41				
SL1	E_{min}	11	19	8	1.22 1.08	0.51	-0.5 +0.1	*500 Hz* *1000 Hz*
	E_{max}	307	406	374				
	E_{avg}	77	119	61				
SL2	E_{min}	19	28	19	1.40 1.20	0.50	-0.9 -0.3	*500 Hz* *1000 Hz*
	E_{max}	188	254	188				
	E_{avg}	56	76	56				
MC1	E_{min}	13	36	9	0.67 0.62	0.59	+3.5 +3.7	*500 Hz* *1000 Hz*
	E_{max}	178	551	156				
	E_{avg}	56	155	41				
MC2	E_{min}	15	38	10	0.69 0.66	0.59	+2.8 +3.2	*500 Hz* *1000 Hz*
	E_{max}	188	668	167				
	E_{avg}	67	181	48				

As seen in Table 5.1 in detail, summary of not only minimum, maximum and average illumination levels, but also reverberation time, speech transmission index and C50 clarity values of existing case and proposed design components are listed. Existing case's illumination values were calculated according to field measurements and then, design components of each model were simulated in DIALux. Similarly, acoustic environment of case study and design components are simulated in ODEON software. As mentioned at previous chapter, there is a slightly improvement or decrease in quality of performance parameters. This thesis searches for minor developments at each design components.

Results of simulations regarding daylighting and acoustics showed that, ceiling geometries are essential to develop a performance development strategy, however, adding one reflector panel creates enough level of improvement, where the second one is not changing the result charts in remarkable level. Because, as seen in Table 5.1, CG1 model did not changed average illumination (156 lux), however it increased the uniformity. Yet, CG2 model, which is addition of the second reflector panel, again has almost the same average (153lux) but its maximum illumination level decreased 584 lux to 569 lux. Adding a single reflective panel to the ceiling rised illuminance uniformity even not adding any system to the façade. Similarly, where existing lecture hall's C50 clarity increased from -1,3 to +4,2 dB and STI level was calculated 0.50, both CG1 and CG2 models are increased it to 0.60 and 0.58 respectively. That implied the addition of the second panel did not provide a significant change in interior environmental qualities.

Only one single step, orientation of the seating area is extremely strategic while considering the lighting and acoustic design and able to solve with analyzing on a sun path, directional placement of the openings and material placements that will be closed to the audience or presenters. As observed from common results (Table 5.1), just changing the seating layout to opposite directions are raised to average illuminances to 77 lux from 59 lux (SL1) or decreased it to 56 lux (SL2) for Sept. 30th 10:30-11:30 calculations and also uniformity got better from 0.15 to 0.36 level with SL1 and got worse with SL2 model. Also at SL1 model, calculated average illumination is decreased from 155 to 119 lux for same day's 15:00-16:00 calculations, yet SL1 has a well-lit surrounding near white board placement and has a higher uniformity. This element is done with no addition of material or any new system to the lecture hall. Opposite of that, SL2 decreases both interior daylighting levels because of raised platform and did not improved the speech intelligibility.

Similarly, adding selected materials to the strategic locations makes the indoor acoustic environment better and may increase the speech transmission level from 0.50 to 0.57 (MC1 and MC2 models) and decrease reverberation time values from 1.1 sec to 0.77 sec. Although, MC1 and MC2 models did not improved the inner lighting quality in remarkable level, they both increased the STI levels from 0.50 to 0.59.

CHAPTER 6

DISCUSSION AND CONCLUSION

The aim of this study was conducting two interior environmental design strategies via each and one design component and in this way, improve daylighting and acoustic performance in an educational space. The case room was in 11.9 m in width and 12 m in depth, so glazing ratio is found to be in a lower level from recommendations. It was assumed that by using interior design components - ceiling geometries, seating layouts and material combinations- daylight and acoustic performance of the lecture hall is to be improved. Also, the amount and distribution of the light comes from glazing was not uniform and that causes glare problems which is an obstacle on a healthy environment in an educational space. Selection of finishing materials are in reflective quality and those were increasing the reverberation times more than recommended values.

In literature, there are several studies found combining lighting and acoustic designs impact together. As an example, Krüger and Zannin's study searched for comfort conditions of a classroom considering the indoor environment elements, namely, lighting, acoustic and thermal environment (Krüger & Zannin, 2004). Their study calculated temperatures, illuminances, noise levels and energy consumptions and they run several programs like Boxcar to achieve related data. Their study resulted with finding each element could affect all comfort conditions in common. So, this thesis becomes another study of analyzing elements' common influences on indoor environment yet covers more field measurements in different conditions and including several design elements to the research. They measured existing conditions with HOBO data loggers and LD-500 illuminance meter analyzed the results via BoxCar and ANALYSIS program, where this study has been worked with Konica Minolta illuminance and luminance meters, Brüel+Kjaer 4296 Omni Power sound source, 2716 amplifier and 2260 Sound Measurement Devices (microphones) to measure and DIALux and ODEON softwares to calculate the design elements. They also search for the effects of light shelf with existing two classrooms. One is light shelf adapted and the other one has no light directive system. This thesis search for wider options of design elements via software and analyzed three different components with two orientations at each of them.

There were more studies like Freewan's search on ceiling geometry (Freewan et al., 2009) which only considers lighting design or Mehta's study on only effects of room geometry on acoustic design (ASA, 2002). Despite the examinations done at previous studies, there was no sufficient example of an integrative aspect of each selected element. While comparing their results between each other and with this thesis outputs, it is strongly considered to find the common issues since there is always a need to find a solution to multiple problems with a single design decision. So, it was considered to connect the effects with the limited index to see the detailed results.

Regarding these considerations, the DIALux and ODEON simulation tools are employed the daylighting and room acoustic simulations with the conduction of three different type of design components which met the considerations of uniform distribution of lighting and reaching to the adequate speech intelligibility level; namely, ceiling geometries, seating layouts and material combinations.

While comparing illuminance and room acoustics of each design components, improvements at each models' average illuminances, uniformity ratio and speech transmission index values are studied. As observed from results of improvement, changing seating layout to the west (SL1) and providing light reflective and acoustically absorptive materials to the ceiling (MC2) was the best options for lighting design. Similarly, changing the ceiling geometry (CG1) and material (MC2) was the best performances for acoustic design.

Considering whole results including lighting and acoustic design performances, MC2 model found to be as the best performing common model and presented as the best solution method. Although there was a slight difference on the values, all the elements are analyzed separately to see the effects of each of them. In conclusion, changing the geometry and material of the ceiling design is found to be advised to the designers to get the best and considerable change at the design performances.

While analyzing results, combining material combination and seating layout design components are able to reach the highest improvement level and advised to be used together in interior designs considering room acoustics and lighting design achievements together. At the same time, SL2 model is found to be in least improvement ratio since it consists having a white board placement in the darkest area and having the minimum illuminance ratio and has no achievements in speech transmission index values. Improvements are limited at each scenario, because the lecture halls' room depth is high, window to wall ratio and room index is not appropriate for higher results. Additionally, most of the literature research were using façade design and adapting new systems on them to improve illuminance and using changes on divider walls and reshape room geometry for room acoustics reflections, yet this research is defined strict limitation which is involving only selected changes from interior, not from façade or divider walls. So, the aim was searching for improvement is very limited conditions and determining each design components' effects that are slight but in found to be in positive way.

Simulations were carried out in ODEON and DIALux and, both of field measurement methods and selected simulation tools are found to be practical. DIALux is able to construct each of the desired geometry and the material quality, however, the material library was limited with reflectance and roughness levels. ODEON is so easy to construct the geometries and assign required material qualities as well as studying on reflector coverages and mappings.

Consequently, it is not always easy to adapt well known daylighting and acoustic design strategies to an existing case and that thesis limited the variations from beginning and search for slight but common effects of each design elements. Yet, literature reviews, existing field measurement charts and comparisons on different times showed the imperceptible but can be treated points of existing conditions and this study deeply searched for the changes. In conclusion, clues for a more uniform lighting and better speech intelligibility is achieved and existing condition's performances comes closer to the recommended values presented in standards. So, this thesis would make an essential contribution to a typical lecture hall and advises helpful clues for better indoor environment and would be a recommendation set while designing a new education place or re-arranging the existing ones.

The base and purpose of this thesis is awareness of conducting design strategies that have influence on the users of those spaces. Since the definition of this study is concluding the educational spaces and interior design components, it is aimed to improve daylight and acoustic performance by several components that are chosen at the design phase or able to be changed after construction phase is completed.

This thesis, last of all results, would made an essential contribution for proposing design components to the Faculty of Architecture in İzmir Institute of Technology in terms of both visual and acoustic performances. Room acoustics results and daylighting distribution obtained from the case and proposed models' results obtained from the study would be helpful for making decisions of retrofitting since the study searches for common design parameters and its methodology was considered to provide a systematic knowledge and simulation series for this kind of connective design system. In this way, the study differs from others by combining the acoustic and lighting conditions at the same time and provides an integrative aspect to the designers.

Field measurements are taken at sunny and overcast days of September and November, in different times of a day and acoustic environment is explored via four receiver point with interrupted noise method. Effect of background noise might be ignored for this thesis' content since it is considering change in room acoustics results without containing exterior elements' change. Then, existing conditions daylighting and room acoustic conditions are simulated in DIALux and ODEON and those models are validated up to 90% correctness degree of a coefficient of determination. In literature, effects of materials, their surface color and qualities, their placements and forms are found to be developing elements for design performances. So, three design components, ceiling geometry, seating layout and material combination are searched and studied on this lecture hall and two options for each component are determined. Simulations are conducted with three design components at the design proposing step. Results are compared with averages, minimum and maximum levels for daylighting between each other. Best improvement levels and proximity to the international standards are discussed. Speech intelligibility levels and speech clarity levels are determined as well as reverberation times. Performance of each model is compared with recommendations and effects of each step at the design component are examined. Some of the changes like seating layout's effect on acoustics was at ignorable level, since the surface square meters were too small to see a remarkable change. Material combinations are found to as a similar development strategy where both of them improved uniformly at daylighting and acoustic results.

The best result was the ceiling material combination's effect. With this minimum intervention, the acoustic performance was improved and the illuminance levels became as uniform as possible. SL1 and CG1 were also affected the existing conditions performance in considerable level. MC1 is an alternative involving a new material combination on wall, while MC2 involves other material combinations on ceiling. So, these two alternatives can show us the separate impacts of new wall and ceiling on visual and acoustic performances. A combination of wall and ceiling materials in one application may be studied at the further researches. Also, that study was based on a case study analysis and the examinations and even simulation models may be extended to the different scaled educational spaces in different volumes and to four season models for lighting design. And current conditions of the lecture hall are determined in several scenarios, yet existing conditions was not calculated in full occupancy acoustic environment conditions since it was not possible to arrange a calculation time during actual lectures. Also, daylight field measurements were only used to validate the lighting simulation models both in two selected days, one representing an overcast sky condition and the other for the clear sky condition. Yet, measurements may be extended to for all seasons, including equinox and solstices or even beginning and ending days of the academic year and not only full and empty occupancy conditions but also half occupied room acoustic conditions.

There is a variation of design components that effect interior environment, lighting and acoustic design and those three are selected among them. Yet, ceiling applications may be extended including anidolic daylighting systems and that may be contributed to the reflective acoustic panel designs.

Further studies may also include glare analysis which was not included however luminance distributions on white board and vertical surfaces were the concerns in this thesis. This study is limited with daylighting and room acoustic design and lighting analysis did not include any part of artificial design. Since ceiling geometry is conducted to the design components, it might also include the artificial lighting and even energy consumption ratios at the further studies.

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APPENDIX A

SOLAR DIAGRAM OF THE FIELD MEASUREMENT DAYS

September 30th, 2016 – 11.00

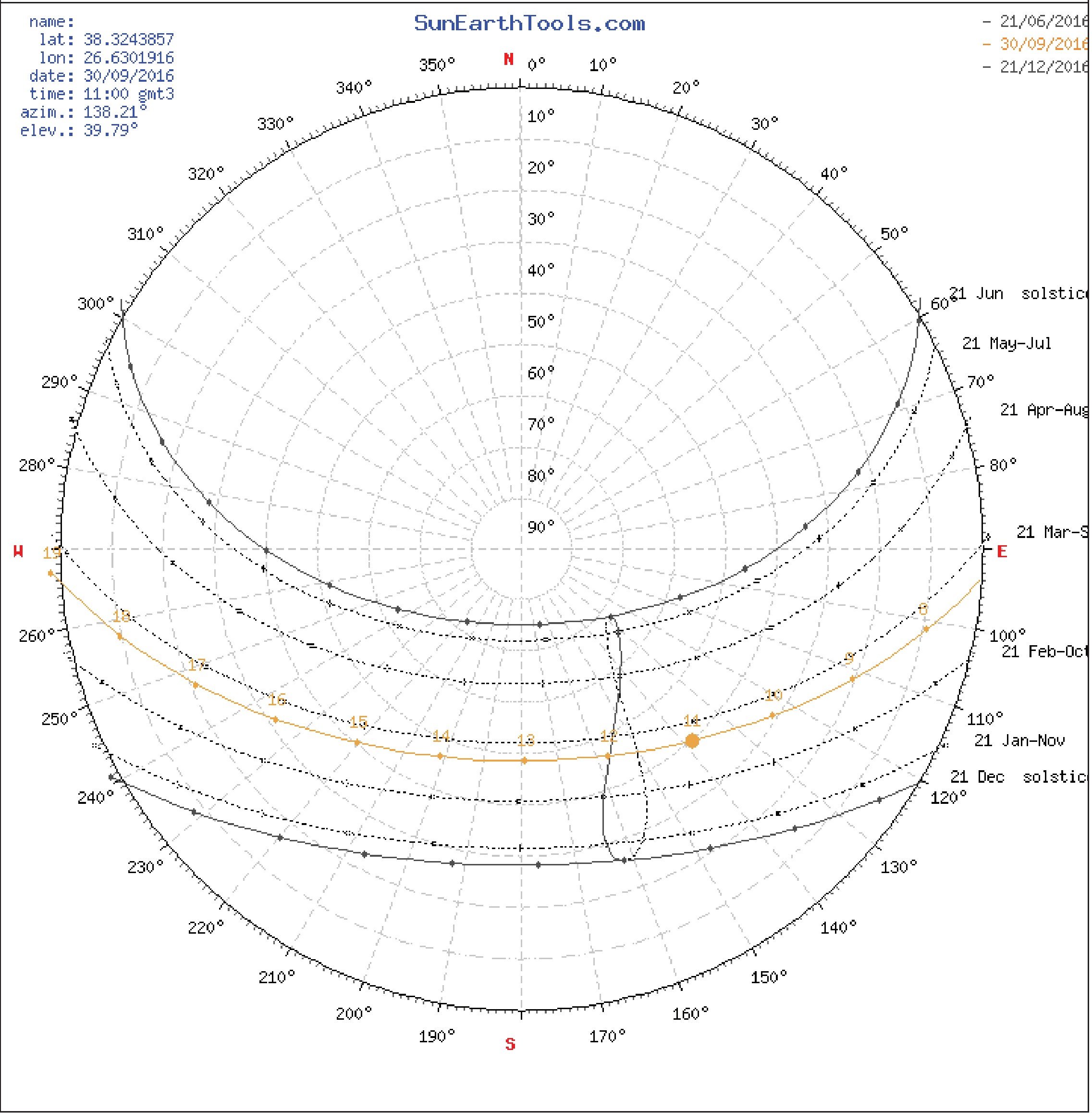
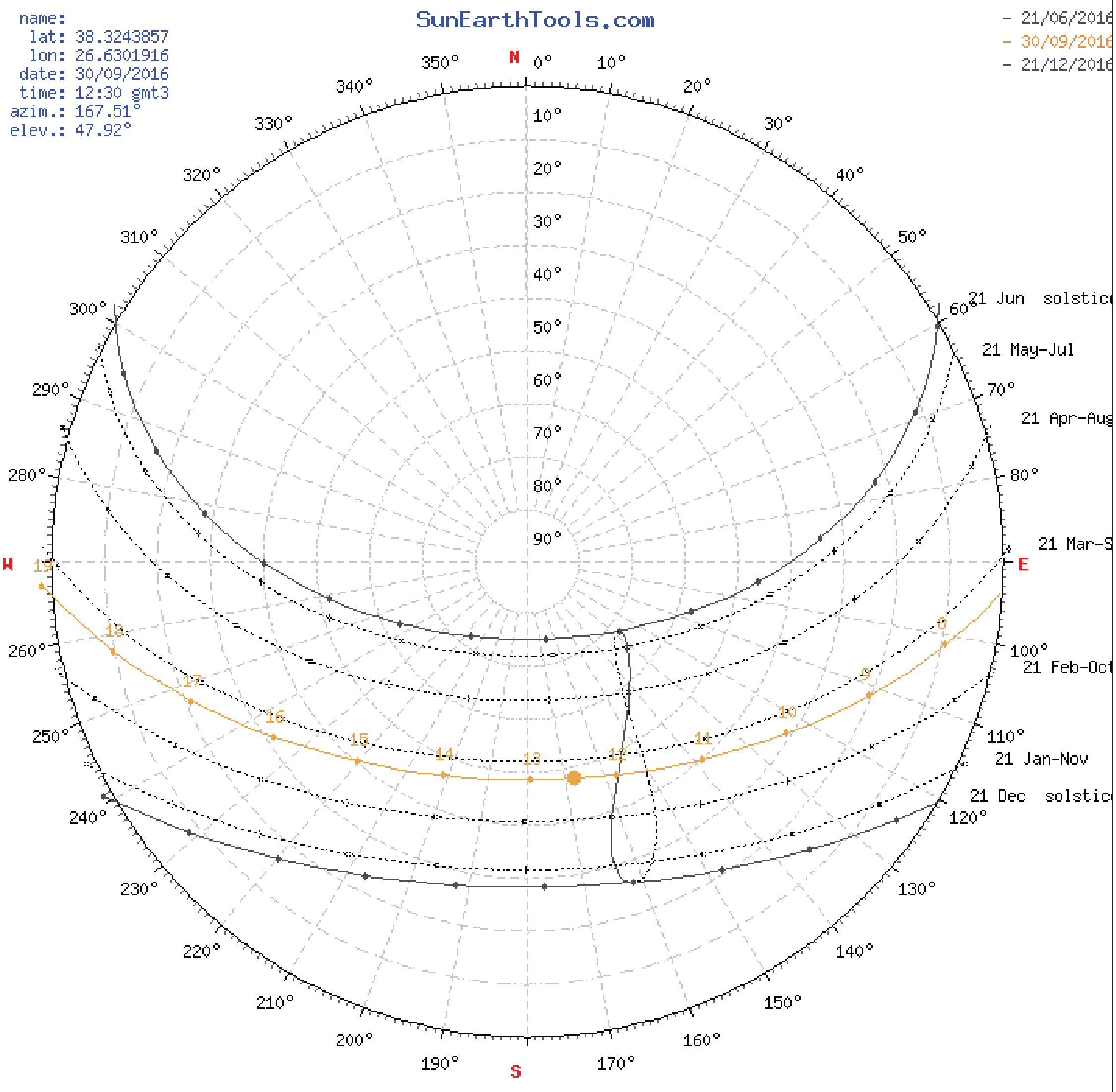


Figure A.1. Solar diagram of September 30th, 2016 – 11.00

September 30th, 2016 – 12.30



name:
lat: 38.3243857
lon: 26.6301916
date: 30/09/2016
time: 12:30 gmt3
azim.: 167.51°
elev.: 47.92°

