Human Centric lighting in school classrooms

الإضاءة المتمحورة حول الإنسان في الصفوف المدرسية

by

REEM MATAR MOHAMED MOBARAK

Dissertation submitted in fulfilment

of the requirements for the degree of

MSc SUSTANIBLE DESIGN OF BUILT ENVIRONMENT

at

The British University in Dubai

August 2020

DECLARATION

I warrant that the content of this research is the direct result of my own work and that any use made in it of published or unpublished copyright material falls within the limits permitted by international copyright conventions.

I understand that a copy of my research will be deposited in the University Library for permanent retention.

I hereby agree that the material mentioned above for which I am author and copyright holder may be copied and distributed by The British University in Dubai for the purposes of research, private study or education and that The British University in Dubai may recover from purchasers the costs incurred in such copying and distribution, where appropriate.

I understand that The British University in Dubai may make a digital copy available in the institutional repository.

I understand that I may apply to the University to retain the right to withhold or to restrict access to my thesis for a period which shall not normally exceed four calendar years from the congregation at which the degree is conferred, the length of the period to be specified in the application, together with the precise reasons for making that application.

____

Signature of the student

COPYRIGHT AND INFORMATION TO USERS

ABSTRACT

Human centric lighting (HCL) is the sum of visual and non-visual effects of light on humans. Not only do we need light to see objects, but recently it was found that light affects much more than that. It was shown that light has an important effect on circadian rhythm of humanbeings, which means that it affects the sleep-wake cycle, in turn it has a significant effect on human's health, psychological and physical wellbing, and productivity. Given the importance of Human Centric Lighting on us as societies and individuals, many researches were done to evaluate this effect. Educational spaces one of the most important environment that need to provide a good Human Centric Lighting. In order to improve the students' sleep/wake cycle, productivity and performance in the school.

The aim of the study is to investigate and evaluate different LED luminaire types with different CCTs and light beam distribution in term of circadian light for a typical classroom. The study was conducted through computer simulation to examine how are different luminaires type can influence vertical illuminance (Ev) by adding six vertical calculation surfaces along the classroom. Moreover, evaluating how much different luminaires can deliver Ev to the eye by adding 31 calculation points positioned in every chair at 1.2 m height with an interval of 15 degrees to simulate human head movement towards the whiteboard. In addition, a horizontal calculation plane at the working plane level (0.76 m) to ensure maintaining the recommended horizontal illuminance (EH) which is 500lux. The study evaluated five luminaire types, which were examined with different light beam distributions (narrow, flood, and wide flood) and various CCTs (3000K,3500K,4000K, and 5000k). Additionally, the study calculated the circadian stimulus (CS) for two positions in the classroom to compare between the different luminaires in their ability to deliver good circadian light. The results showed that the lumen value plays an important role in delivering vertical illuminance, and it showed that the luminaire with the highest lumen value delivered the highest CS. The research provided recommendations for lighting designers and architects in order to deliver good circadian lighting design using artificial lighting.

الملخص

الإضاءة المتمحورة حول الإنسان هي مجموع التأثيرات المرئية وغير المرئية للضوء على البشر. فقد وجدت الأبحاث مؤخراً ان الإنسان لا يحتاج للضوء لرؤية الأشياء فقط بل أن للضوء تأثير مهم على إيقاع الساعة البيولوجية للإنسان، و الذي يؤثر بدوره على دورة النوم للإنسان، كما يمكن أن يكون له تأثير كبير على صحة الإنسان ورفاهه النفسي والجسدي وإنتاجيته. ونظرًا لأهمية الإضاءة المتمحورة حول الإنسان، تم إجراء العديد من الأبحاث لتقييم هذا التأثير.

تعد البيئة التعليمية واحدة من أهم المساحات التي تستدعي دراسة الإضاءة ذات الإيقاع البيولوجي حيث أن تصميم الصفوف المدرسية اعتمادًا على ذلك يؤدي إلى رفع كفاءة دورة النوم لدى الطلاب وانتاجيتهم و أدائهم الدراسي.

تهدف هذه الدراسة إلى دراسة وتقييم أنواع مختلفة من المصابيح الموفرة للطاقة ذات شعاع ضوئي مختلف وبدرجات حرارة متعددة لصف مدرسي ذو أبعاد قياسية.

تم دراسة تأثير هذه المتغيرات على نموذج محاكاه باستخدام برنامج متخصص لدراسة كل من الإنارة الرأسية والأفقية، كما تم الأخذ بعين الاعتبار مستوى النظر لدى الطلاب وعليه تم قياس الإنارة الرأسية على ارتفاع 1.2 متر. أما الإنارة الأفقية فتم قياسها من خلال سطح أفقي على ارتفاع 76 سنتيمتر على أن تتوافق مع القيم القياسية المعتمدة والتي تبلغ 500 وحدة ضوئية.

تم دراسة 5 أنواع مختلفة من الإنارات و5 درجات حرارة مختلفة و 3 توزيعات مختلفة لأشعة الضوء، والتي أظهرت كمية تدفق الضوء المنبعث من الانارة التي ساعدت بدورها على حساب معدل التحفيز اليومي اعتمادًا على المعدل الموصى به.

أظهرت نتائج البحث أن كمية تدفق الضوء المنبعث تلعب دورًا مهمًا في كمية الإنارة الرأسية المتوفرة، وعليه فإن المصابيح ذات التدفق العالي تعمل على توفير معدل تحفيز يومي أفضل.

ACKNOWLEDGEMENT

I would like to express my sincere gratitude for my supervisor and mentor Prof. Riad Saraiji, who tirelessly guided me throughout all the stages of my work . His patience, valuable advice and profound care enabled me to overcome the difficulties the I faced during the work