Figure A.2. Solar diagram of September 30th, 2016 – 12.30

September 30th, 2016 – 15.30

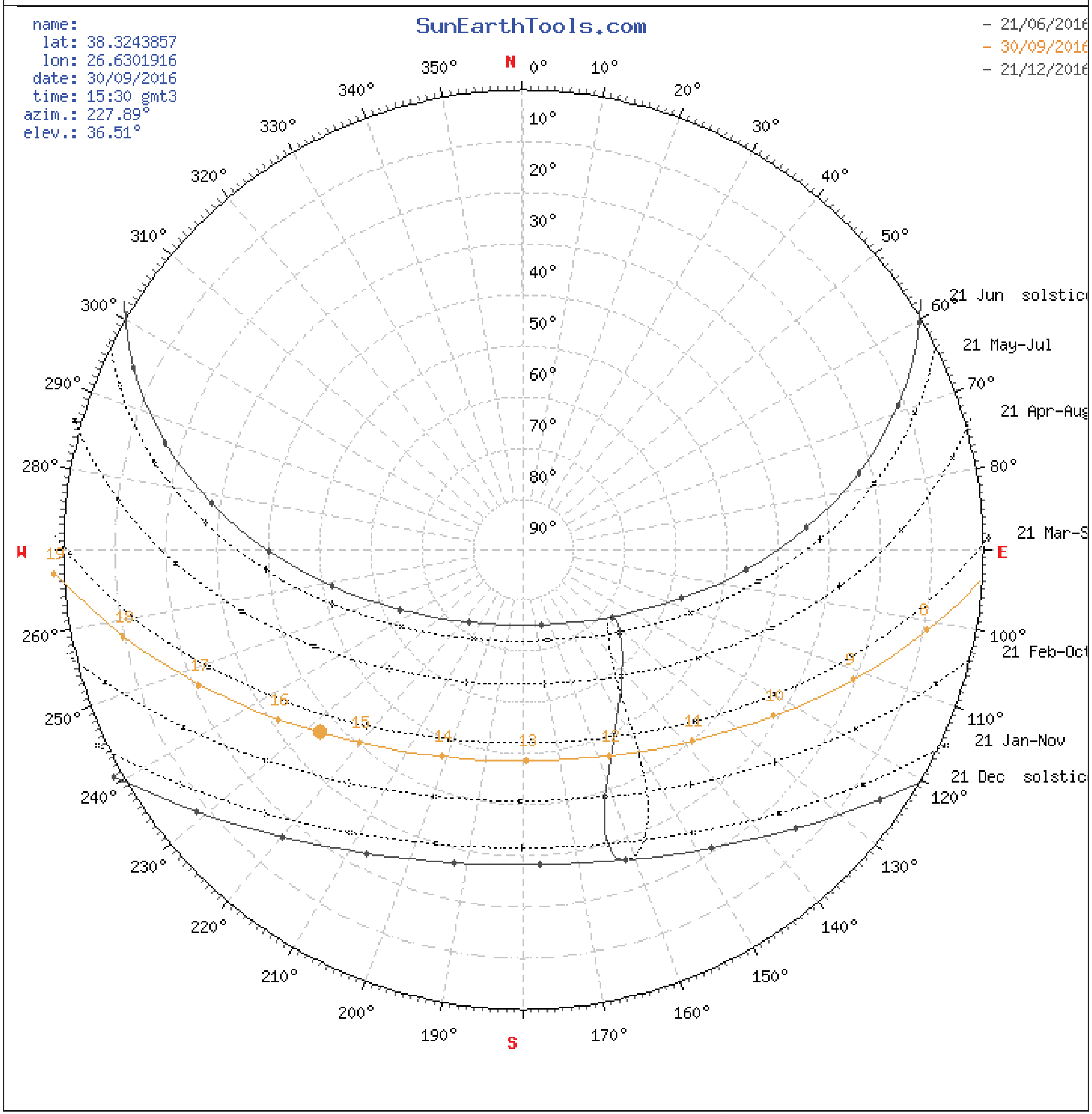


Figure A.3. Solar diagram of September 30th, 2016 – 15.30

November 4th, 2016 – 11.00

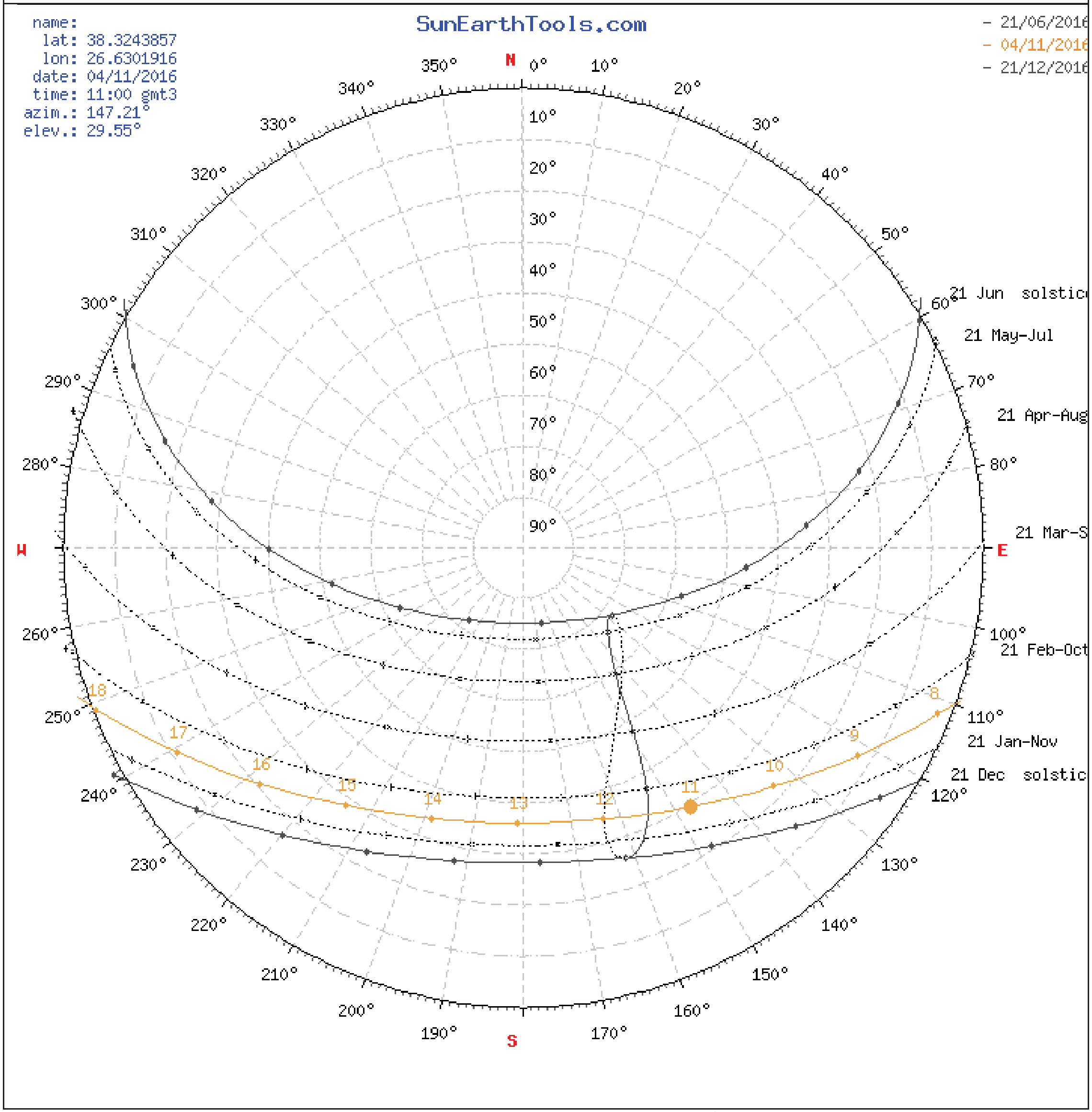


Figure A.4. Solar diagram of November 4th, 2016 – 11.00

November 4th, 2016 – 12.30

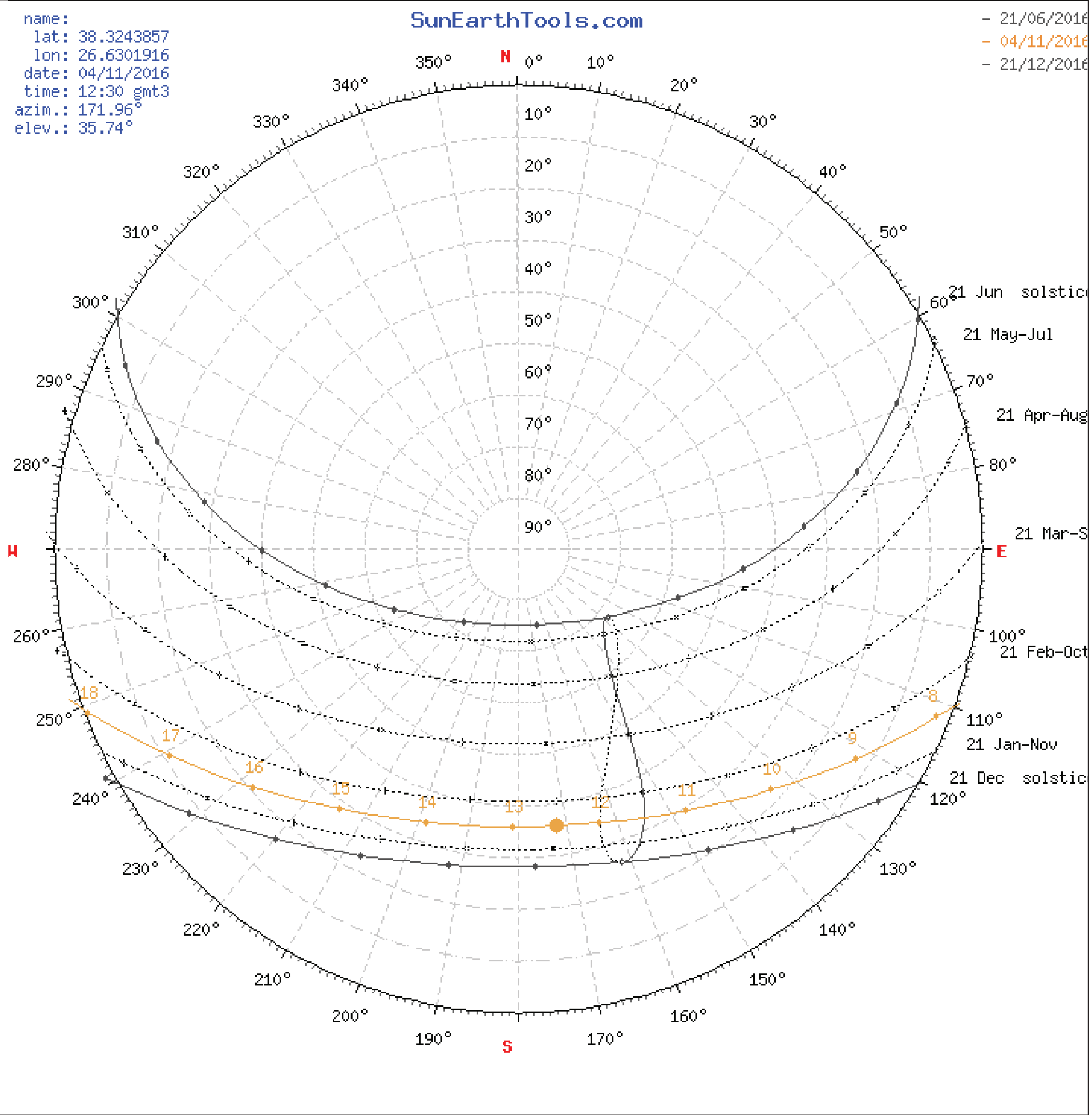


Figure A.5. Solar diagram of November 4th, 2016 – 12.30

November 4th, 2016 – 15.30

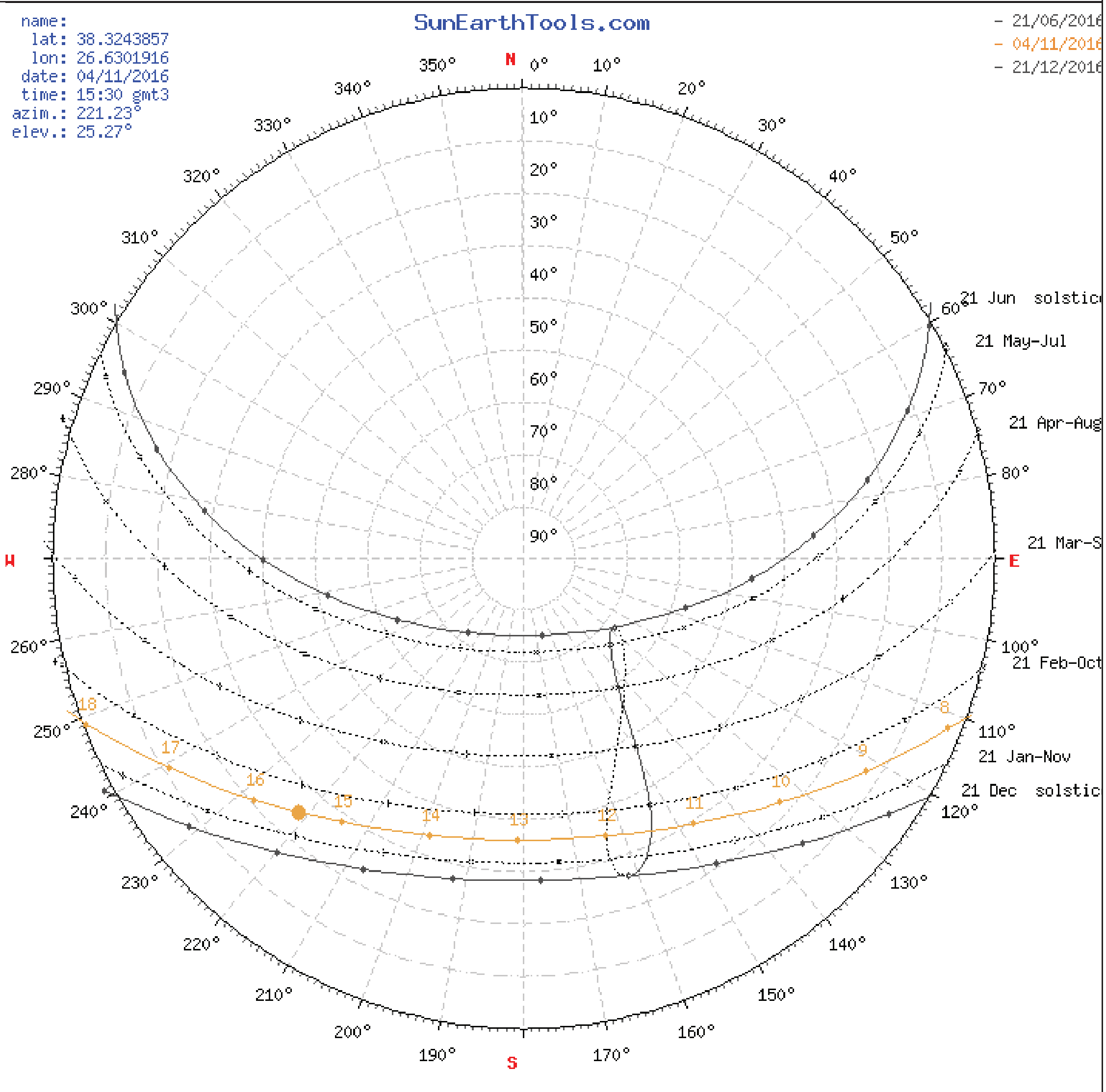


Figure A.6. Solar diagram of November 4th, 2016 – 15.30

APPENDIX B

DISTRIBUTION OF SIMULATED DAYLIGHT ILLUMINANCE REGARDING MEASUREMENT POINTS ON SEPTEMBER 30TH (10:30-11.30) WITH THE APPLICATION OF DESIGN COMPONENTS

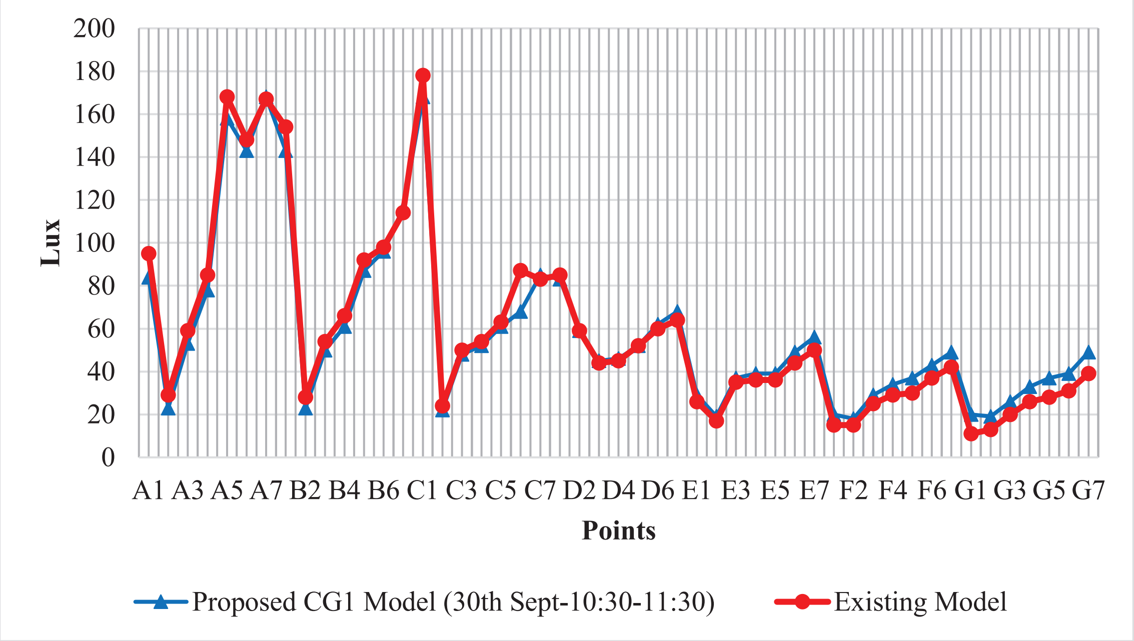


Figure B.1. Comparison of ceiling geometry conducted study CG1 and existing model

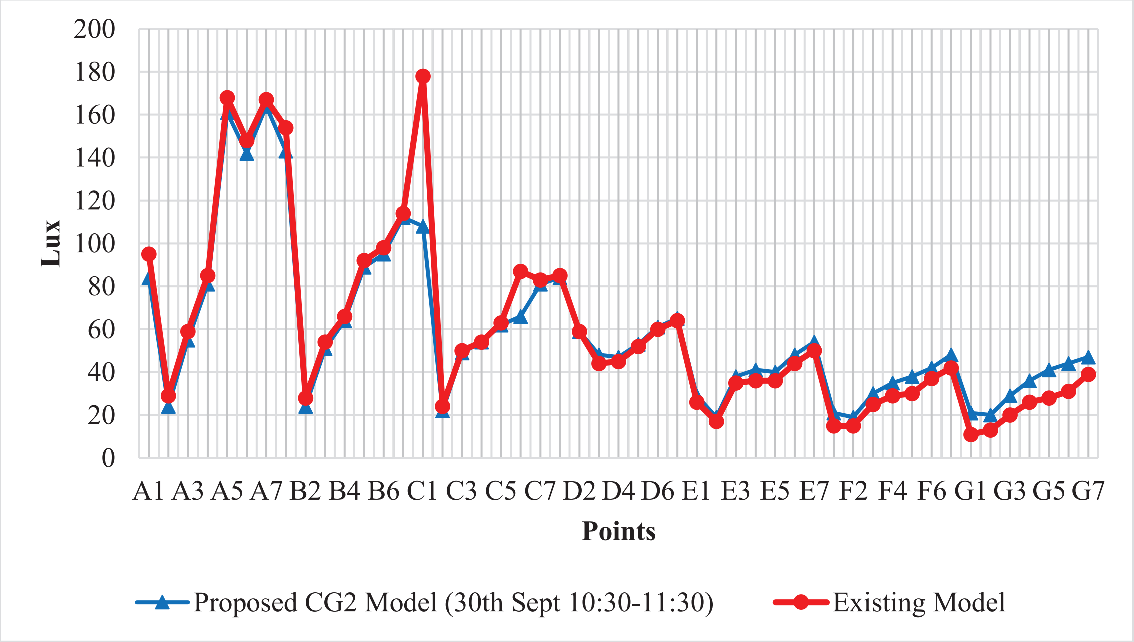
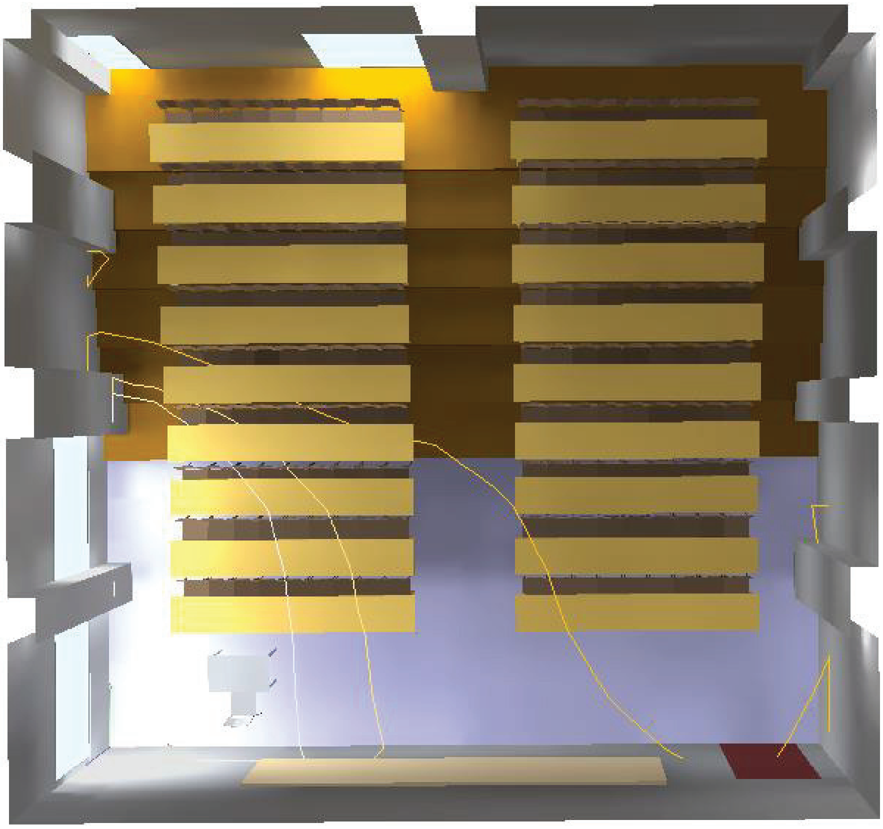
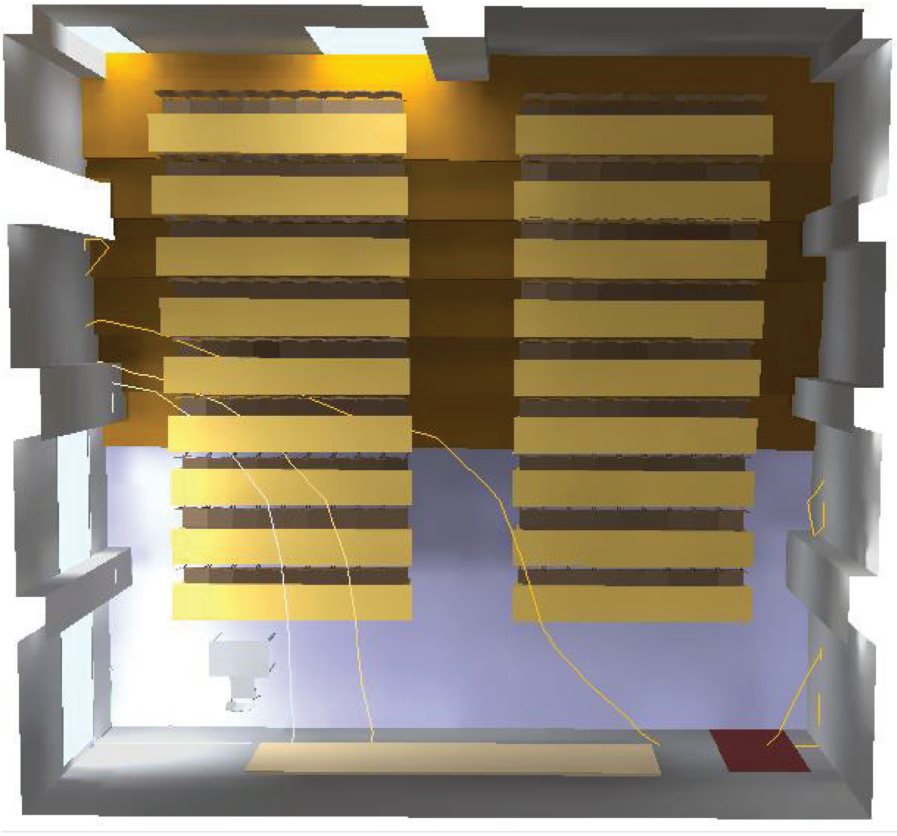


Figure B.2. Comparison of ceiling geometry conducted study CG2 and existing model



(a)



(b)

Figure B.3. Illumination level distribution for CG1(a) and CG2(b). Each line presents 50 lux,100 lux and 150 lux values respectively to the darkest to lightest

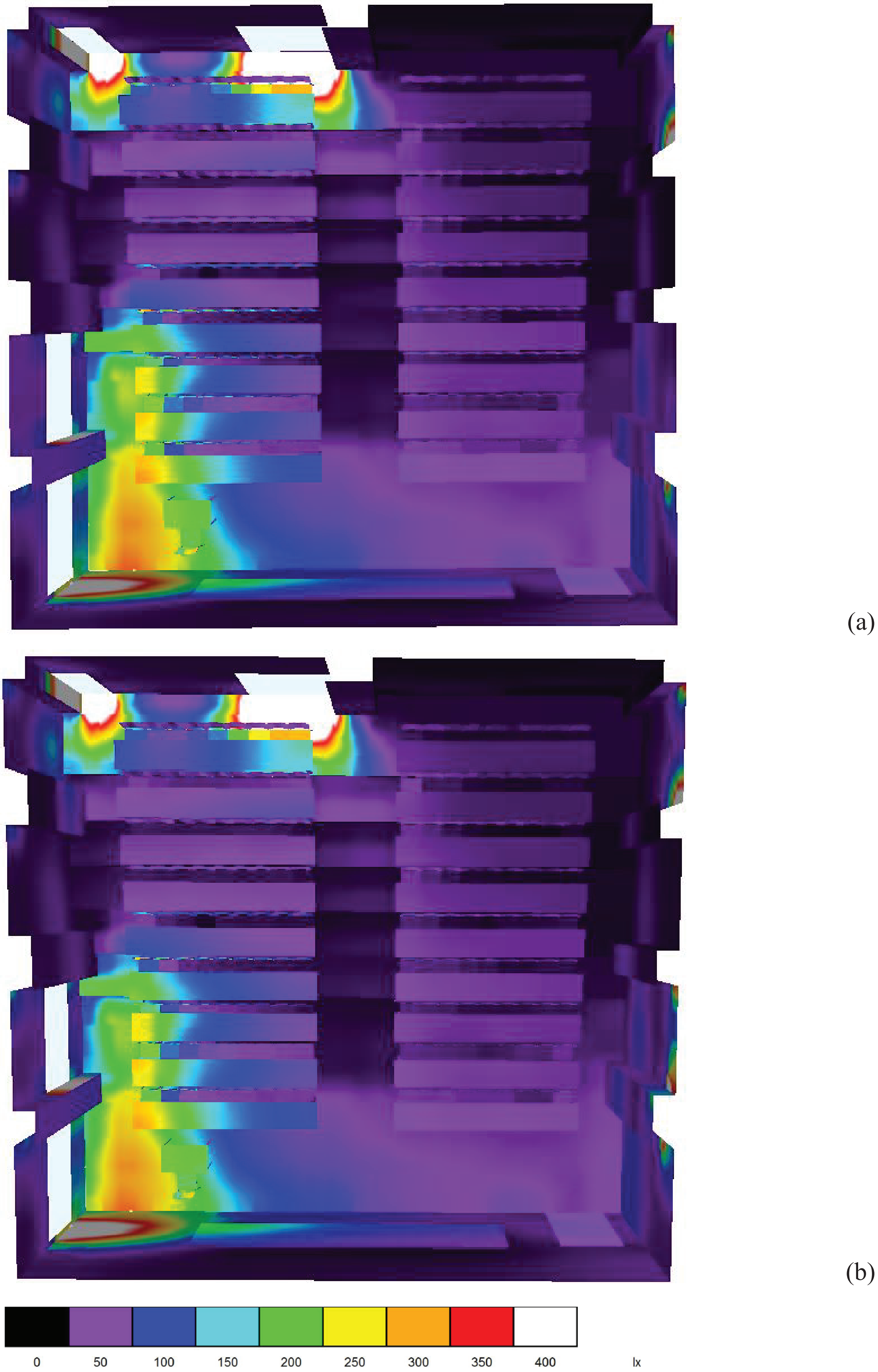
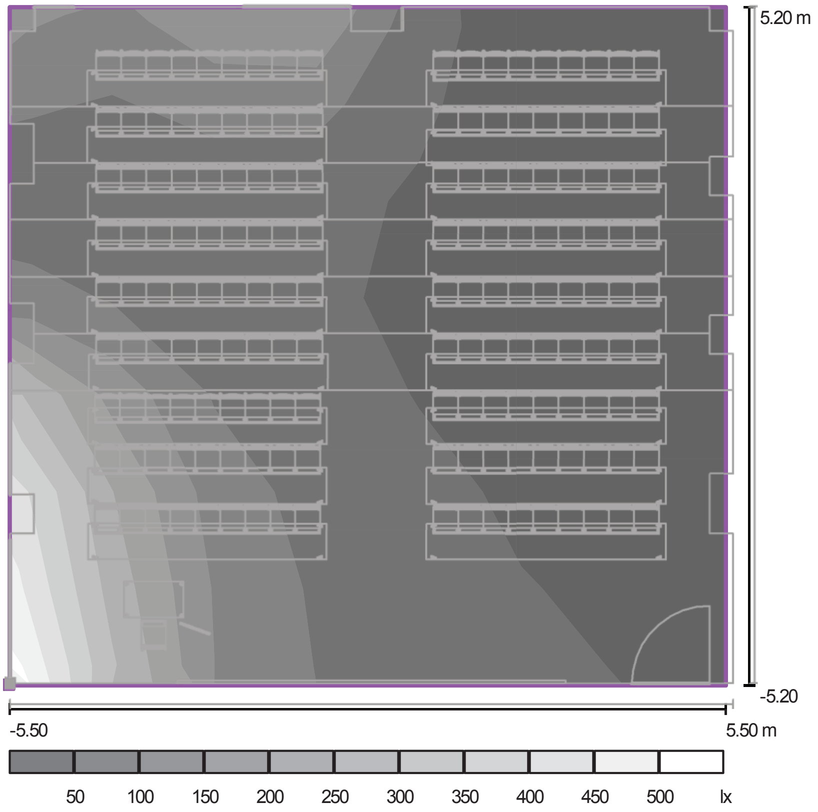
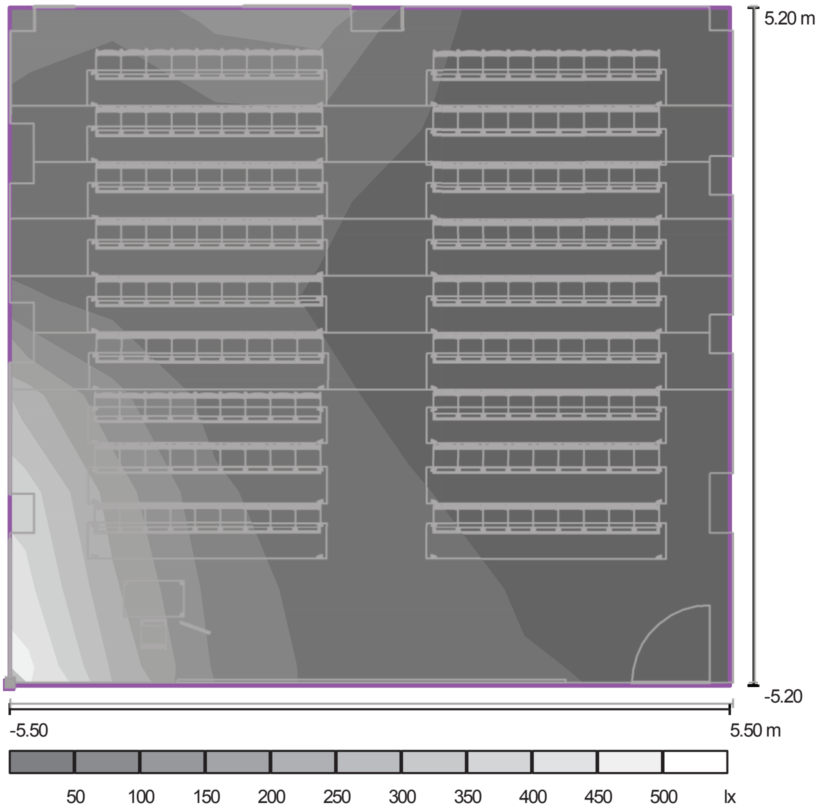


Figure B.4. False color distribution for CG1 (a) and CG2 (b) (unit: lux)



(a)



(b)

Figure B.5. Illuminance distribution on working level for CG1 (a) and CG2 (b) (unit: lux)

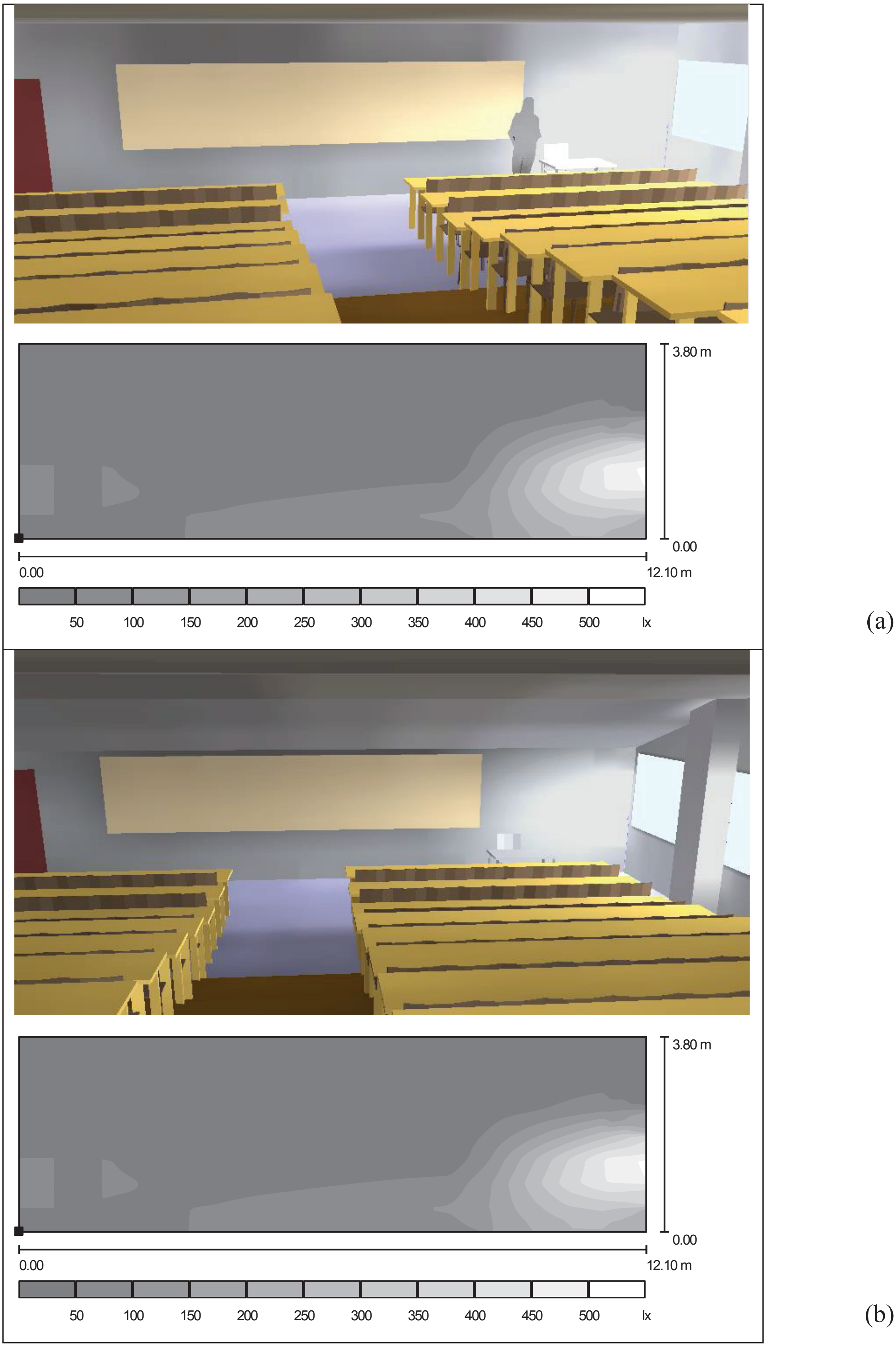


Figure B.6. Illuminance distribution on white board's wall for CG1 (a) and CG2 (unit: lux)

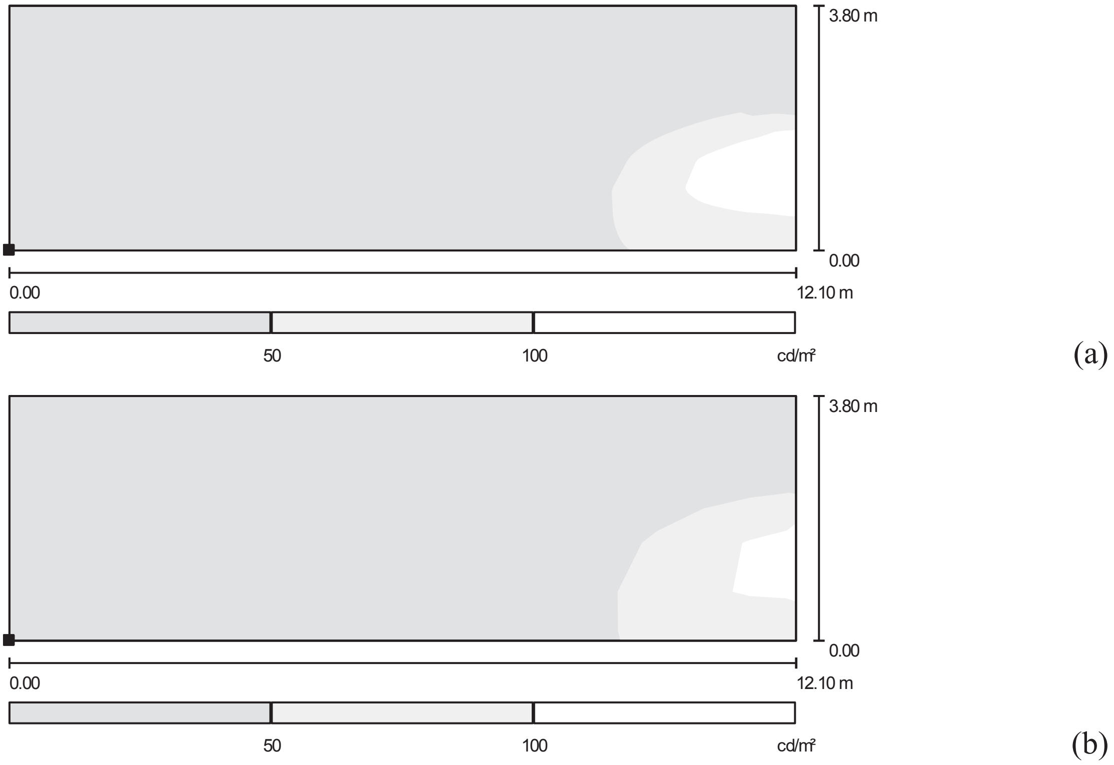


Figure B.7. Luminance distribution on white board's wall for CG1 (a) and CG2 (unit: cd/m^2)

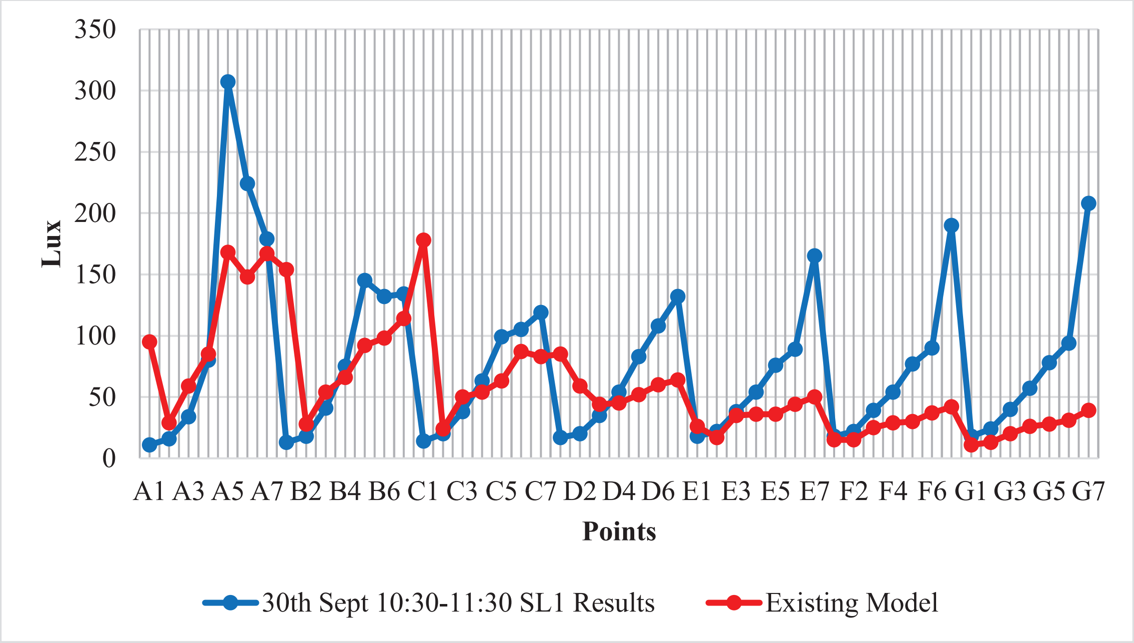


Figure B.8. Comparison of seating layout changed study SL1 and existing model

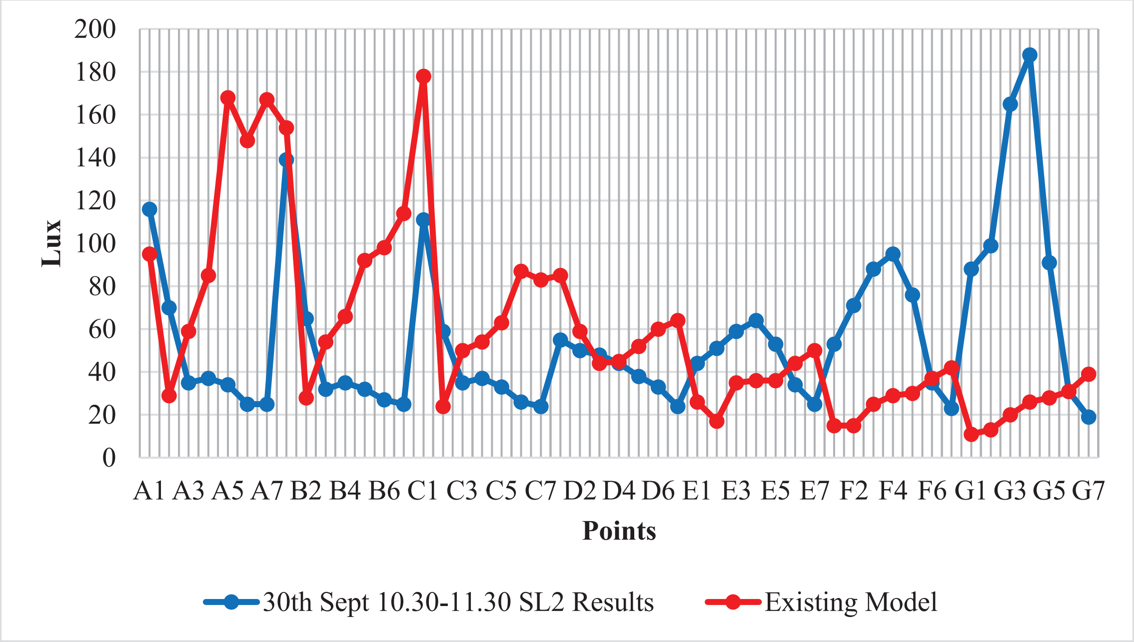
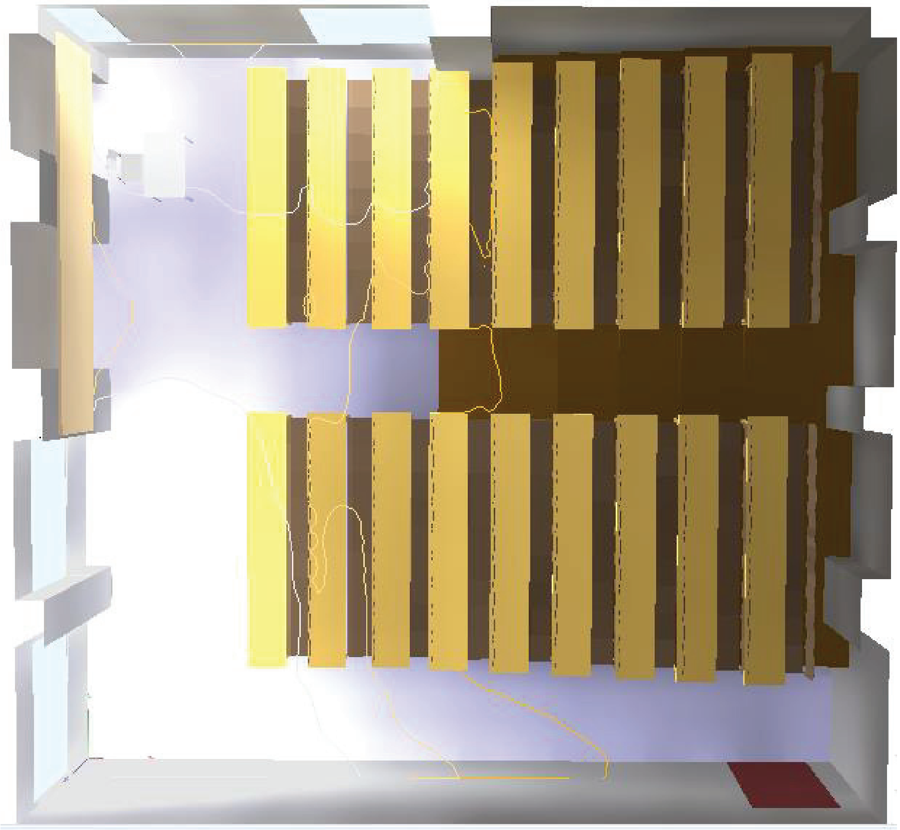
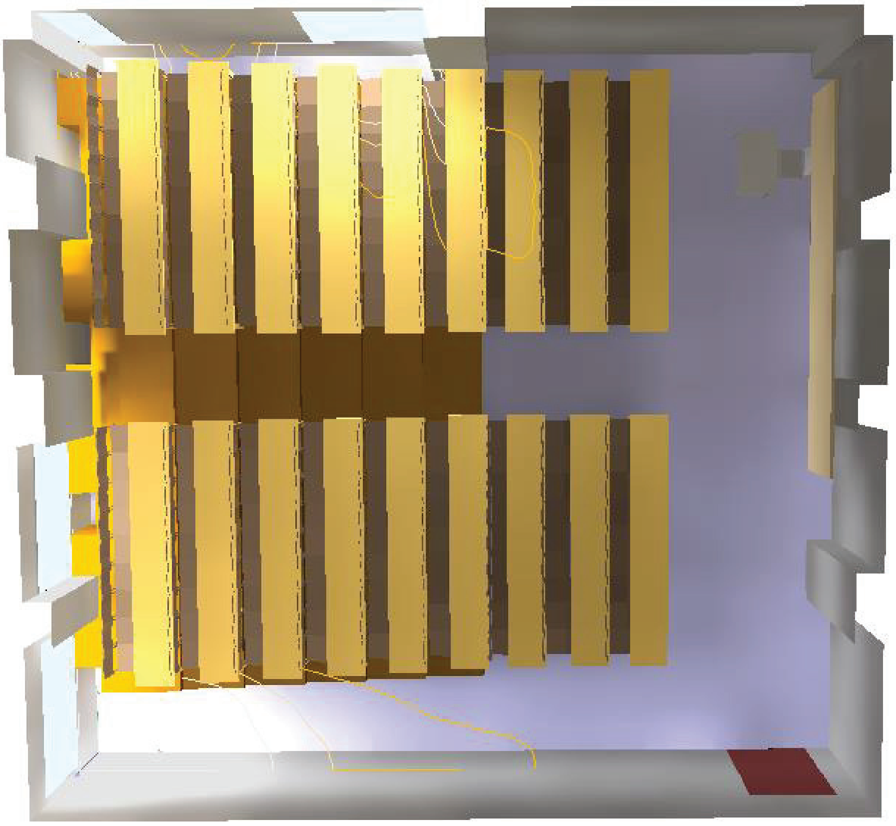


Figure B.9. Comparison of seating layout changed study SL2 (facing east) and existing ………….. model



(a)



(b)

Figure B.10. Illumination level distribution for SL1(a) and SL2(b). Each line presents 50 lux,100 lux and 150 lux values respectively to the darkest to lightest

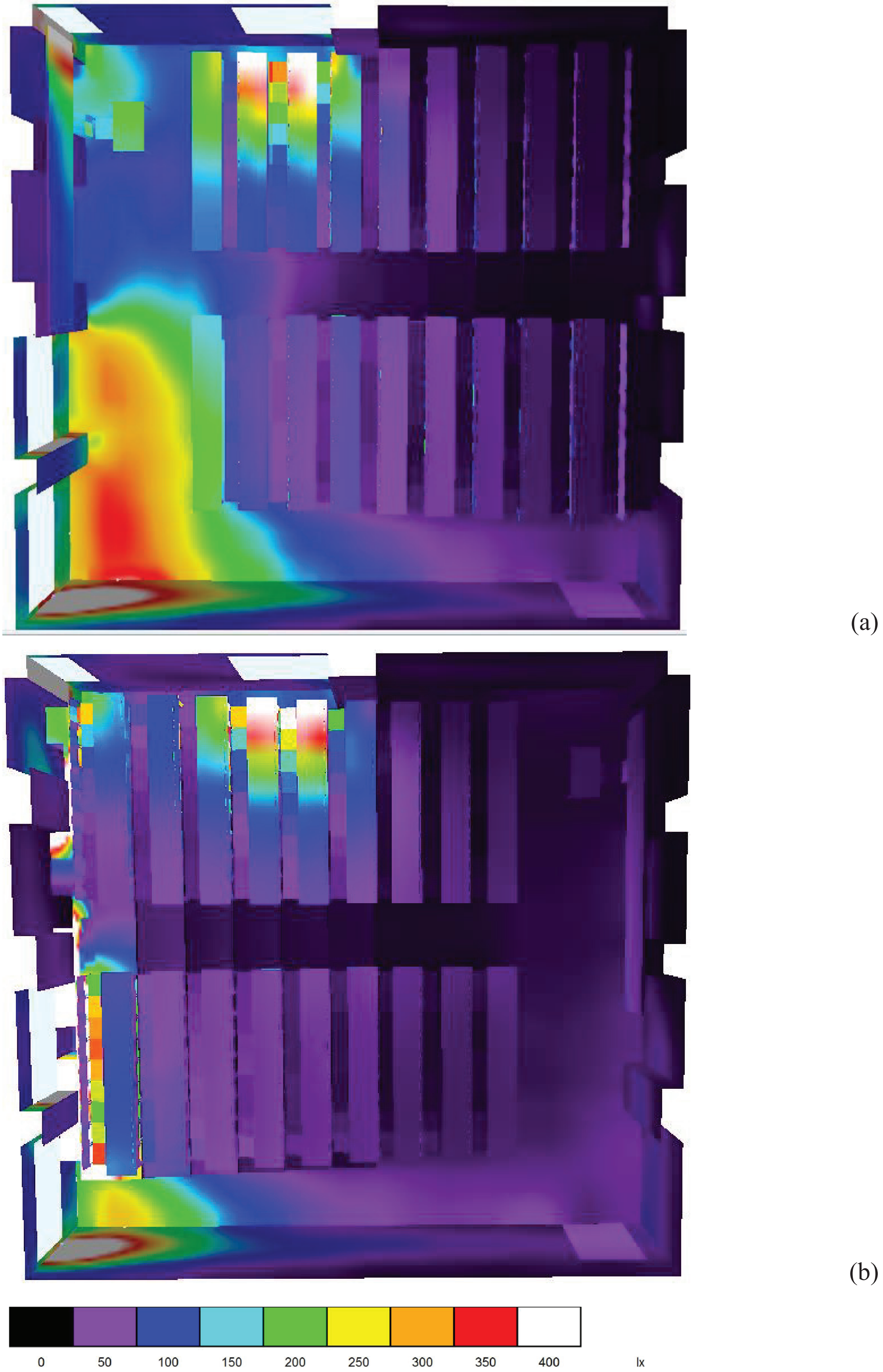
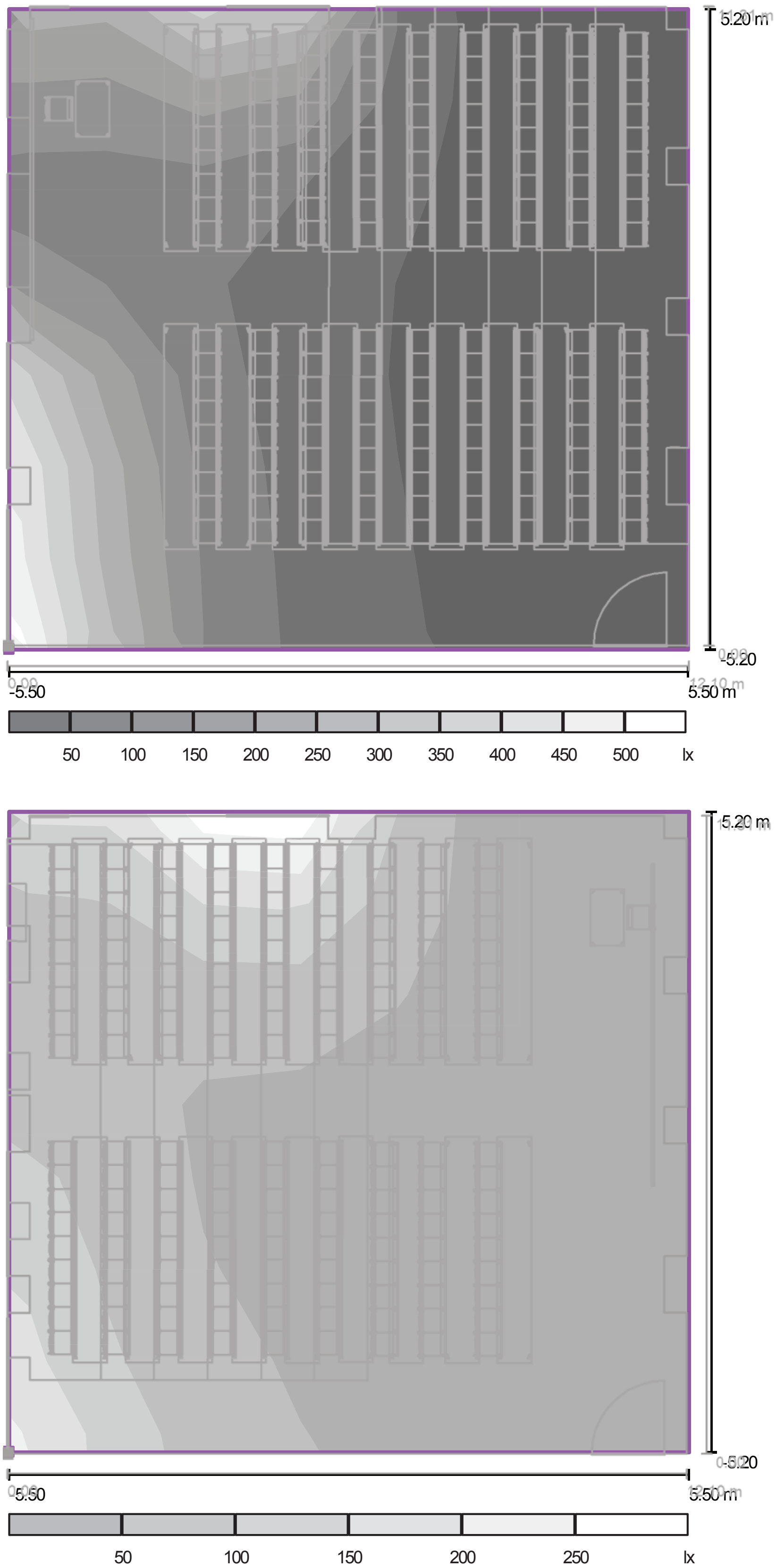


Figure B.11. False color distribution for SL1 (a) and SL2 (b) (unit: lux)



(a)

(b)

Figure B.12. Illuminance distribution on working level for SL1 (a) and SL2 (b) (unit: lux)

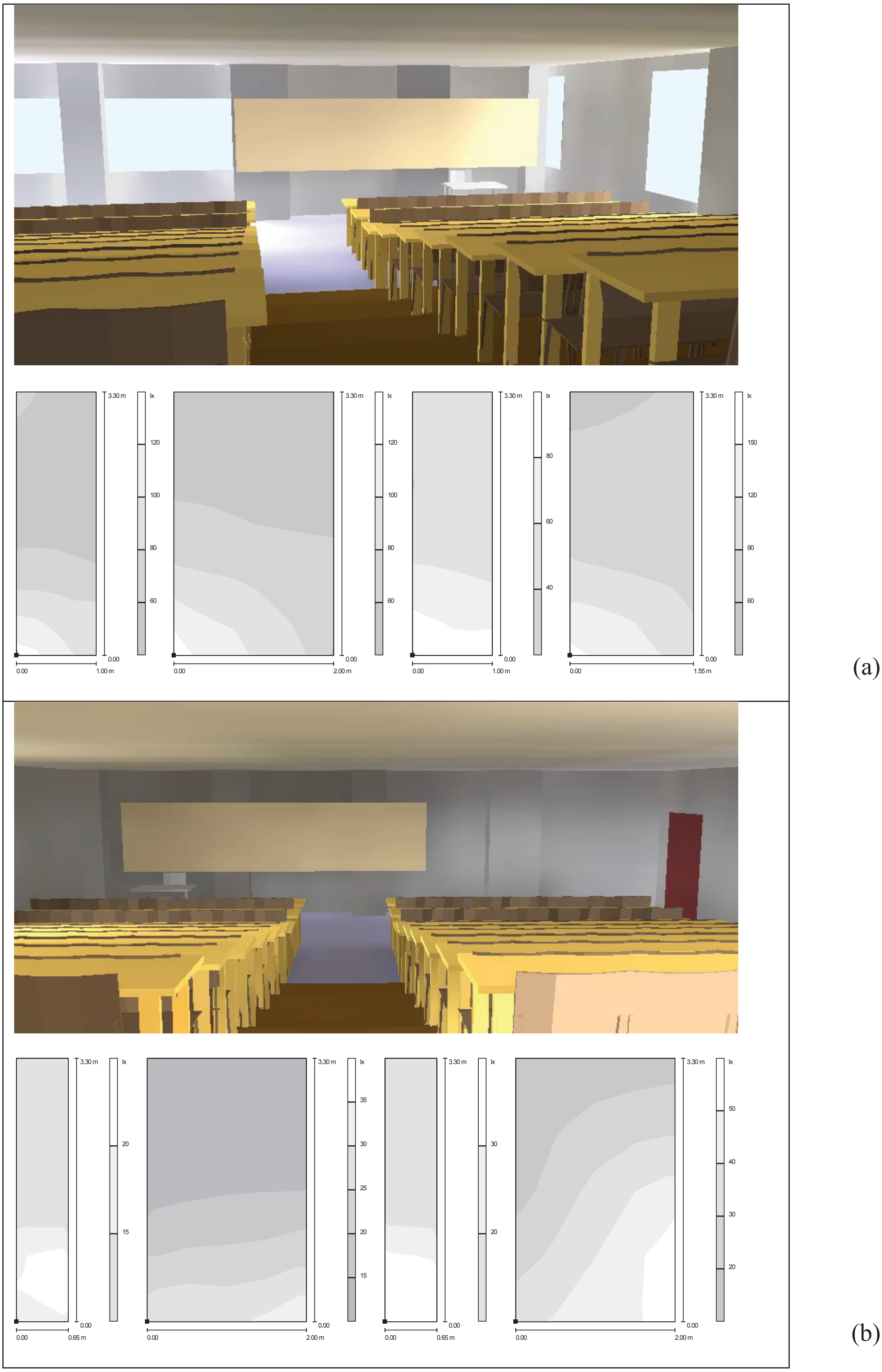


Figure B.13. Illuminance distribution on white board’s wall for SL1 (a) and SL2 (unit: cd/m^2)

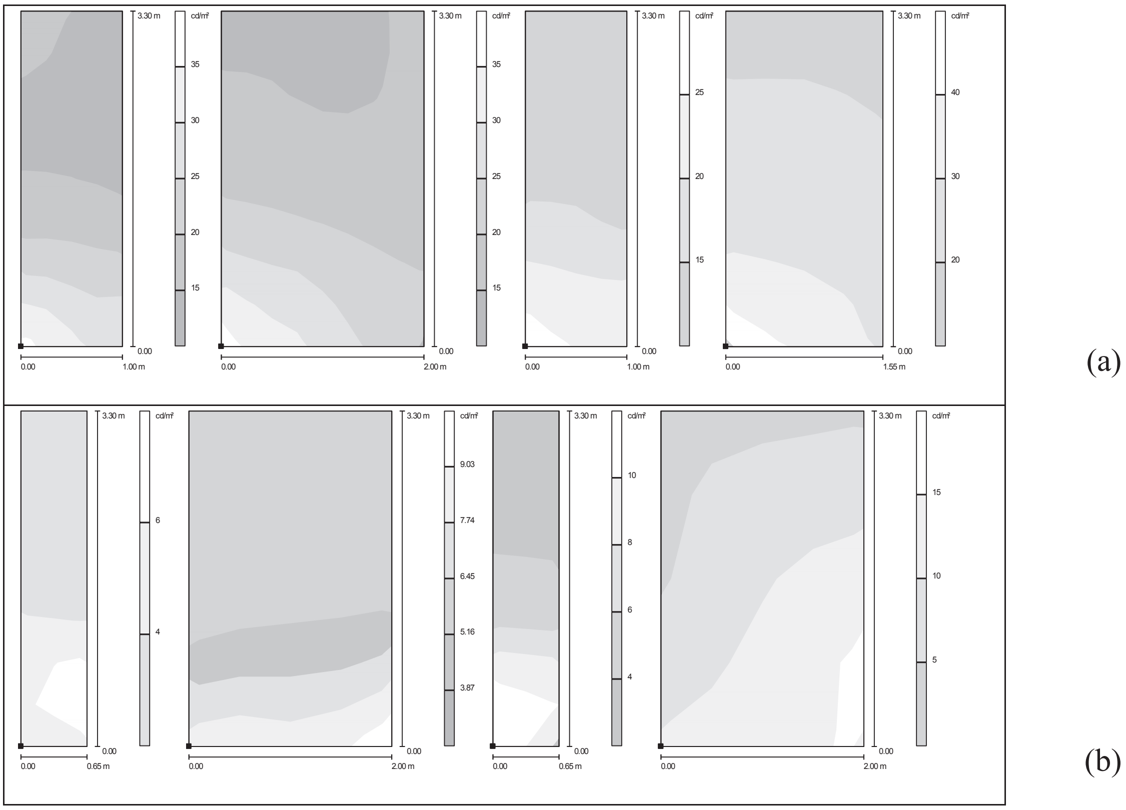


Figure B.14. Luminance distribution on white board's wall for SL1 (a) and SL2 (unit: cd/m^2)

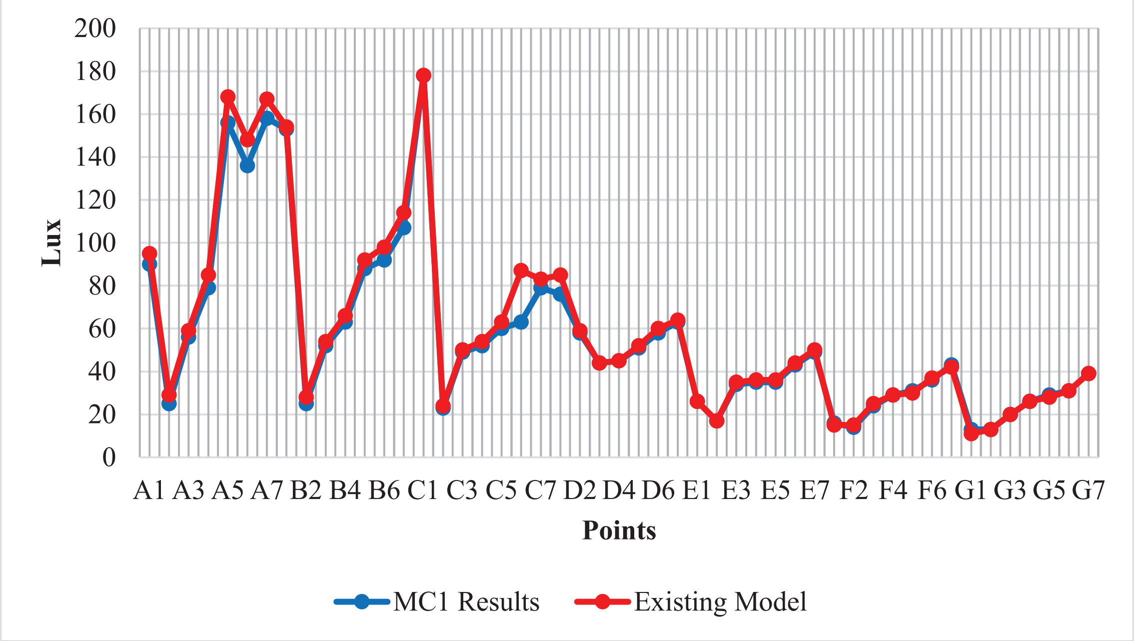


Figure B.15. Comparison of material combination changed study MC1 and existing ……………. model

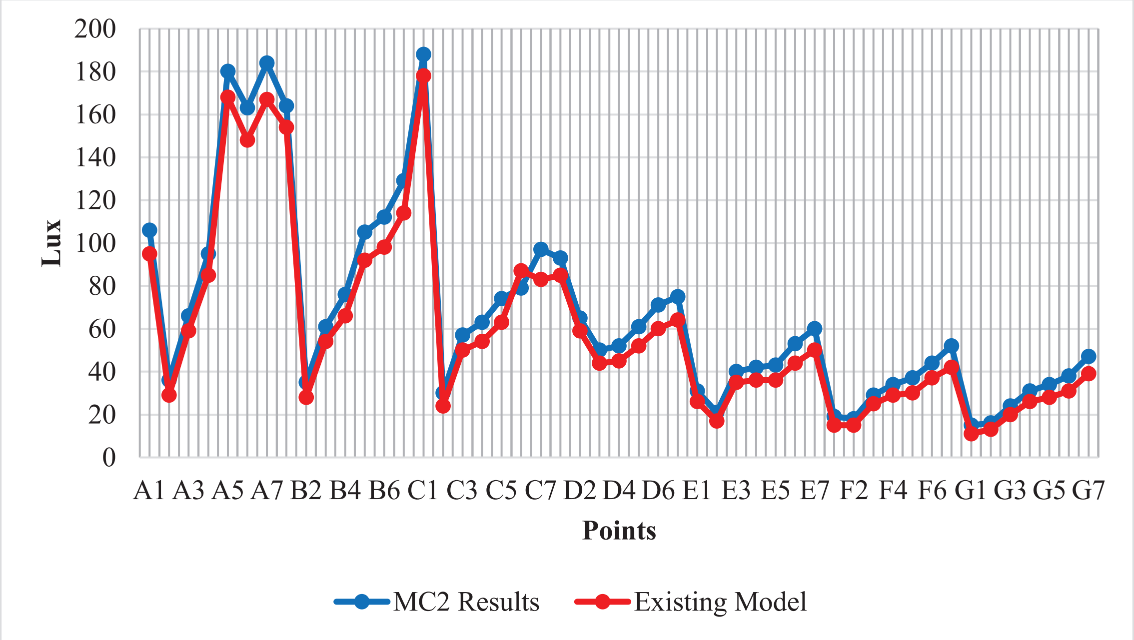
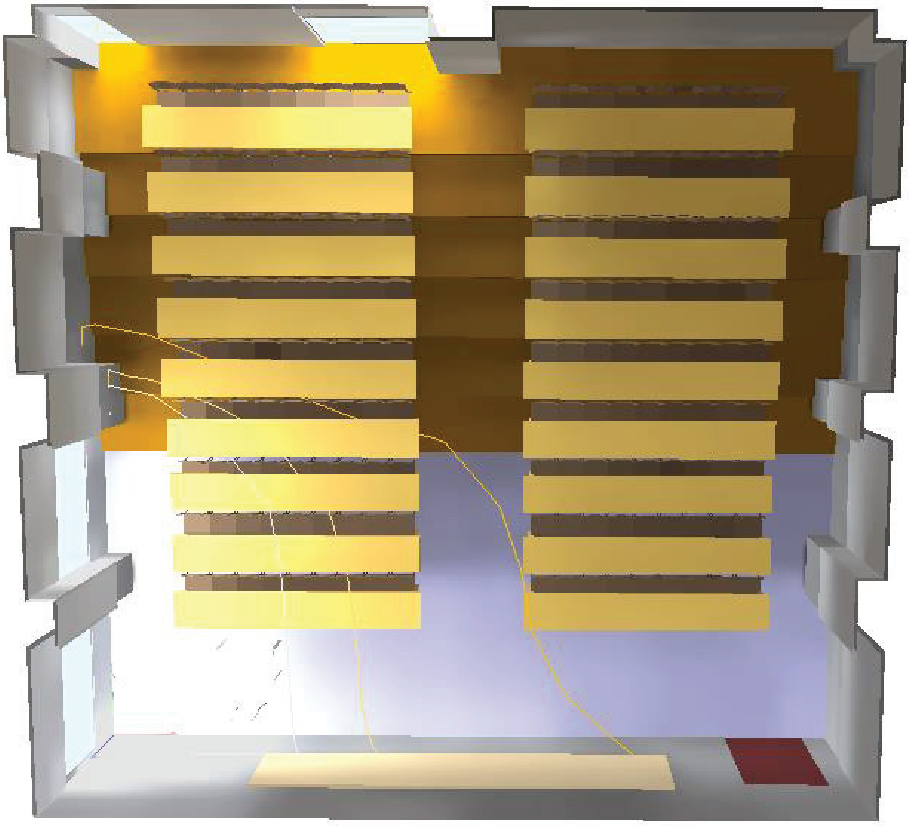
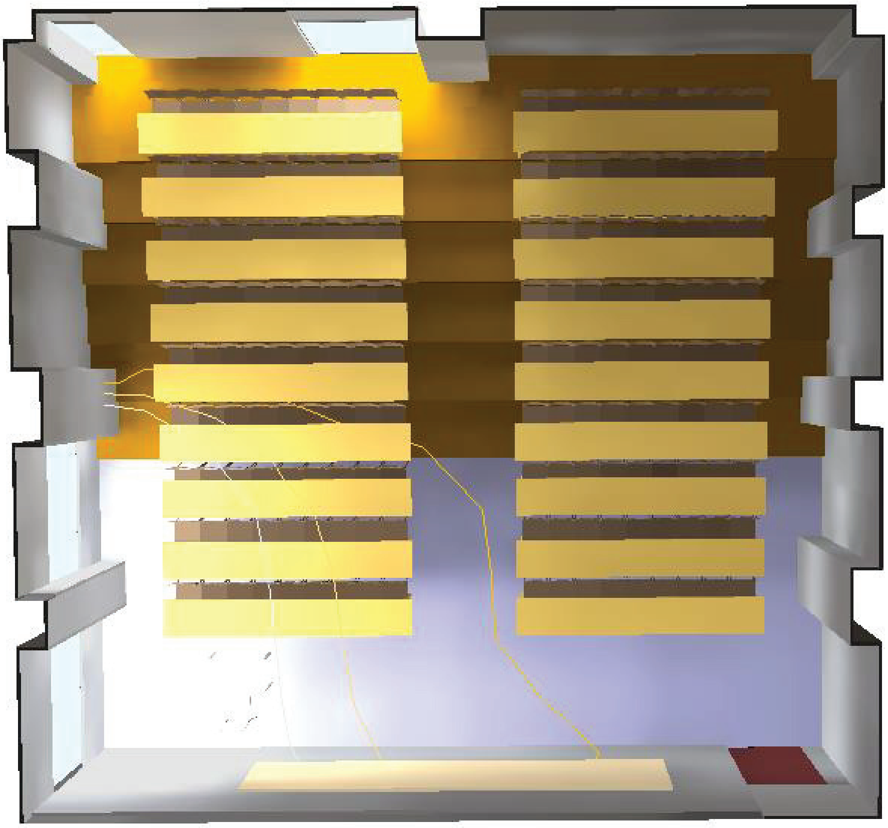


Figure B.16. Comparison of material combination changed study MC2 and existing ……………. model



(a)



(b)

Figure B.17. Illumination level distribution for SL1(a) and SL2(b). Each line presents 50 lux,100 lux and 150 lux values respectively to the darkest to lightest

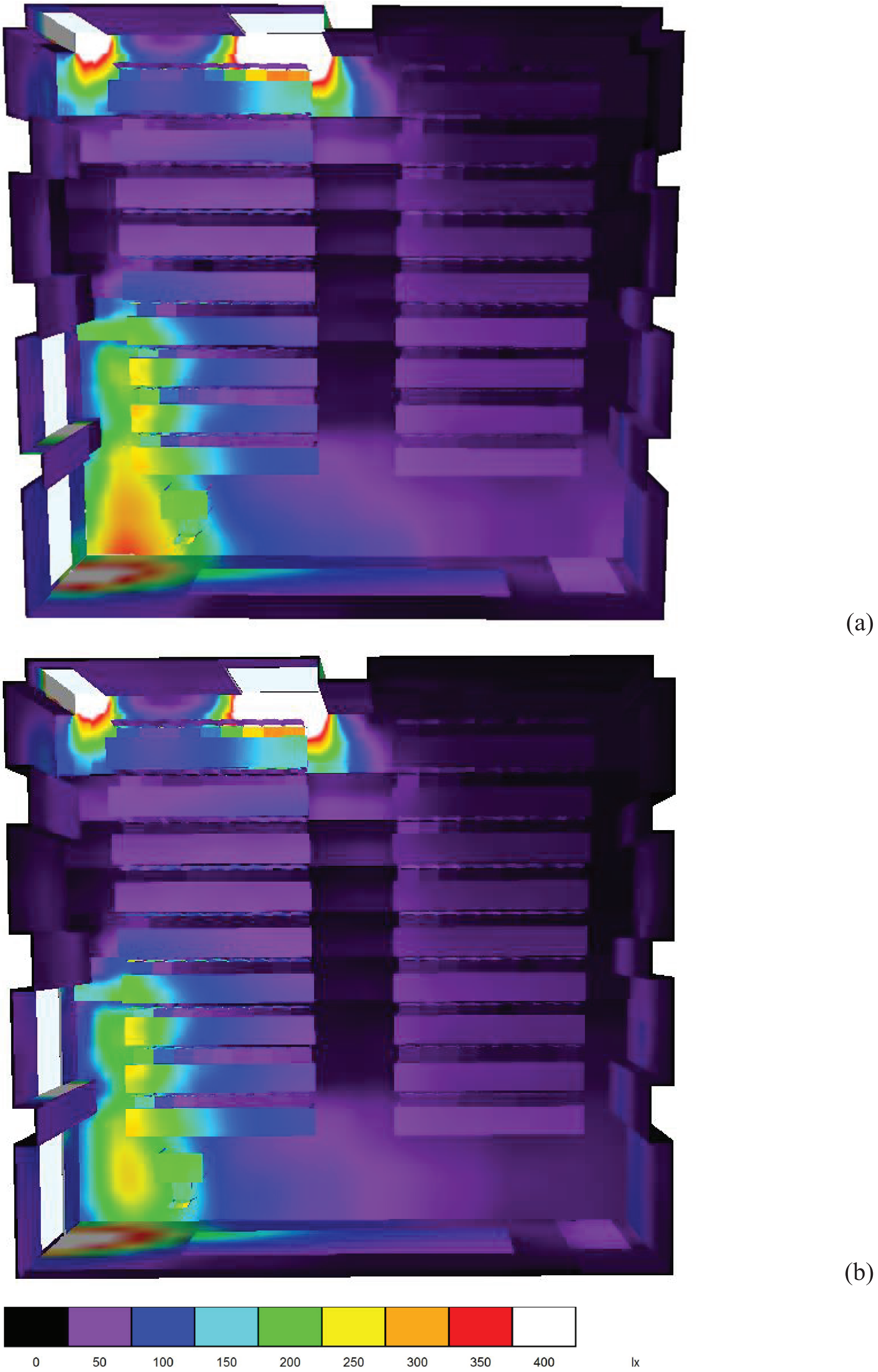


Figure B.18. False color distribution for SL1 (a) and SL2 (b) (unit: lux)

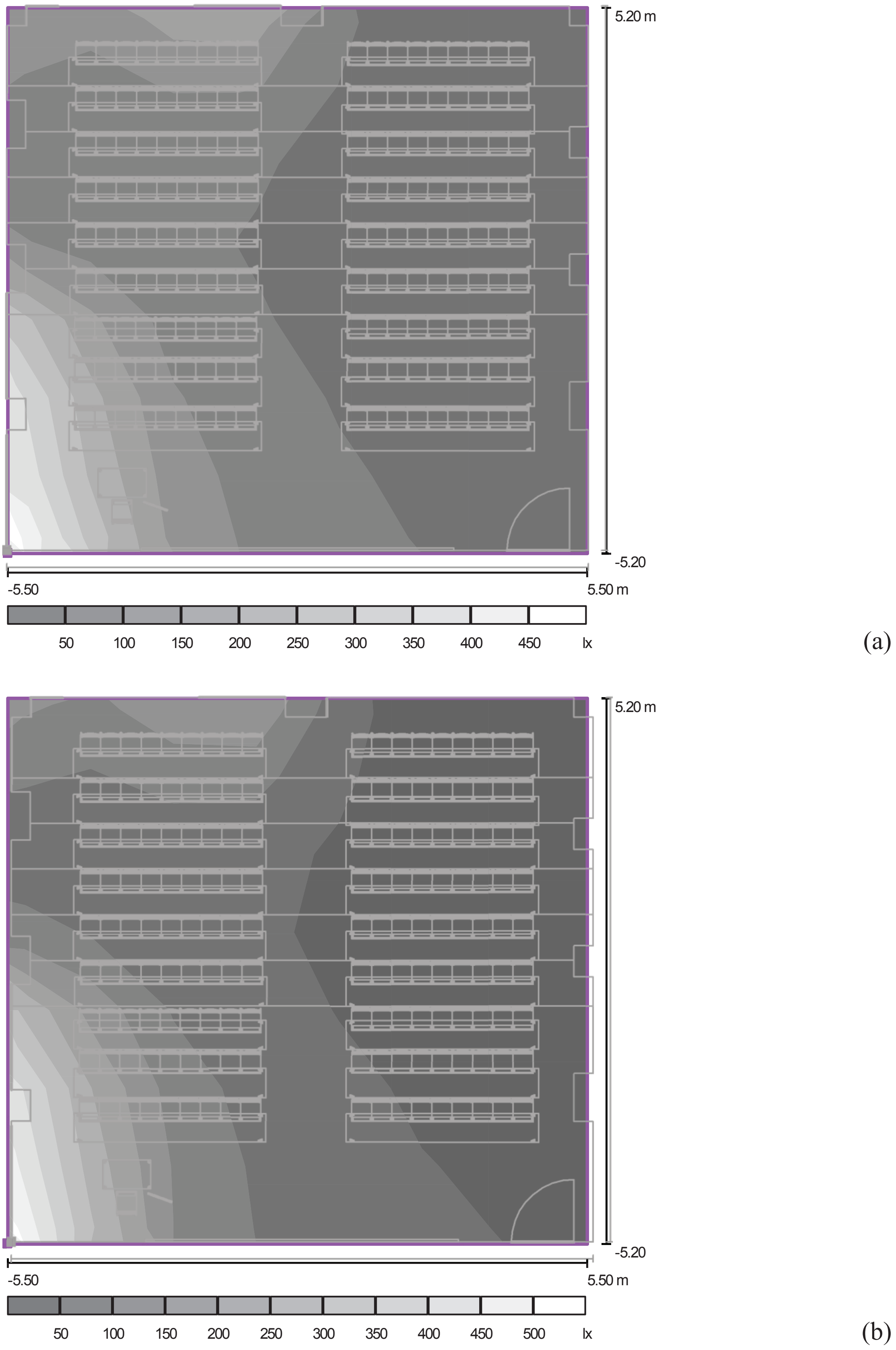


Figure B.19. Illuminance distribution on working level for MC1 (a) and MC2 (b) (unit: lux)

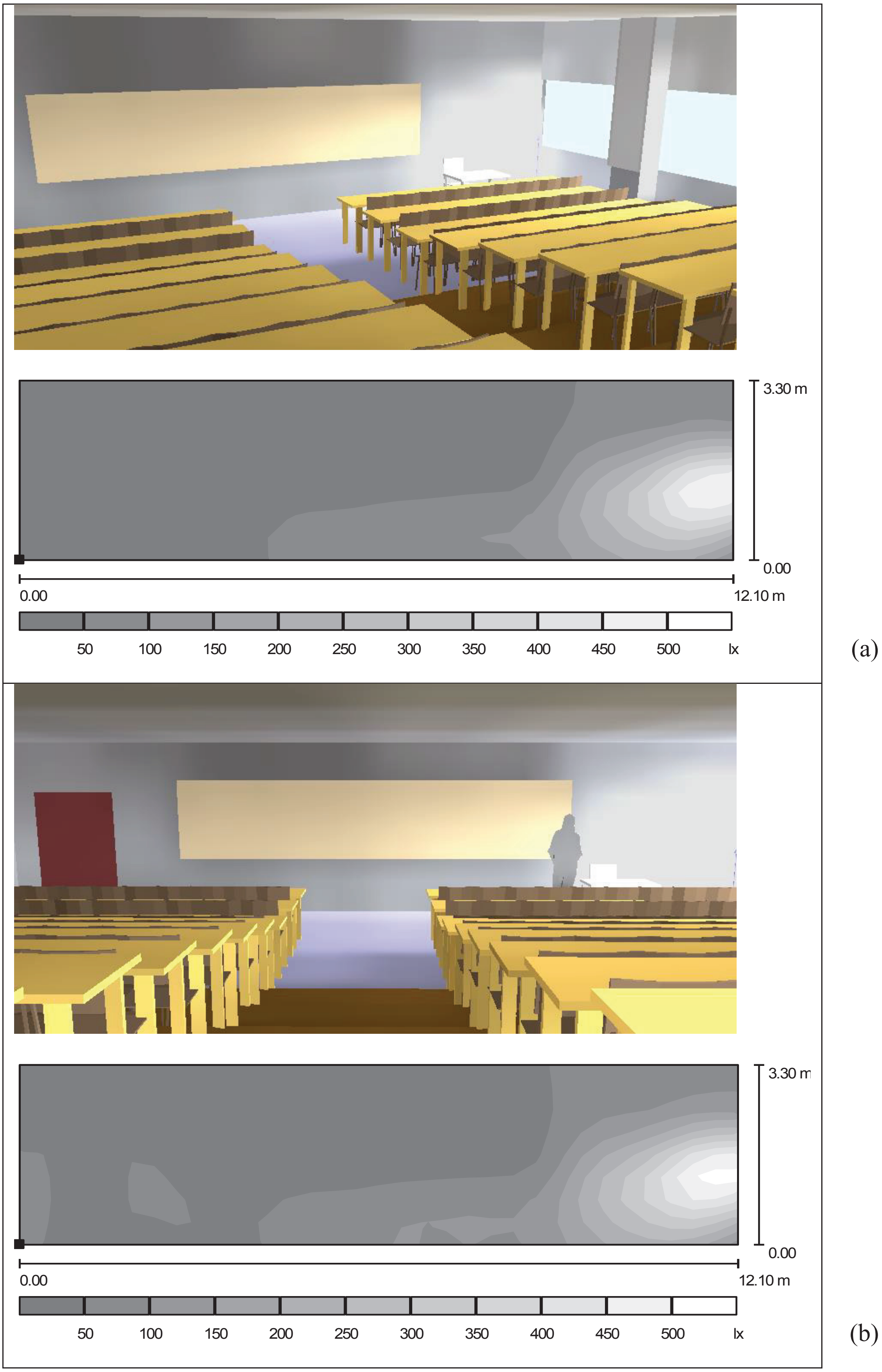


Figure B.20. Illuminance distribution on white board's wall for SL1 (a) and SL2 (unit: cd/m^2)

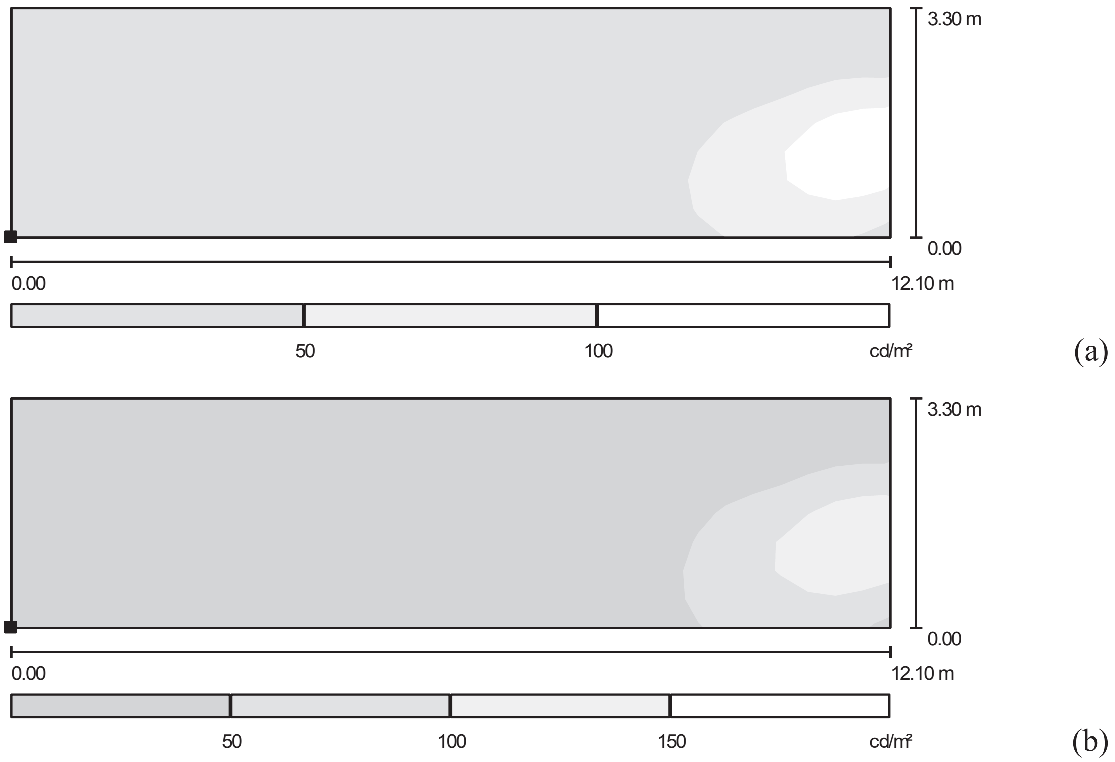


Figure B.21. Luminance distribution on white board’s wall for MC1 (a) and MC2 (unit: cd/m^2)

APPENDIX C

DISTRIBUTION OF SIMULATED DAYLIGHT ILLUMINANCE REGARDING MEASUREMENT POINTS ON 4TH NOVEMBER (12:00-13.00) WITH THE APPLICATION OF DESIGN COMPONENTS

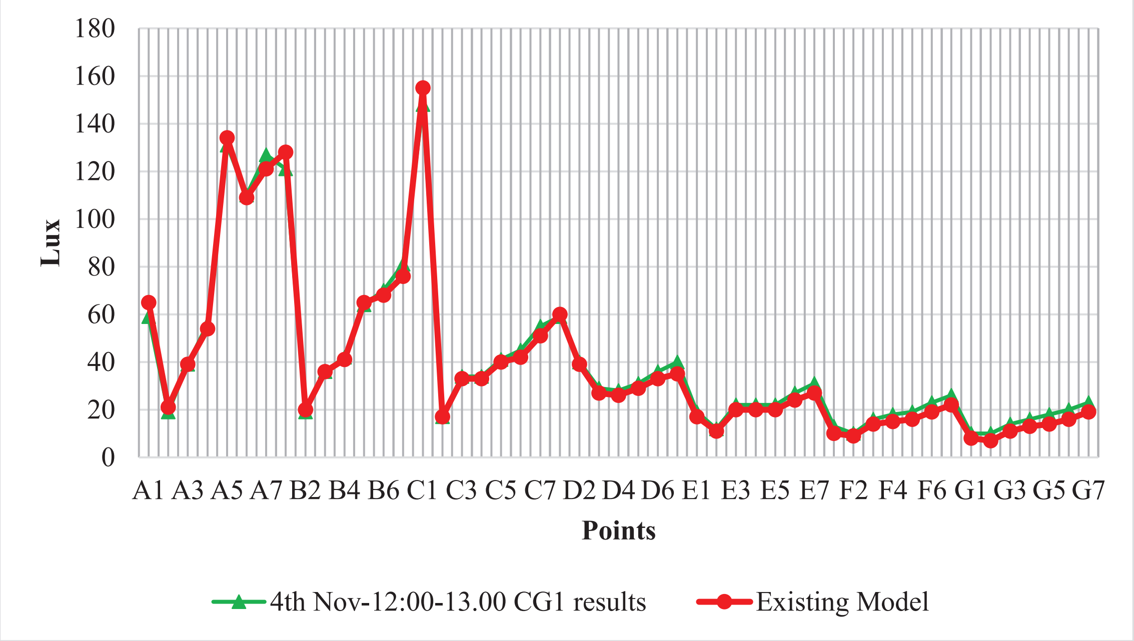


Figure C.1. Comparison of ceiling geometry conducted study CG1 and existing model

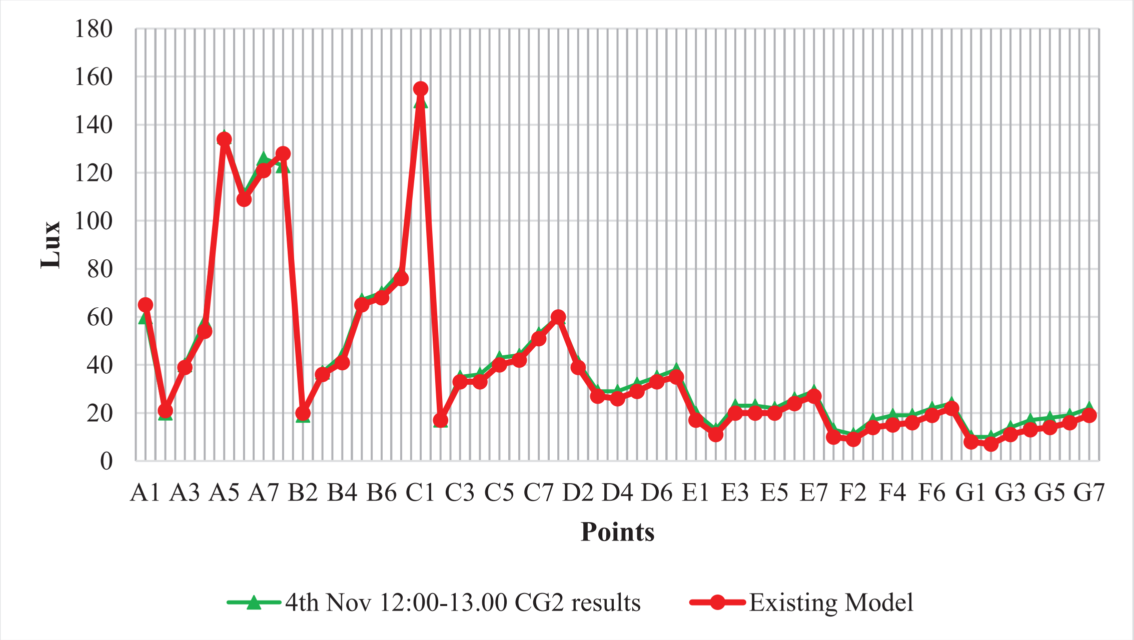
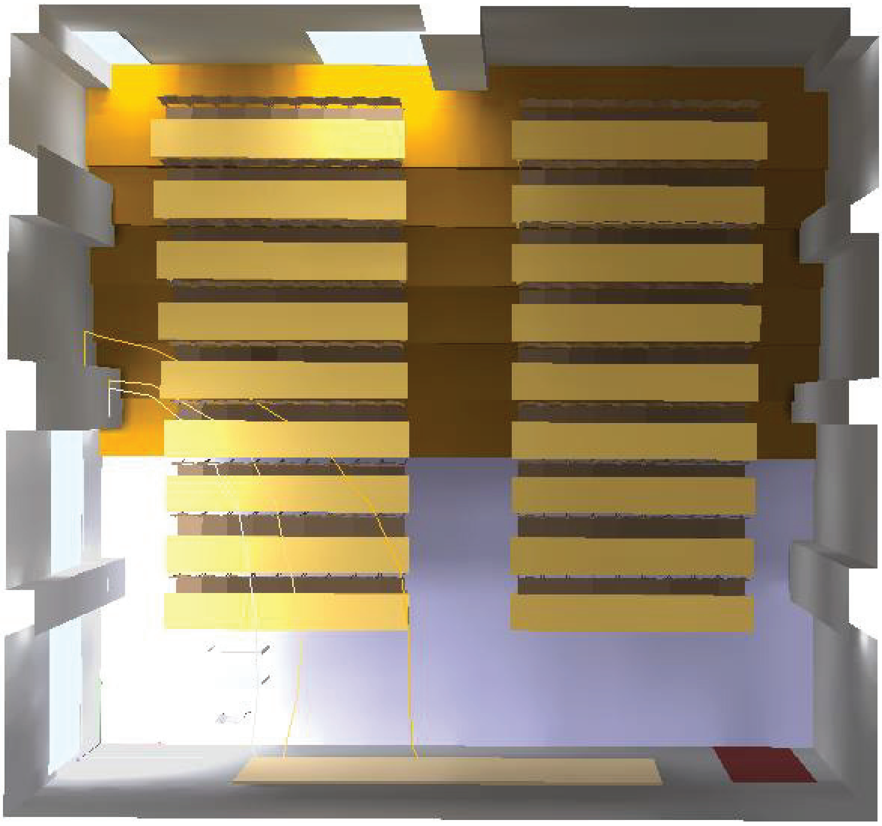
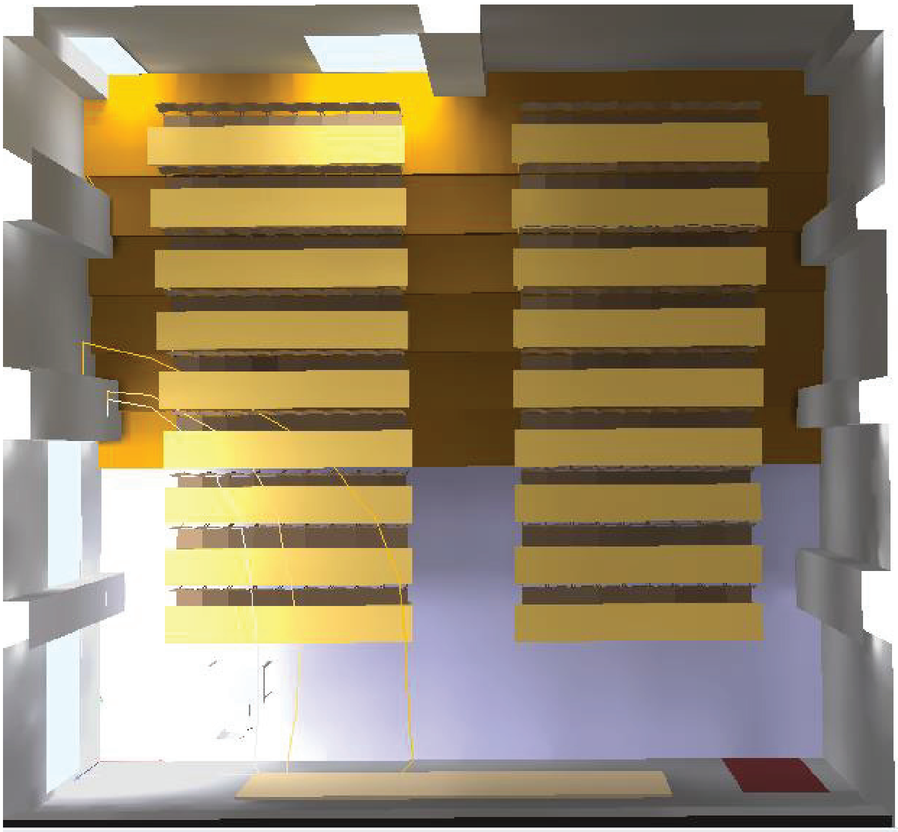


Figure C.2. Comparison of ceiling geometry conducted study CG2 and existing model



(a)



(b)

Figure C.3. Illumination level distribution for CG1(a) and CG2(b). Each line presents ………….. 50 lux,100 lux and 150 lux values respectively to the darkest to lightest

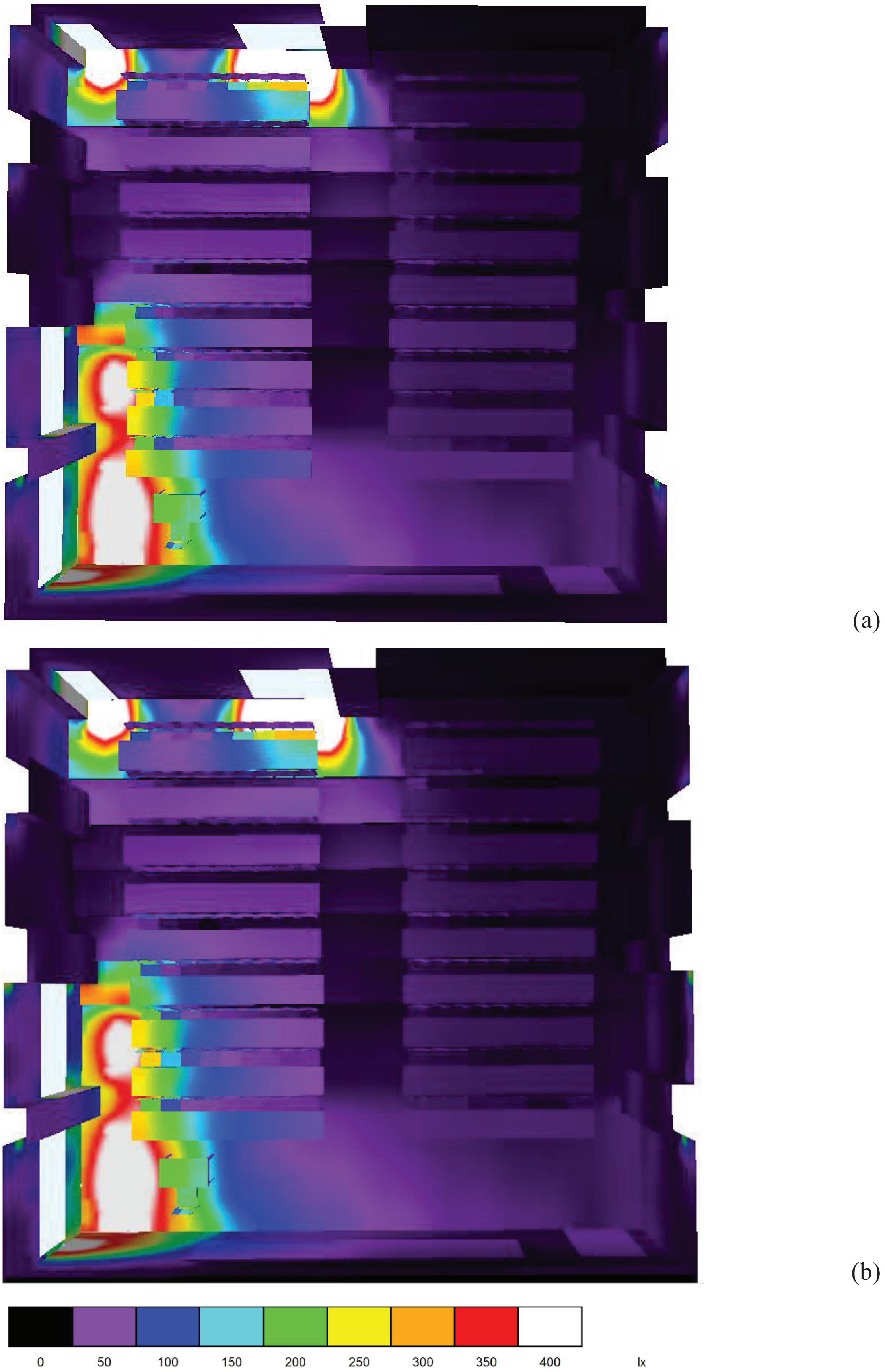


Figure C.4. False color distribution for CG1 (a) and CG2 (b) (unit: lux)

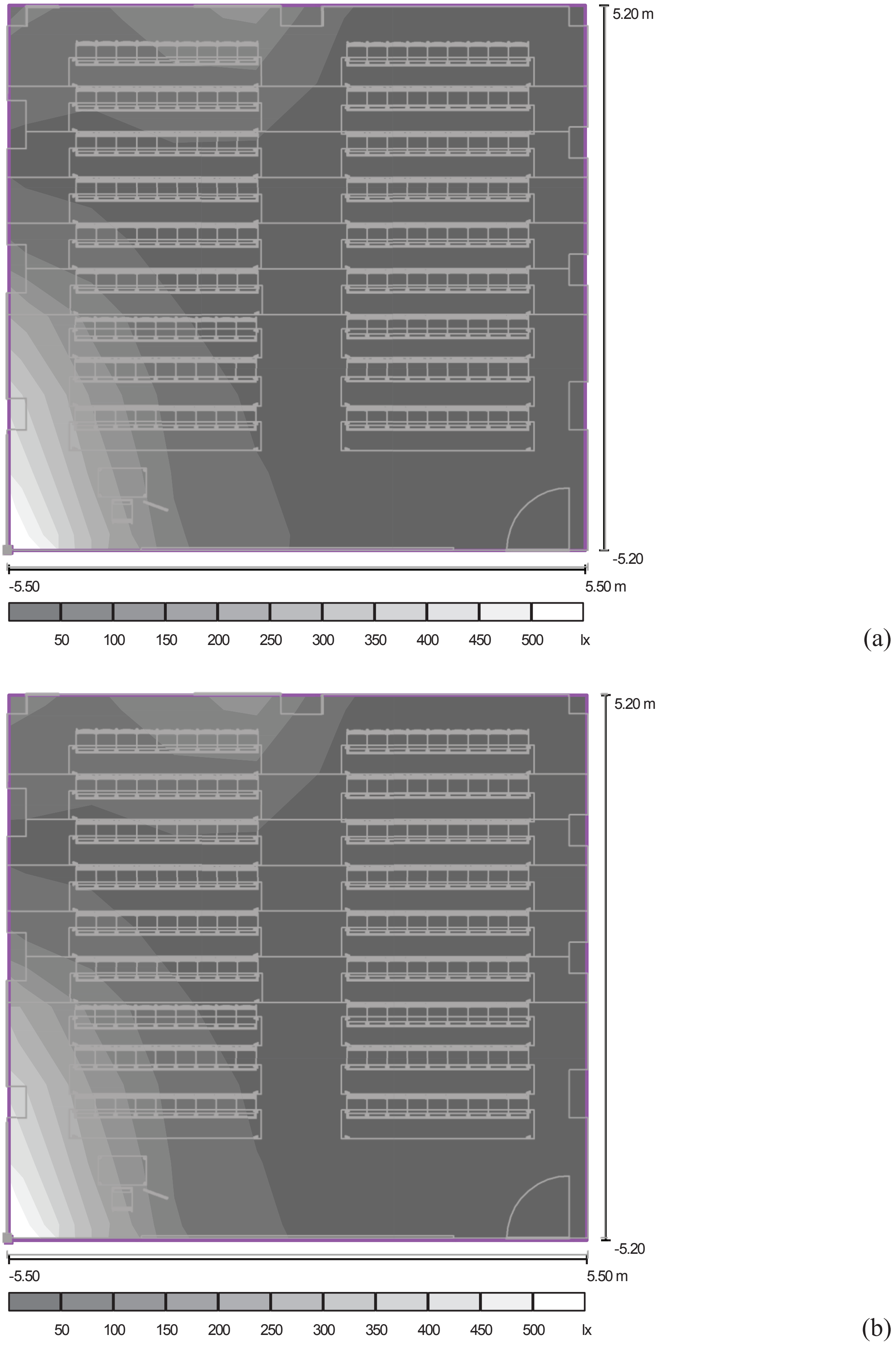


Figure C.5. Illuminance distribution on working level for CG1 (a) and CG2 (b) (unit: lux)

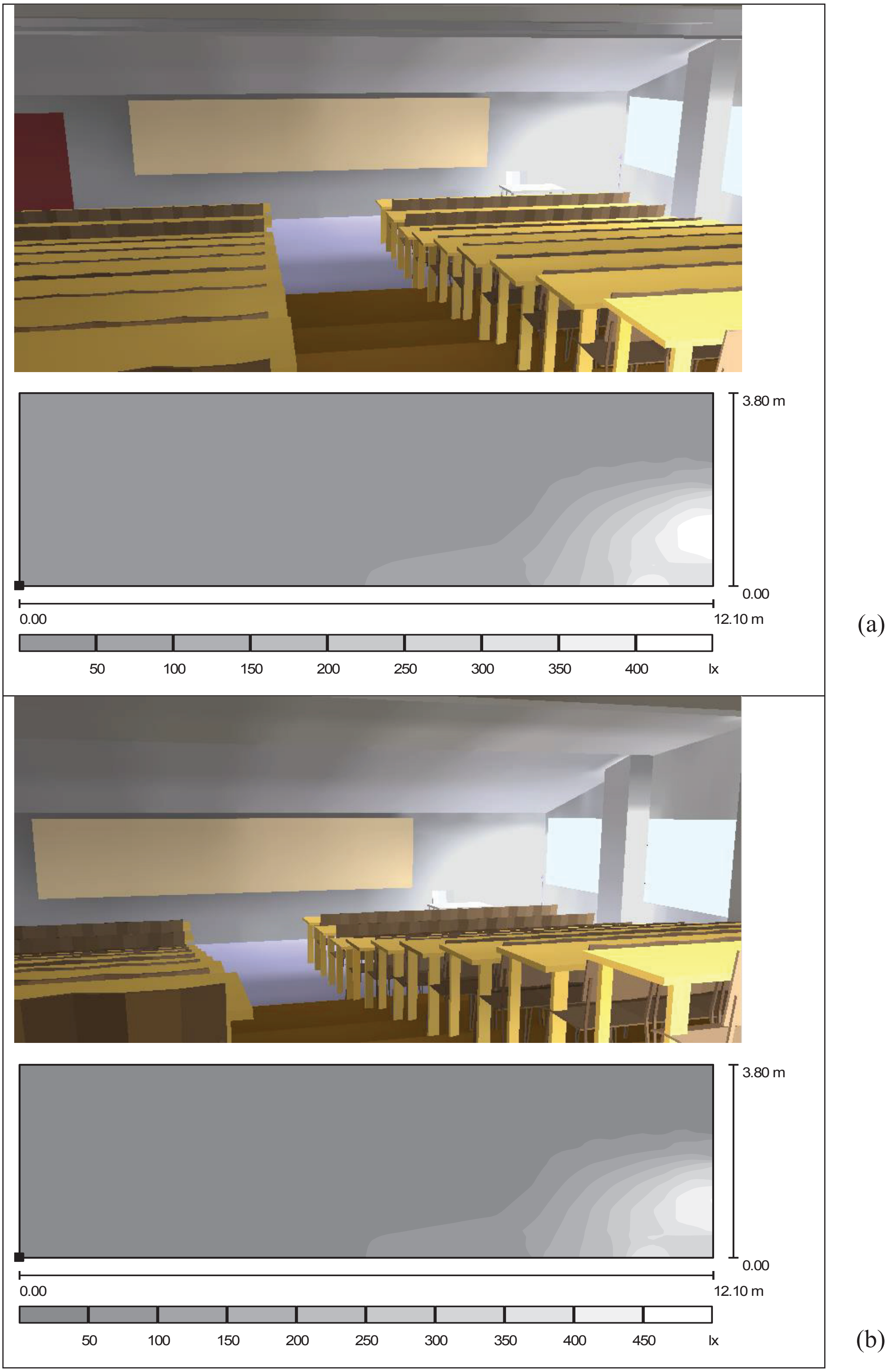


Figure C.6. Illuminance distribution on white board's wall for CG1 (a) and CG2 (unit: cd/m^2)

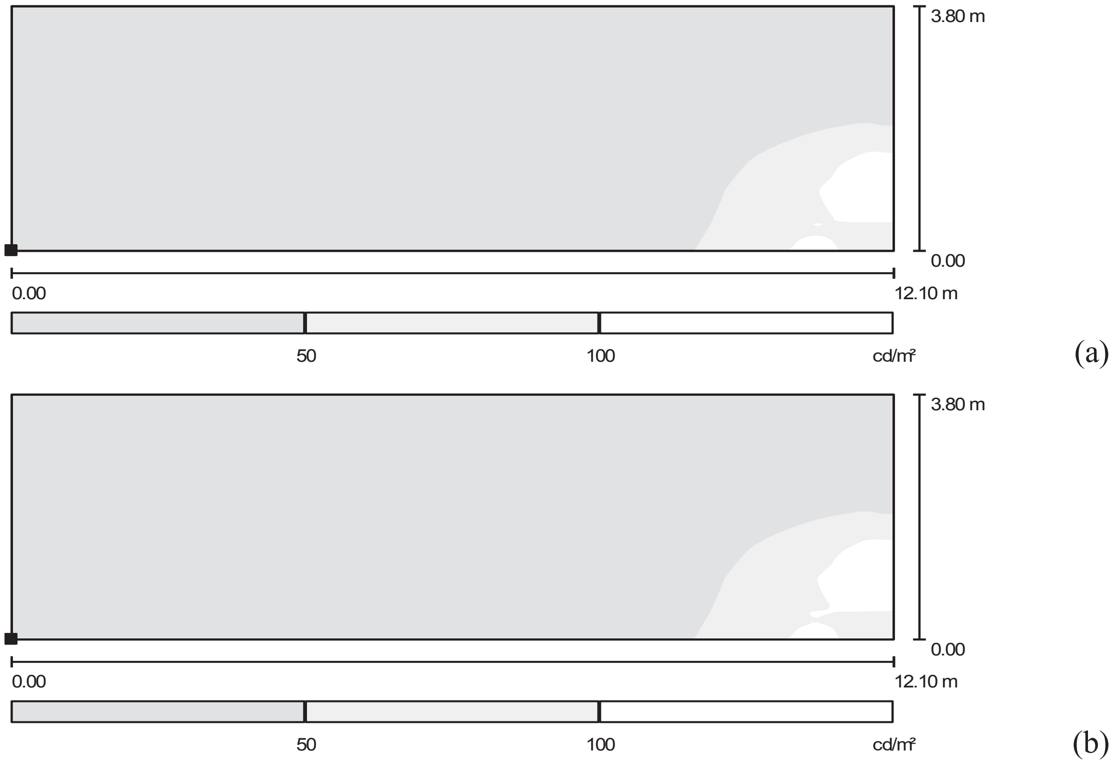


Figure C.7. Luminance distribution on white board’s wall for CG1 (a) and CG2 (unit: cd/m^2)

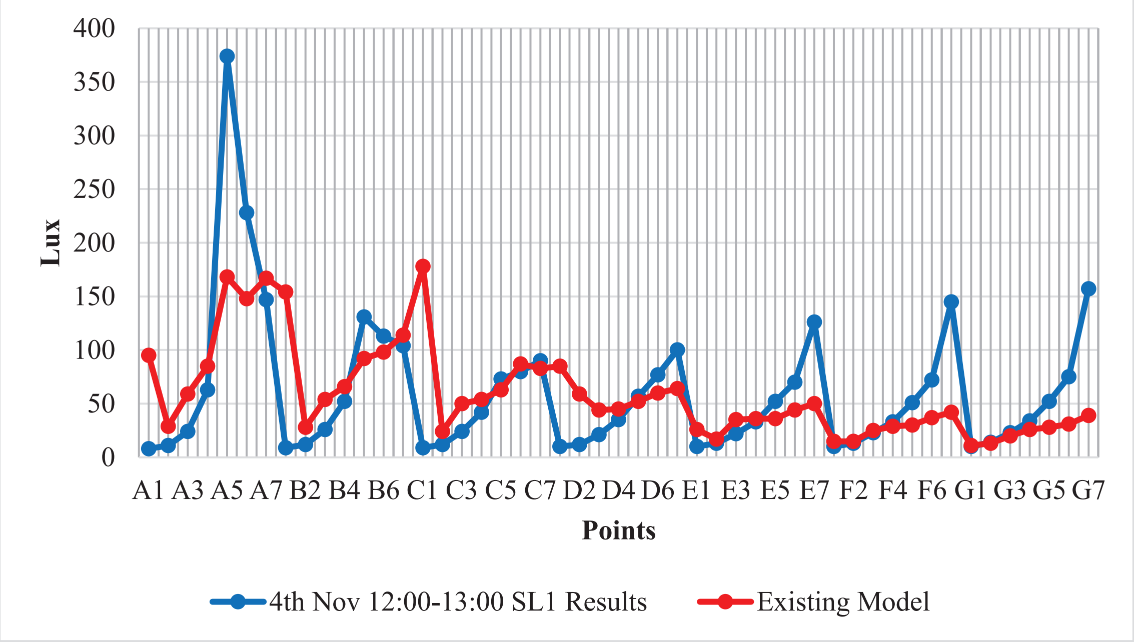


Figure C.8. Comparison of seating layout changed study SL1 and existing model

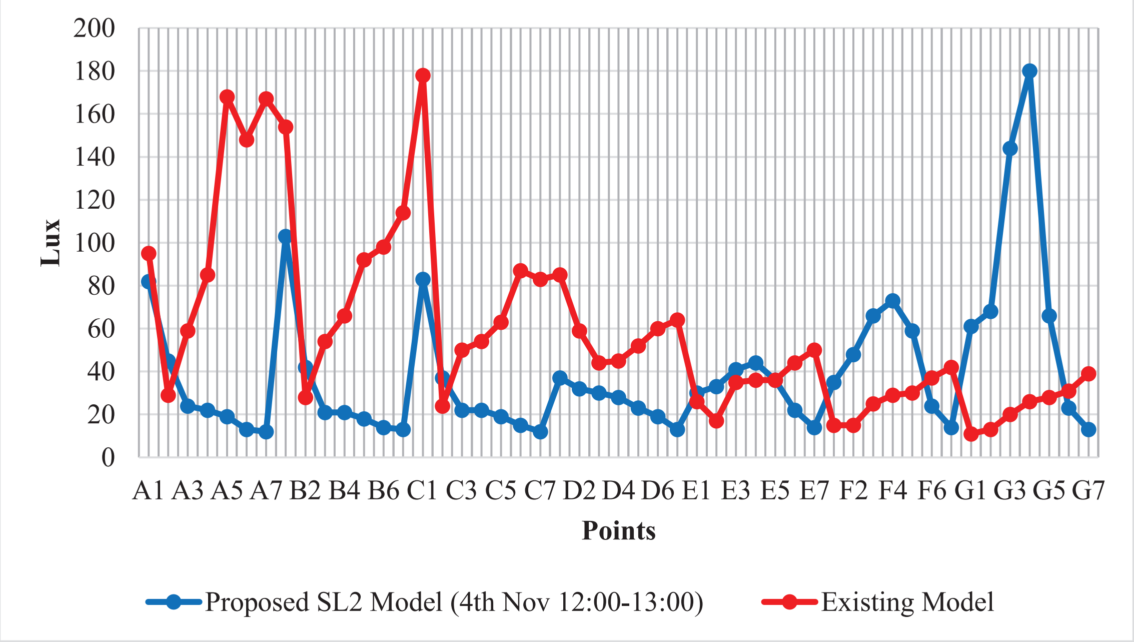
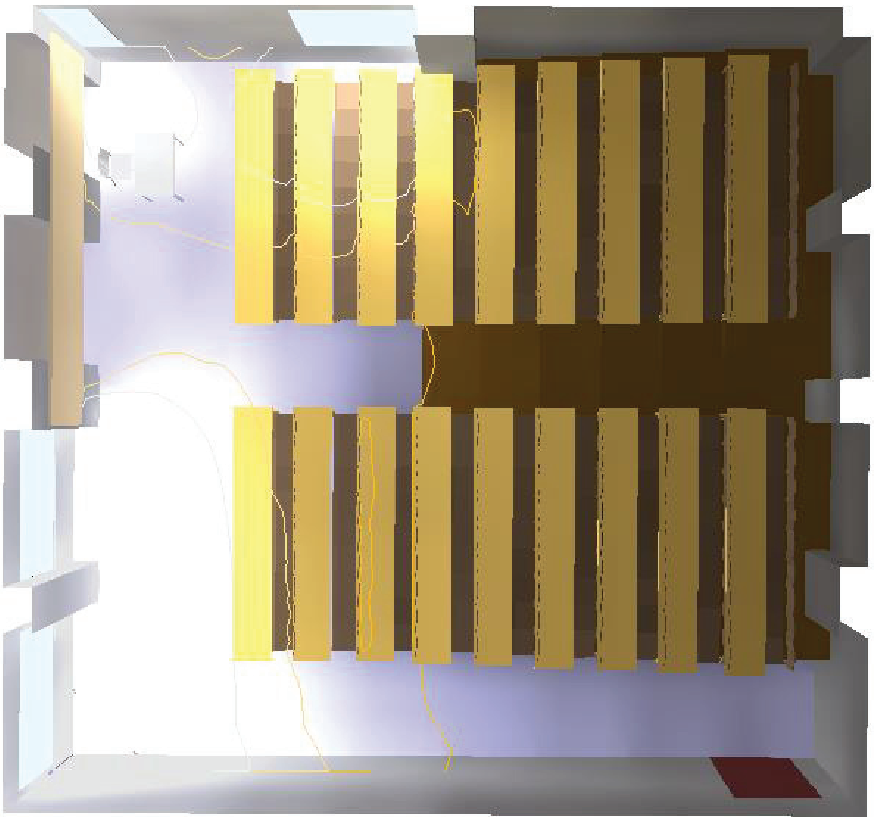
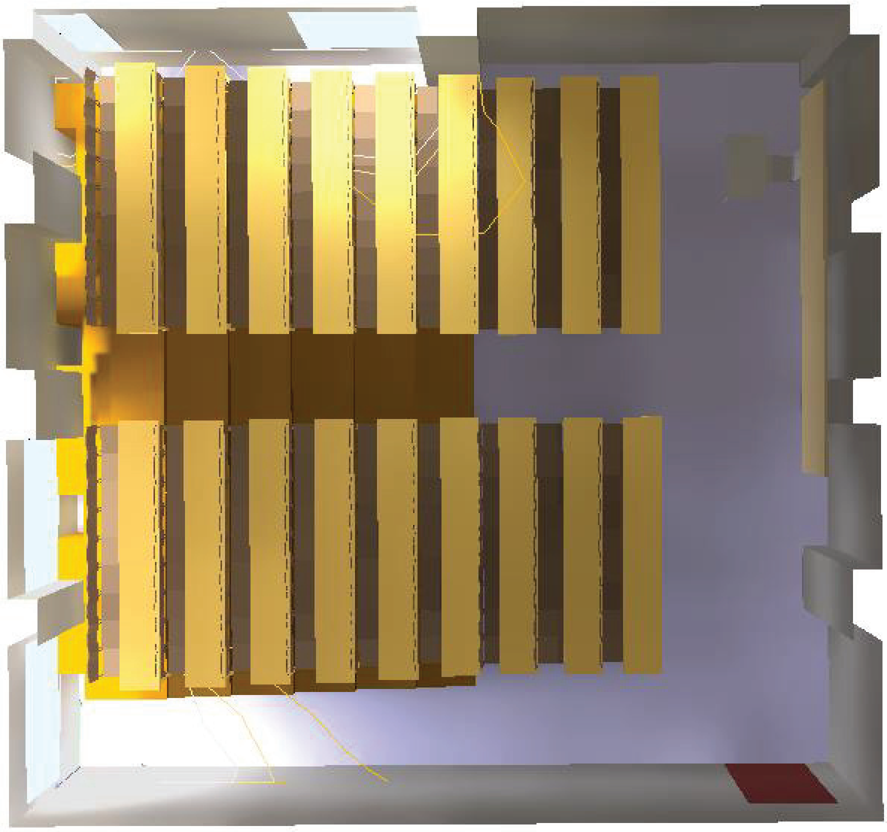


Figure C.9. Comparison of seating layout changed study SL2 (facing east) and existing model



(a)



(b)

Figure C.10. Illumination level distribution for SL1(a) and SL2(b). Each line presents 50 lux,100 lux and 150 lux values respectively to the darkest to lightest

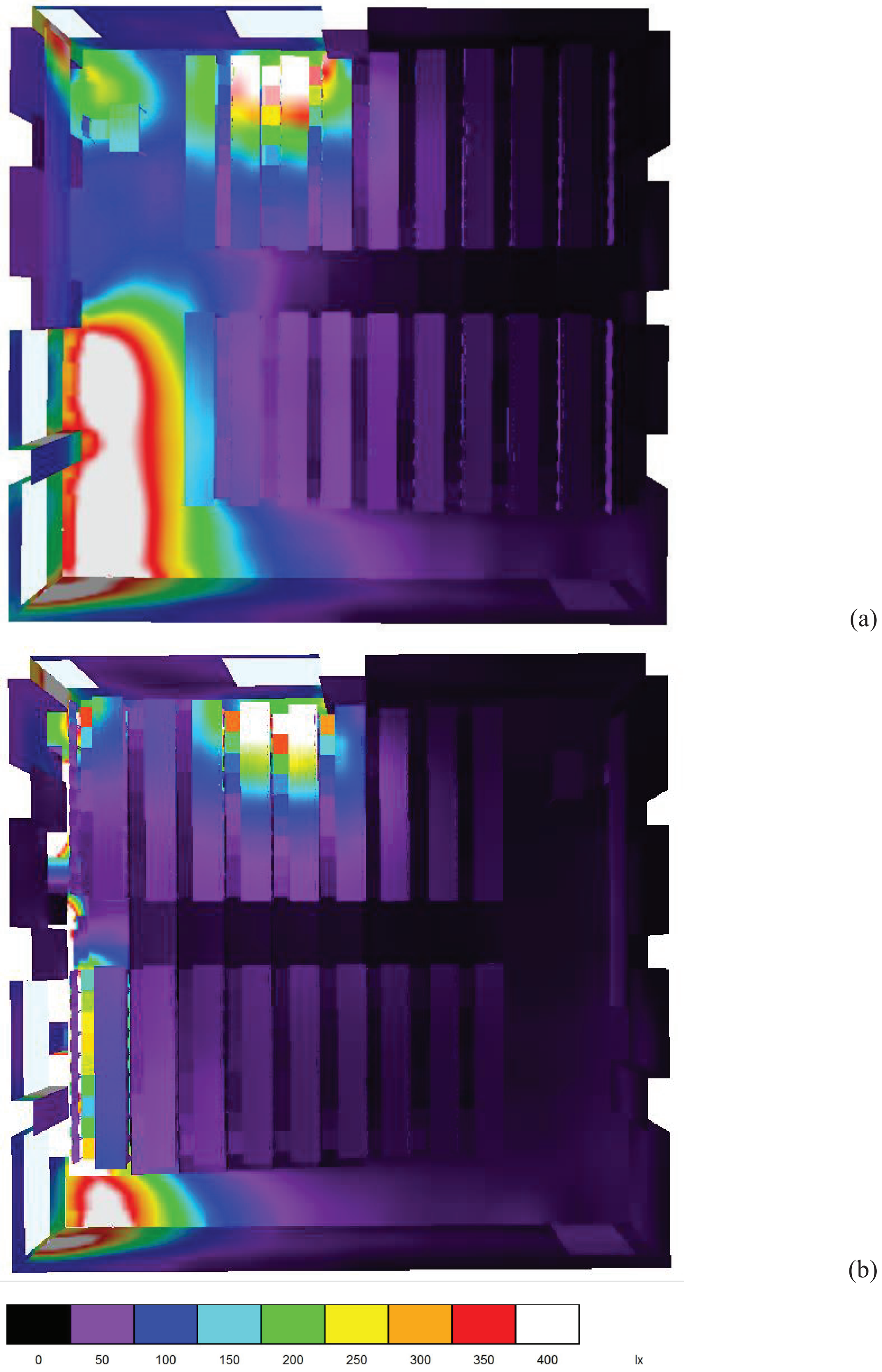


Figure C.11. False color distribution for SL1 (a) and SL2 (b) (unit: lux)

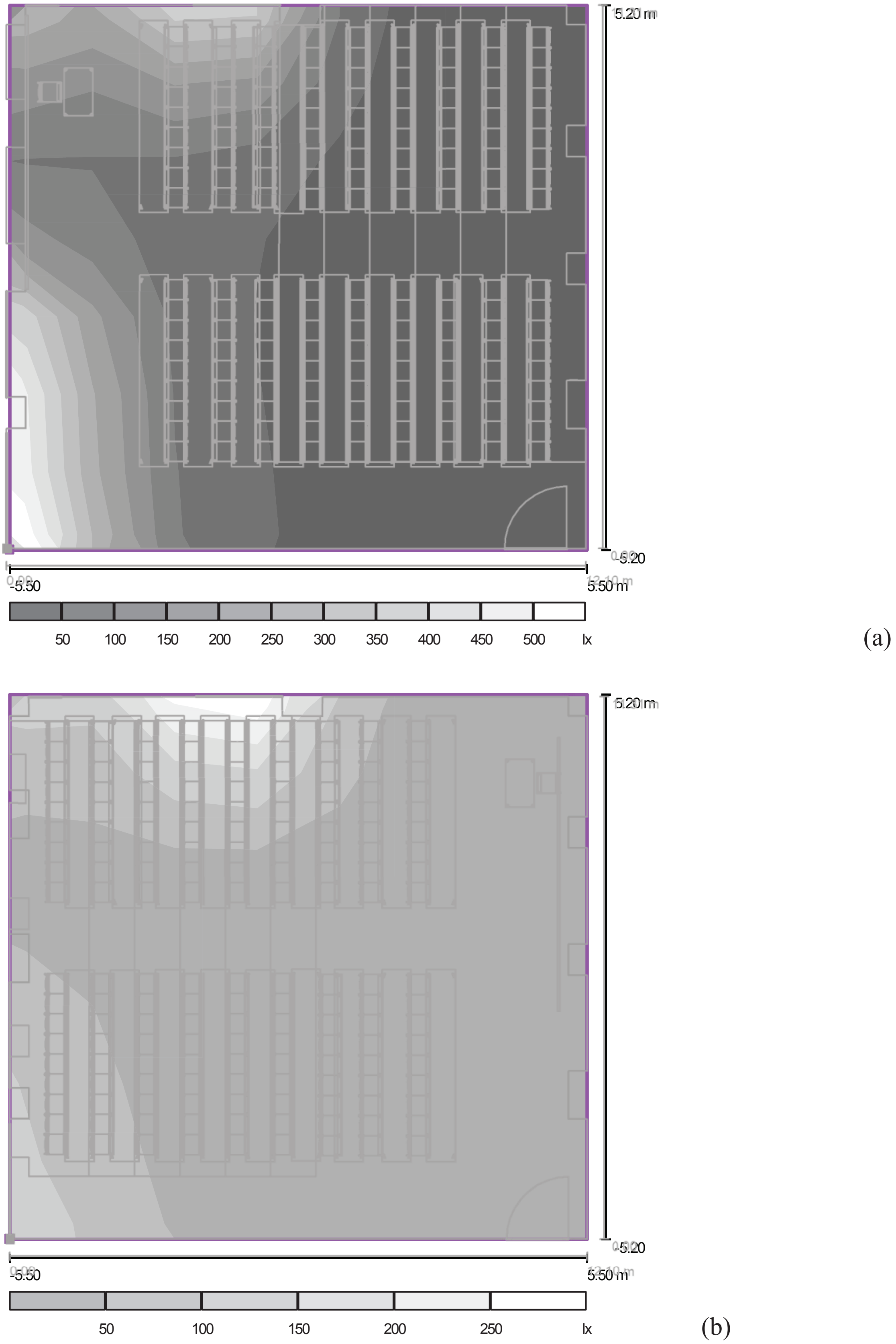


Figure C.12. Illuminance distribution on working level for SL1 (a) and SL2 (b) ……………. (unit: lux)

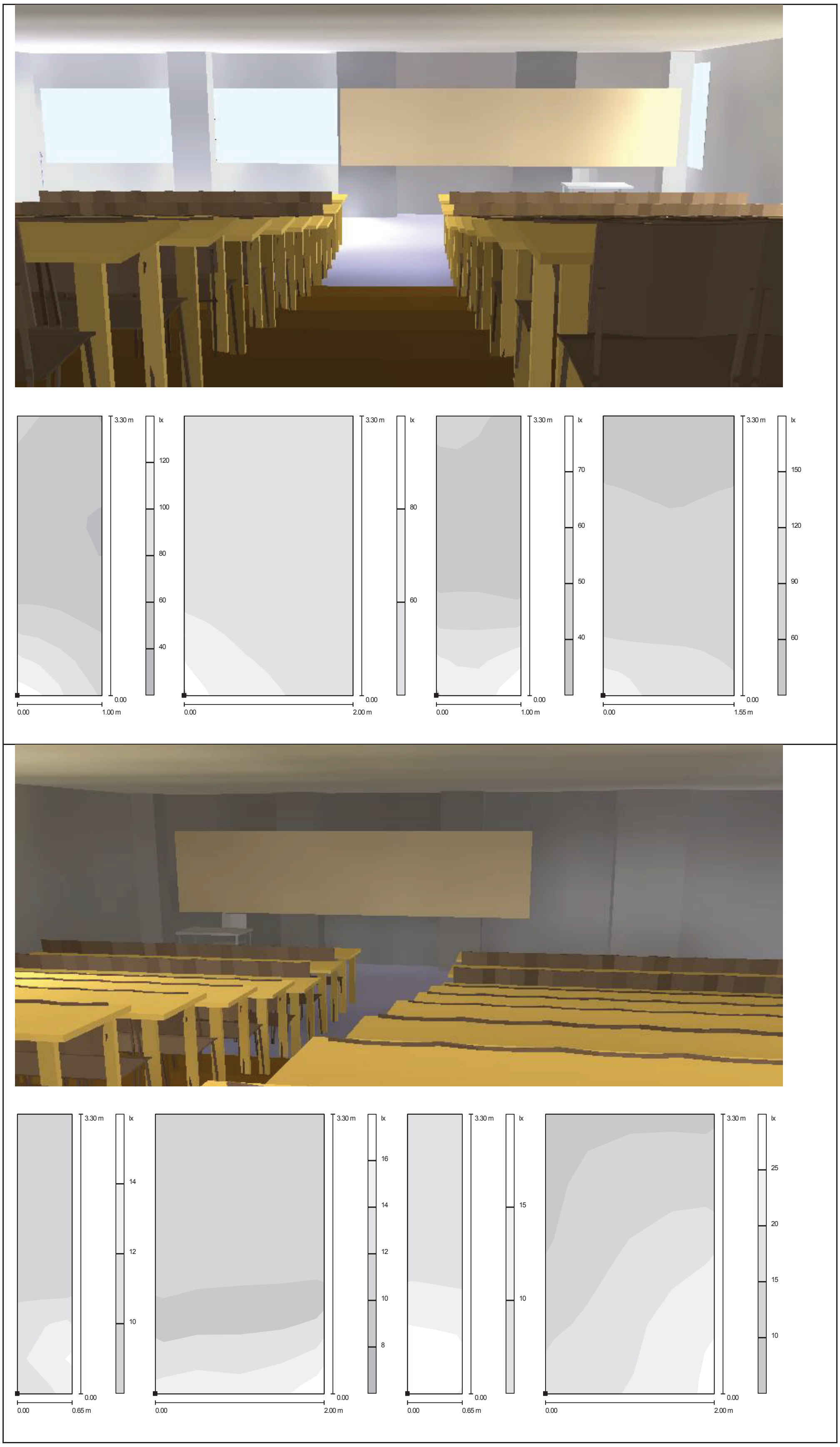


Figure C.13. Illuminance distribution on white board's wall for SL1 (a) and SL2 (unit: cd/m^2)

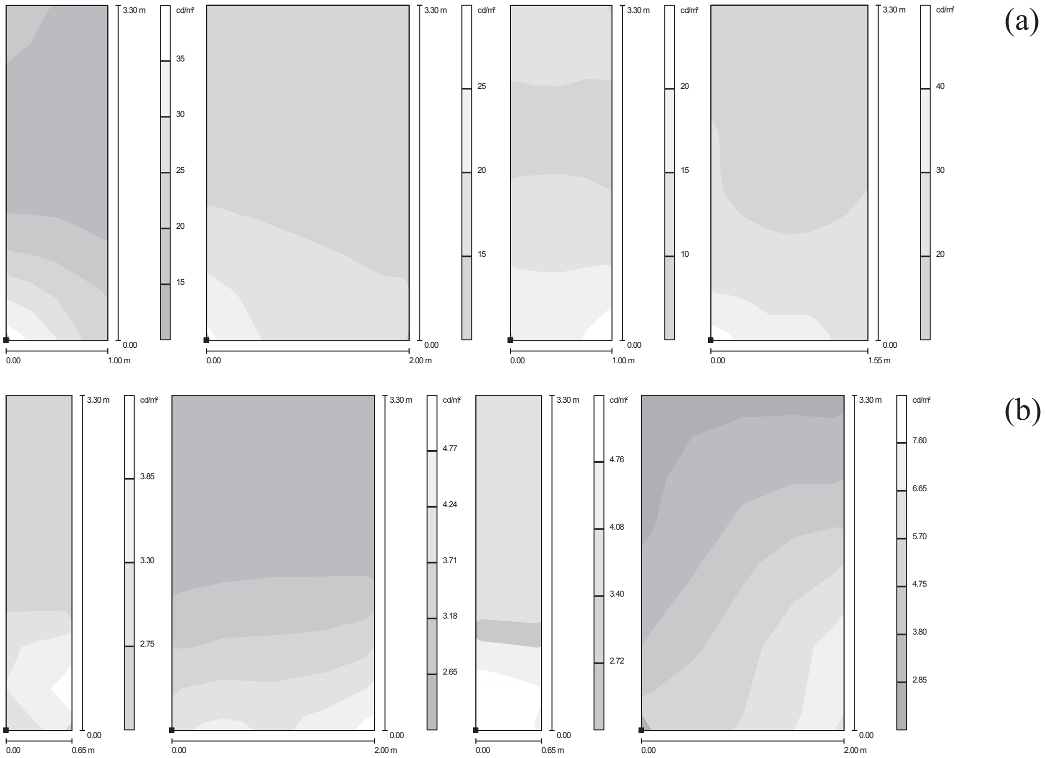


Figure C.14. Luminance distribution on white board's wall for SL1 (a) and SL2 …………… (unit: cd/m^2)

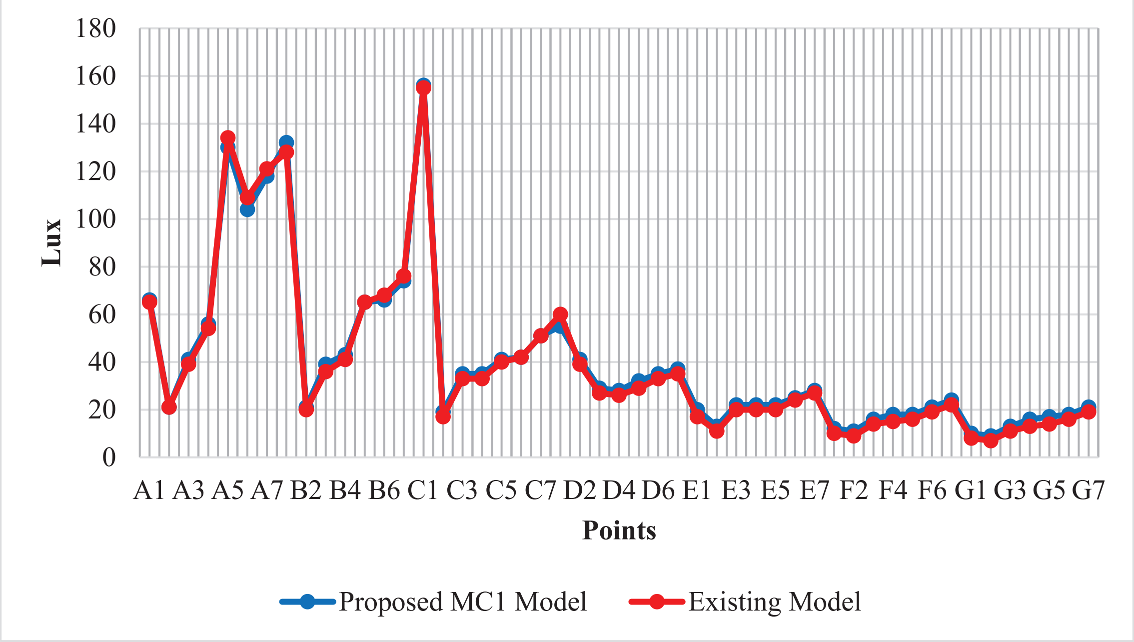


Figure C.15. Comparison of material combination changed study MC1 and existing ……………. model

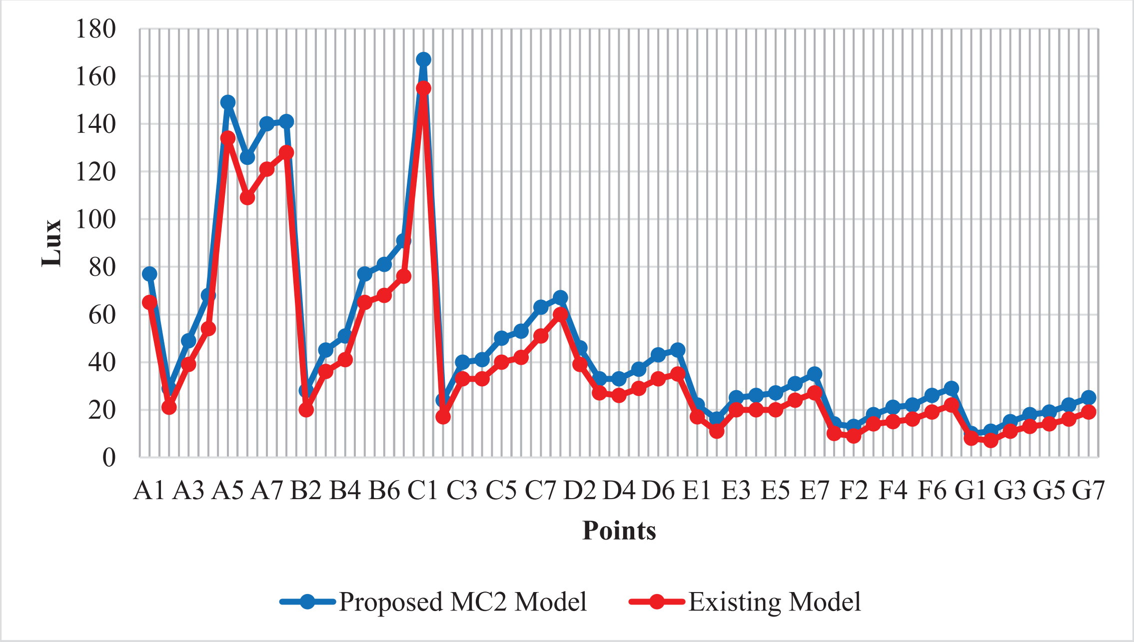
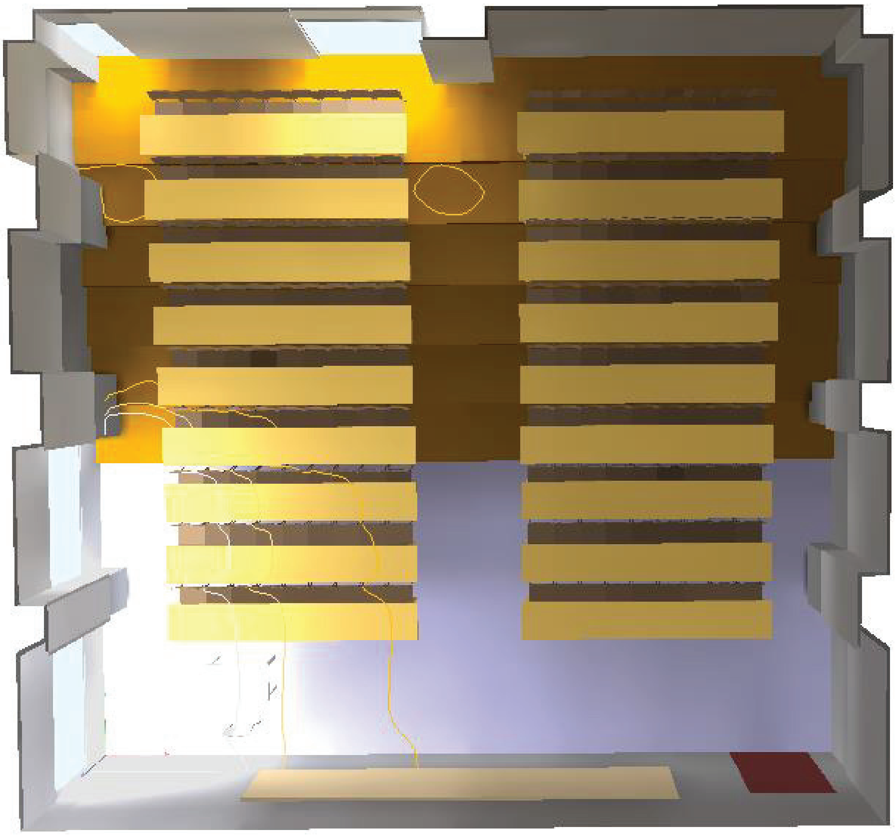
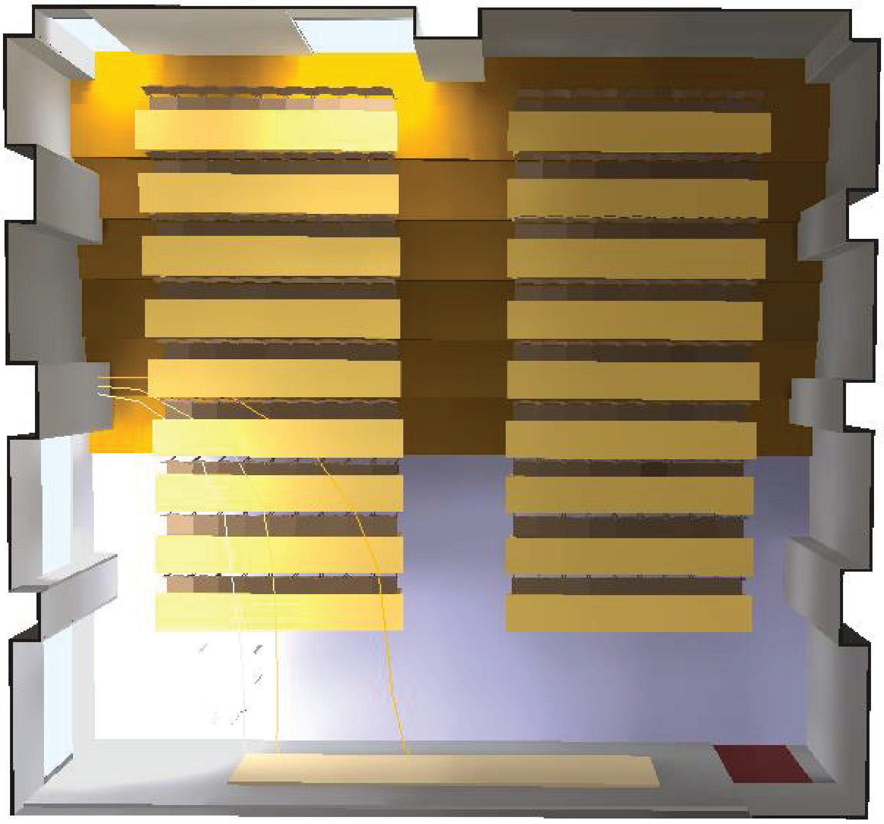


Figure C.16. Comparison of material combination changed study MC2 and existing ……………. model



(a)



(b)

Figure C.17. Illumination level distribution for MC1(a) and MC2(b). Each line presents 50 lux,100 lux and 150 lux values respectively to the darkest to lightest

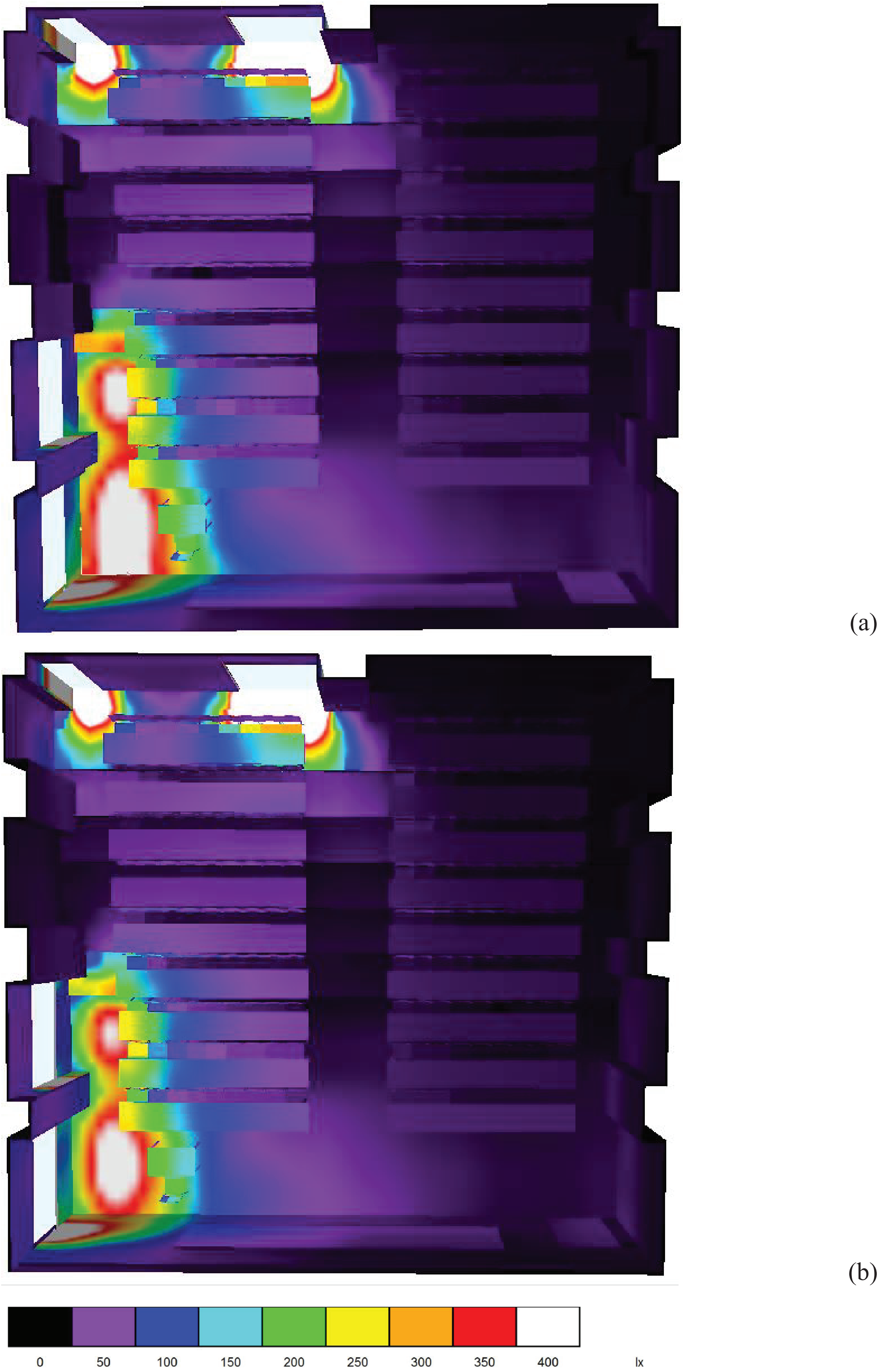


Figure C.18. False color distribution for MC1 (a) and MC2 (b) (unit: lux)

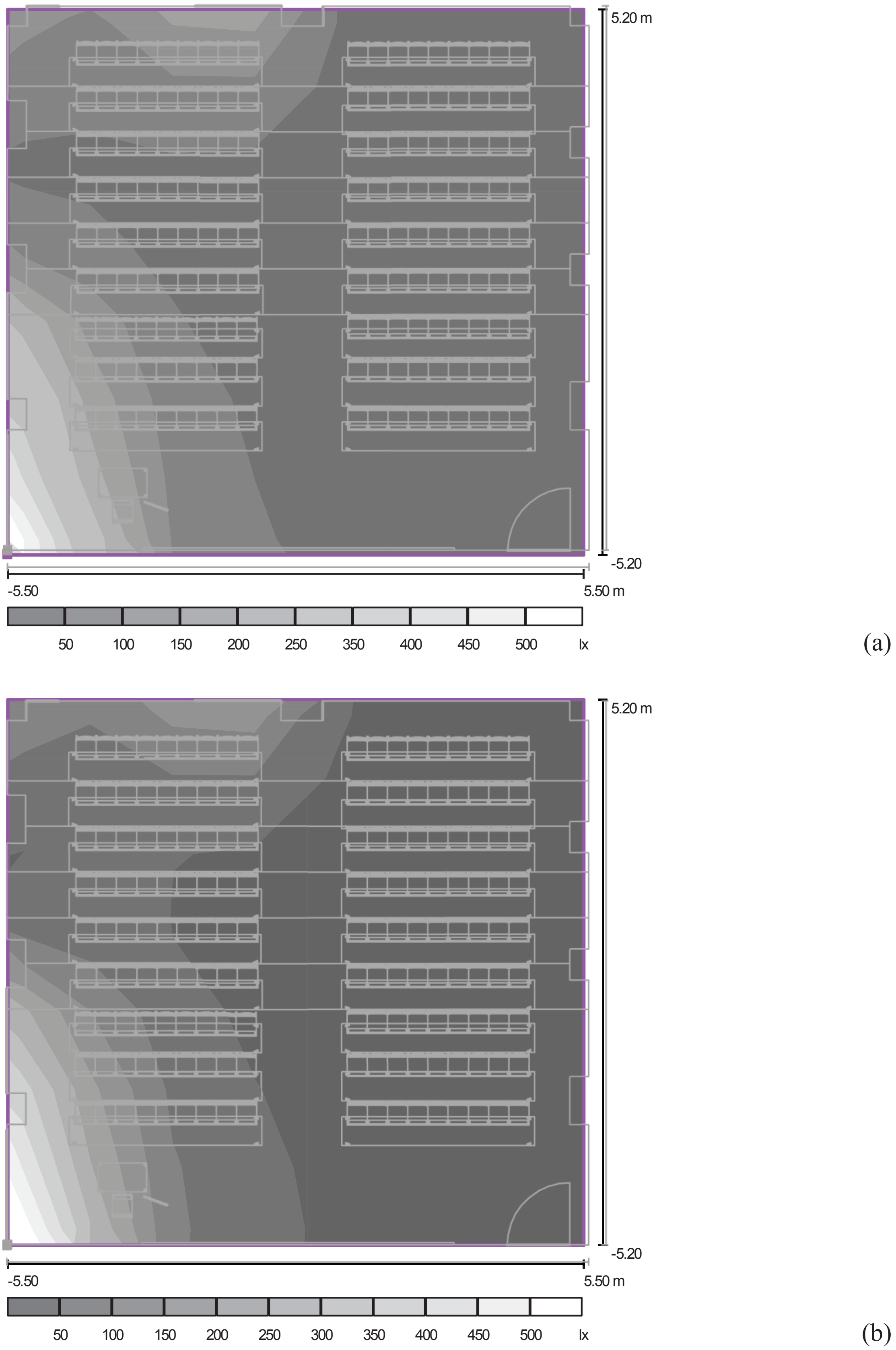


Figure C.19. Illuminance distribution on working level for MC1 (a) and MC2 (b) ……………. (unit: lux)

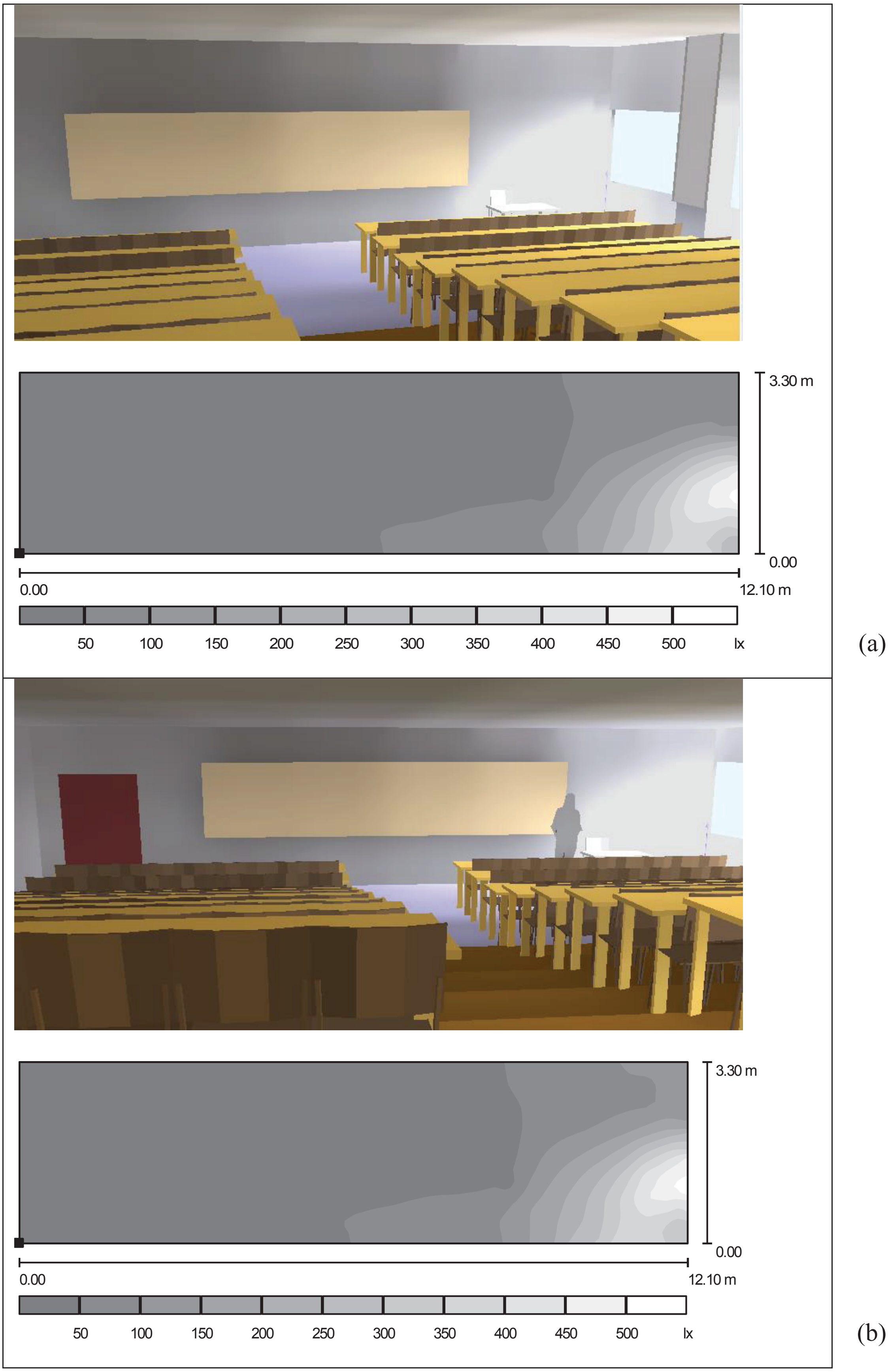


Figure C.20. Illuminance distribution on white board's wall for MC1 (a) and MC2 .... (unit: lux)

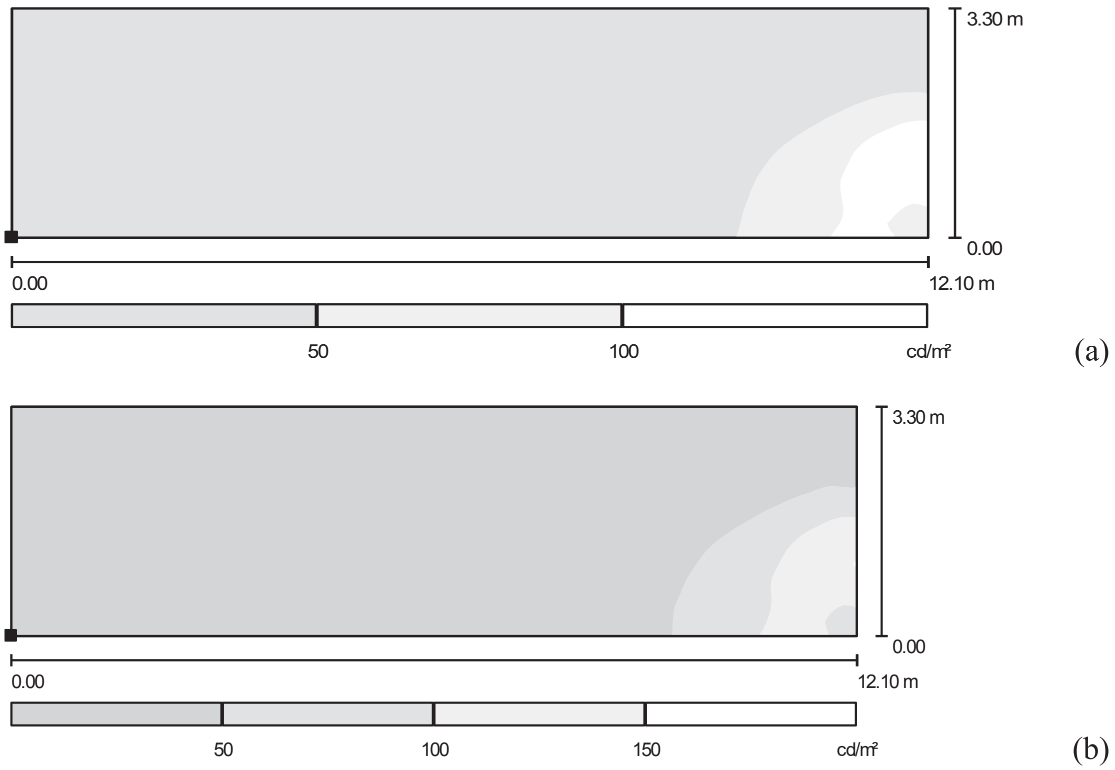


Figure C.21. Luminance distribution on white board's wall for MC1 (a) and MC2 ……………. (unit: cd/m^2)

APPENDIX D

COMPARISON OF SIMULATED DAYLIGHT ILLUMINANCE REGARDING MEASUREMENT POINTS ON 30TH SEPTEMBER (10:30-11.30) WITH THE APPLICATION OF DESIGN COMPONENTS

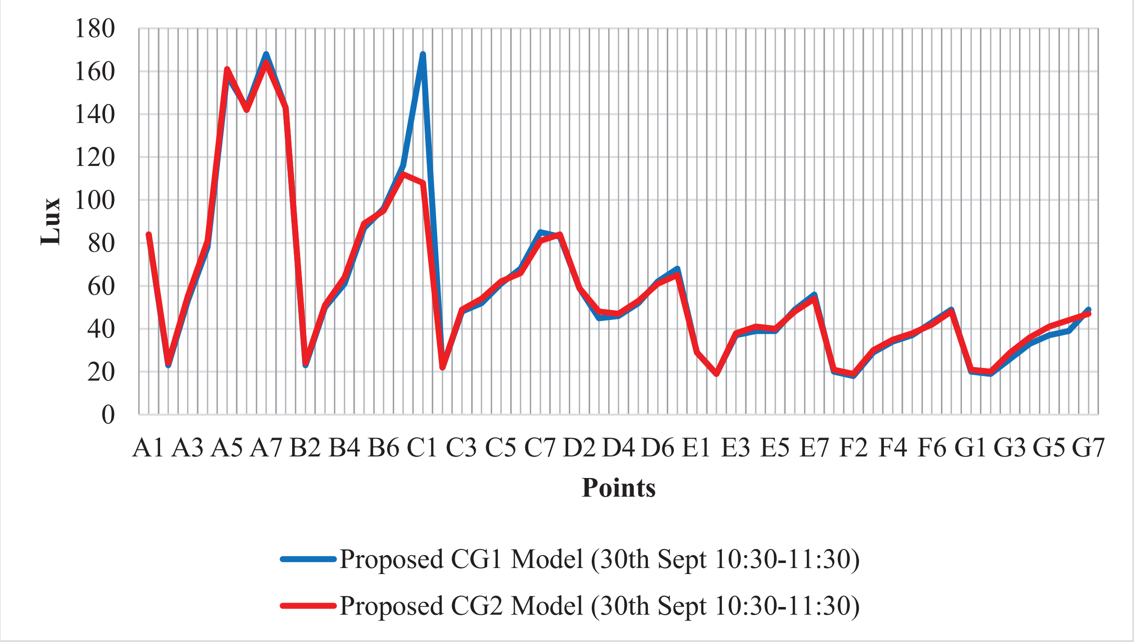


Figure D.1. Comparison of measurement points results for 30th Sept 10:30-11:30

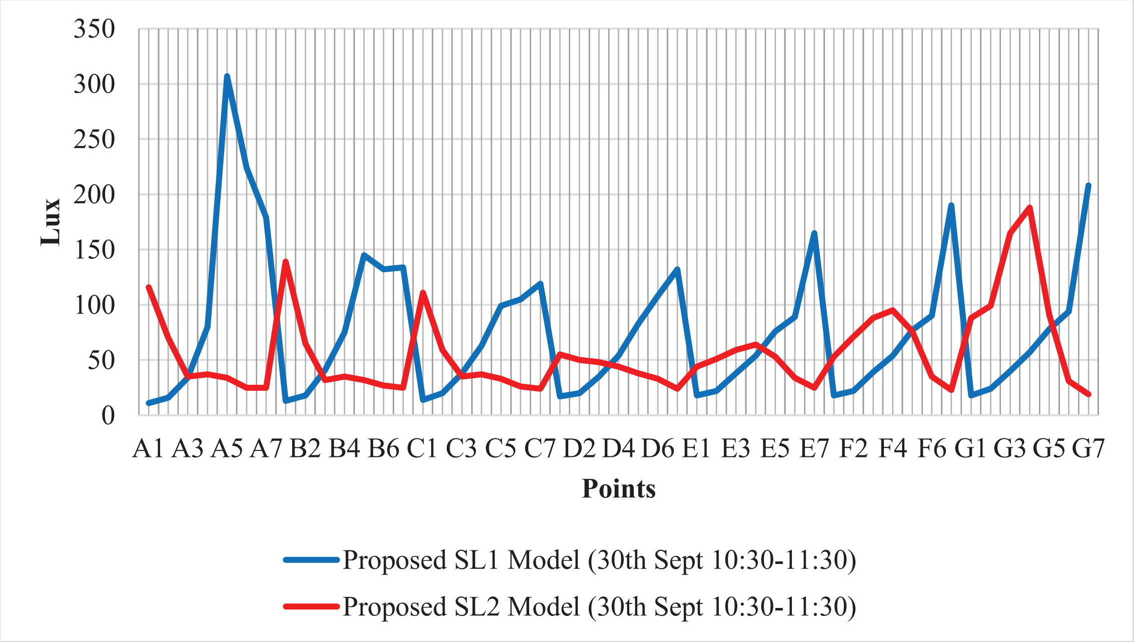


Figure D.2. Comparison of measurement points results for 30th Sept 10:30-11:30

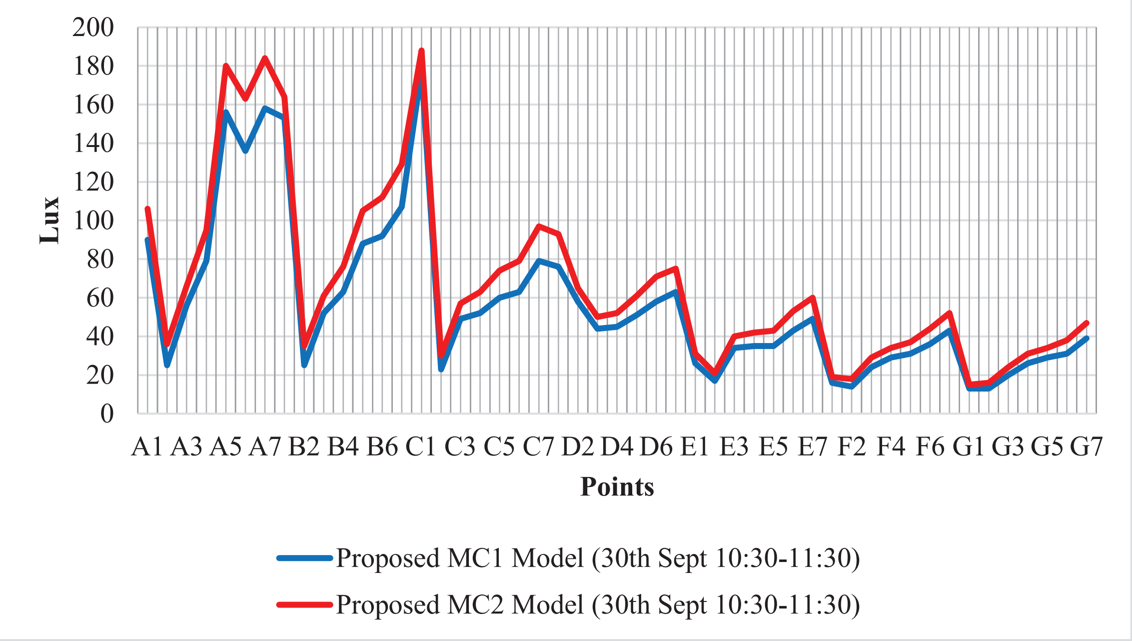


Figure D.3. Comparison of measurement points results for 30th Sept 10:30-11:30

APPENDIX E

COMPARISON OF SIMULATED DAYLIGHT ILLUMINANCE REGARDING MEASUREMENT POINTS ON 4TH NOVEMBER (12:00-13.00) WITH THE APPLICATION OF DESIGN COMPONENTS

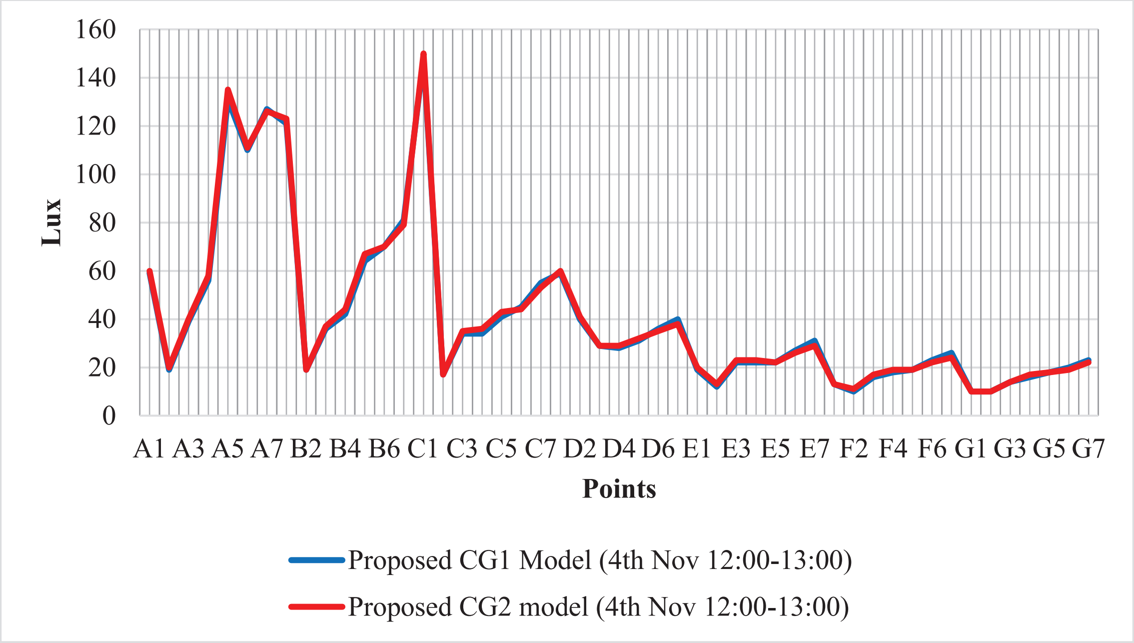


Figure E.1. Comparison of measurement points results for 4th Nov. 12:00-13:00

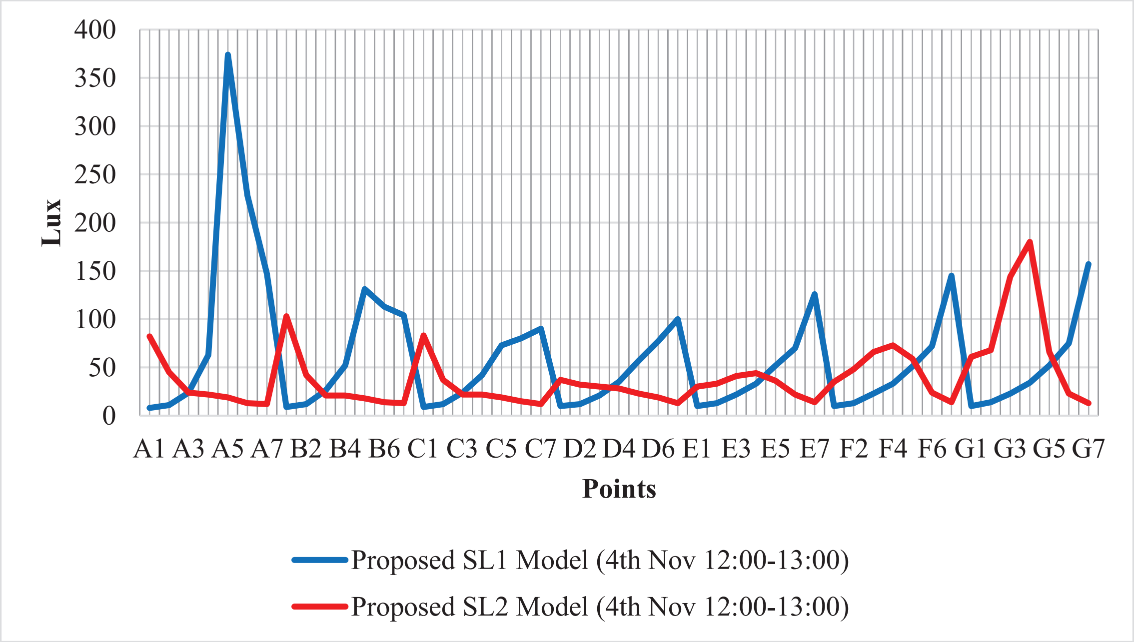


Figure E.2. Comparison of measurement points results for 4th Nov. 12:00-13:00

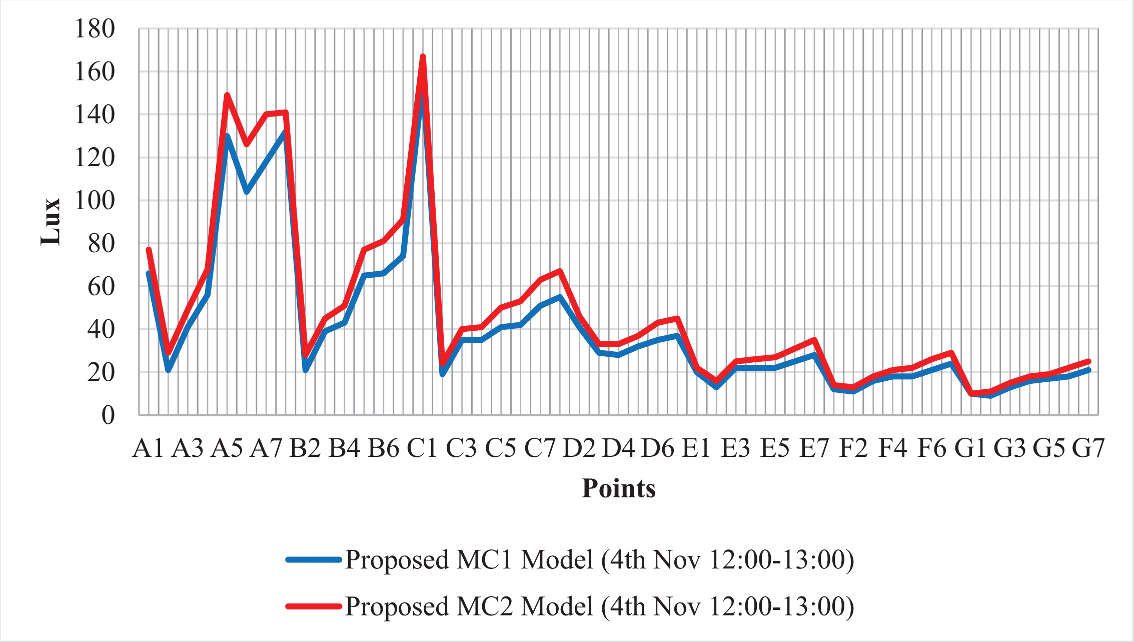


Figure E.3. Comparison of measurement points results for 4th Nov 12:00-13:00

APPENDIX F

COMPARISON OF SIMULATED ACOUSTIC ANALYSES WITH THE APPLICATION OF DESIGN COMPONENTS

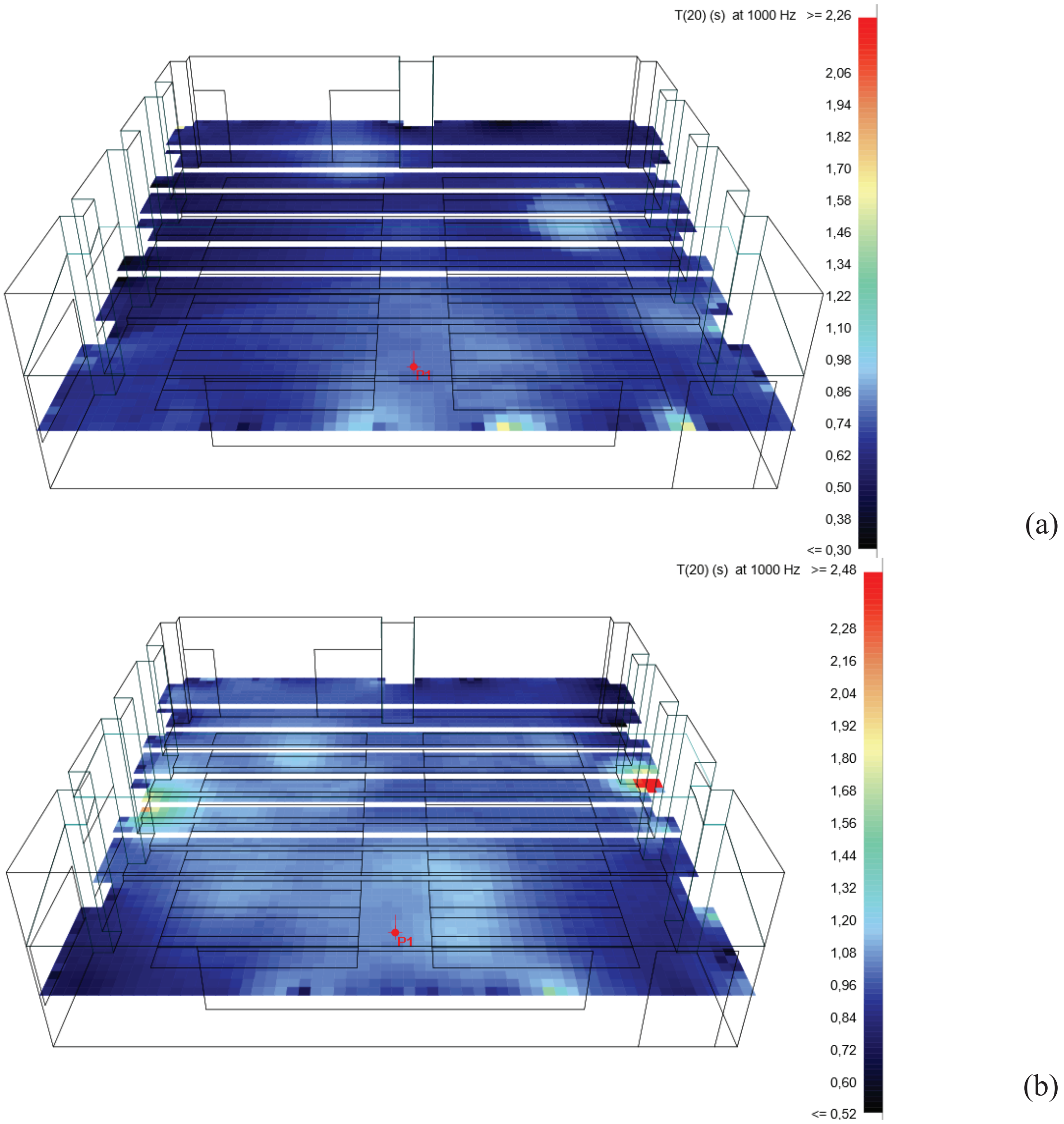


Figure F.1. T20 results of grid calculation at 1000 Hz for CG1 (a) and CG2 (b) (unit: s)

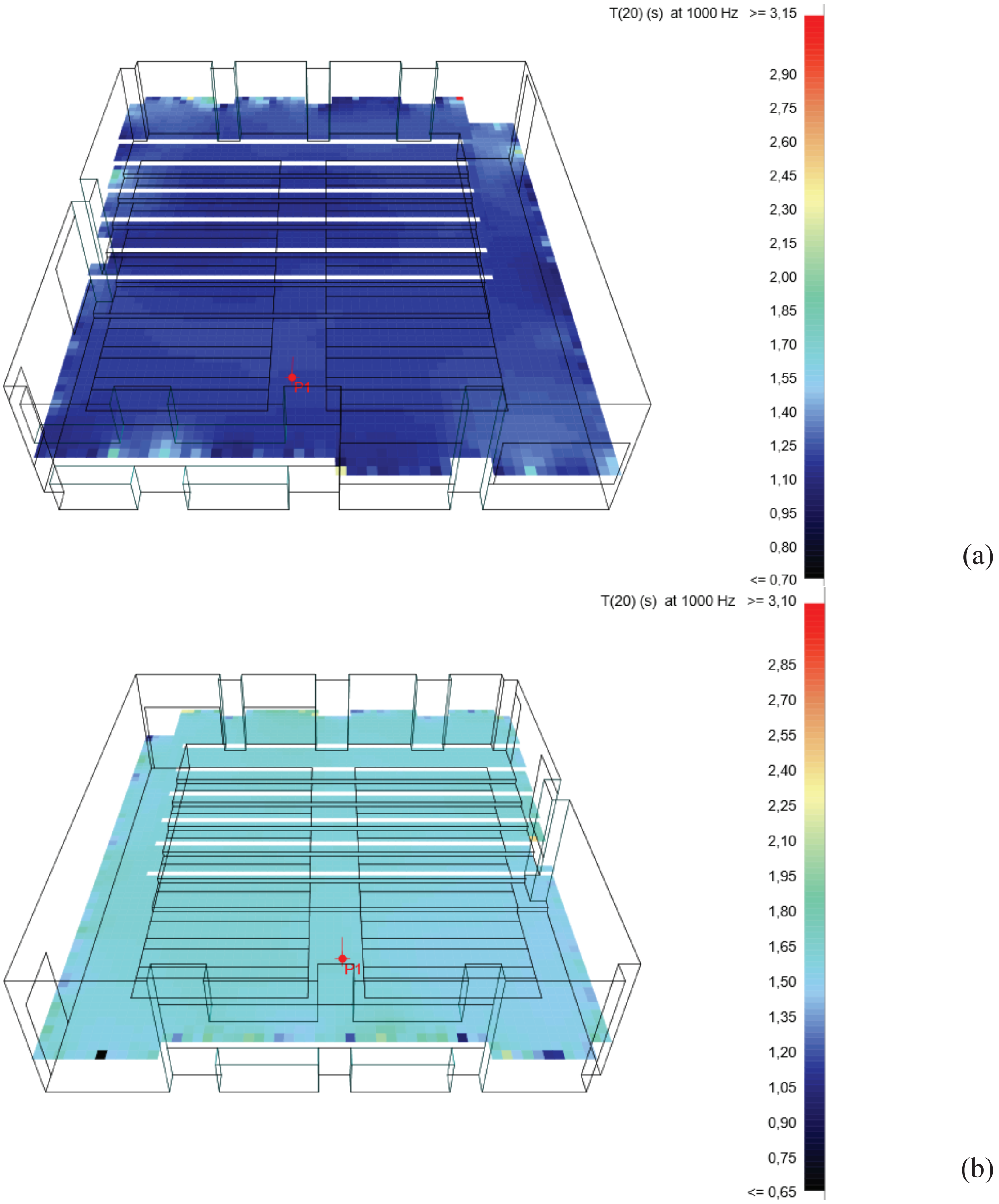


Figure F.2. T20 results of grid calculation at 1000 Hz for SL1 (a) and SL2 (b) (unit: s)

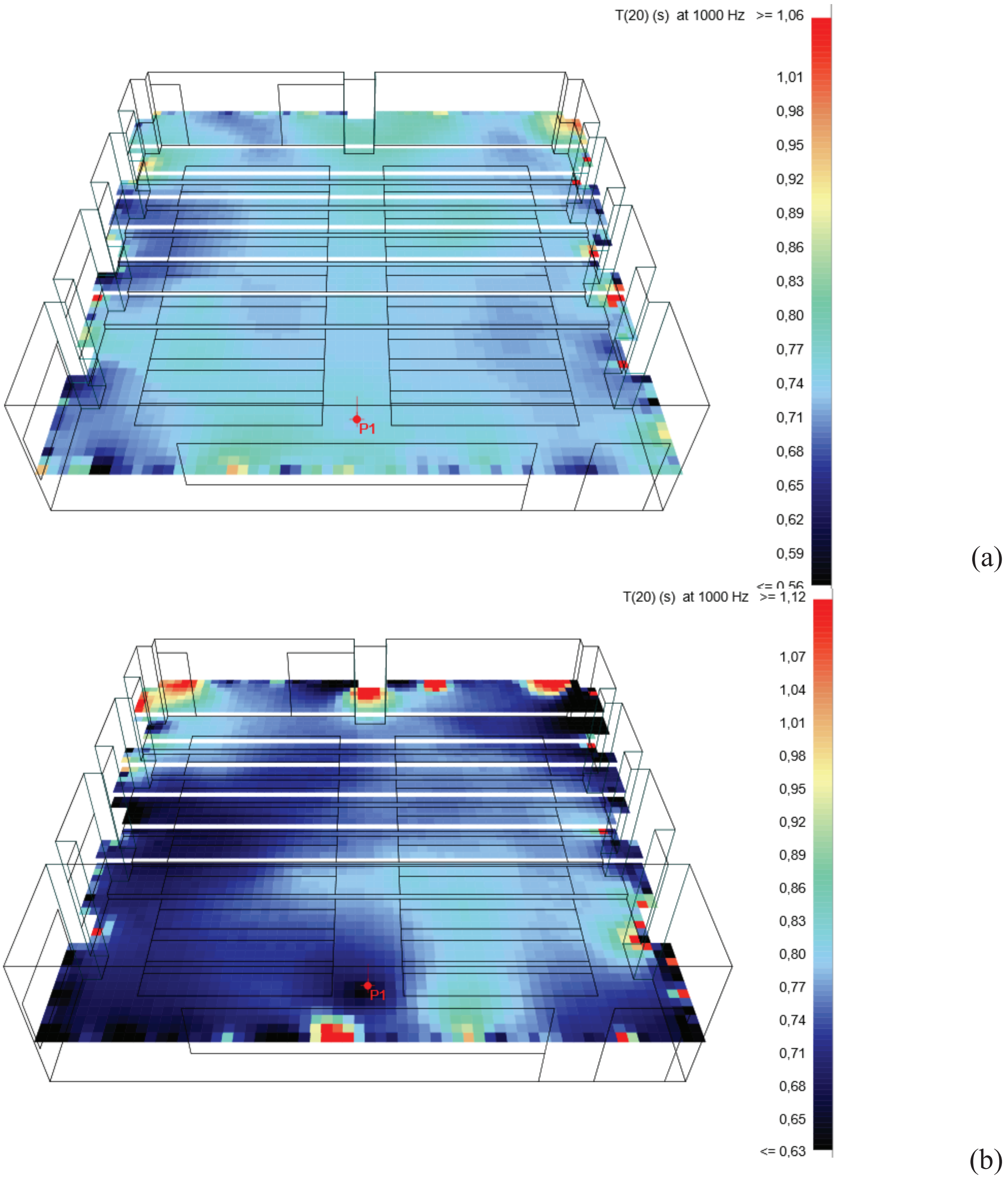


Figure F.3. T20 results of grid calculation at 1000 Hz for MC1 (a) and MC2 (b) (unit: s)

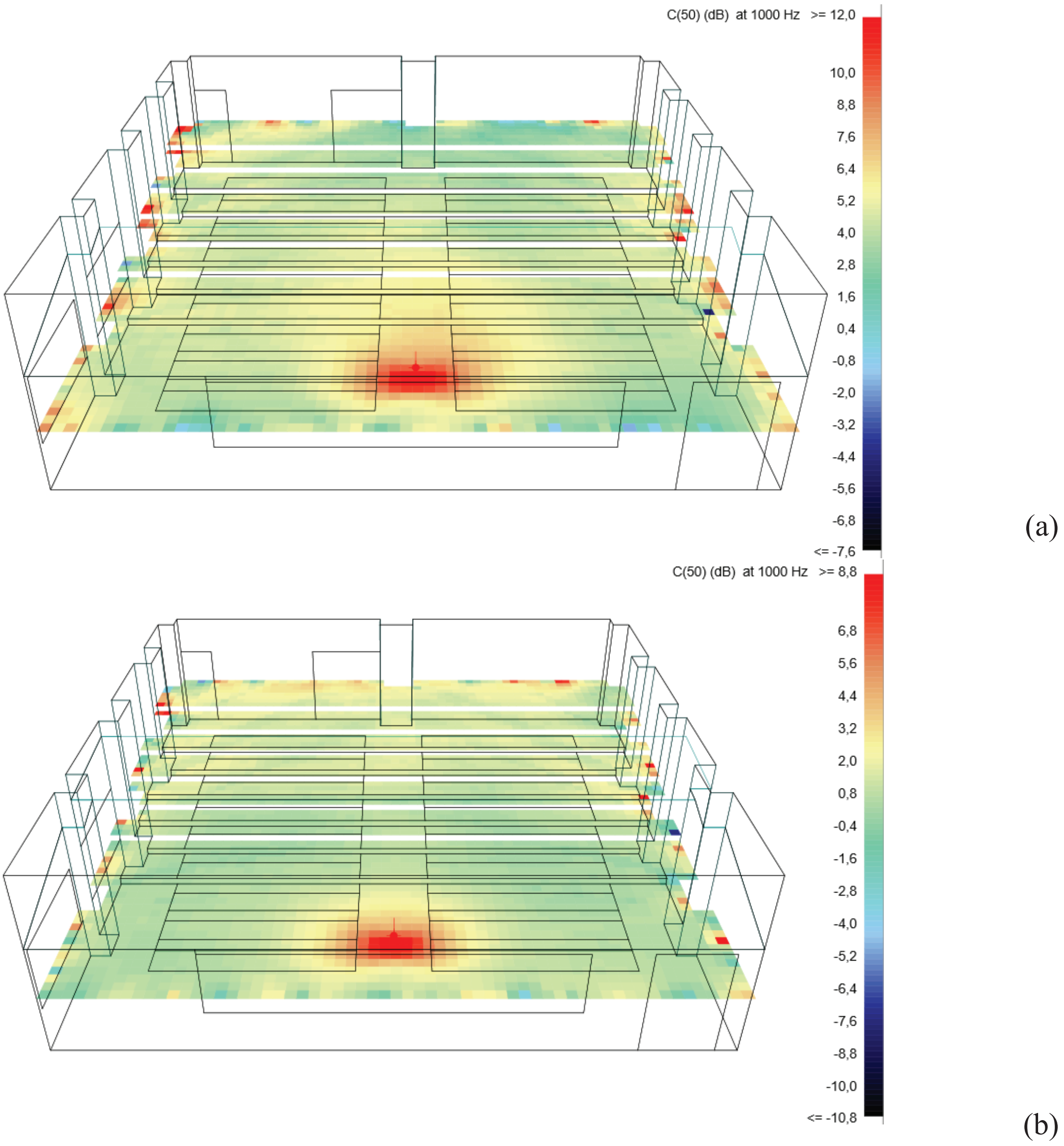


Figure F.4. C50 results of grid calculation at 1000 Hz for CG1 (a) and CG2 (b) (unit: dB)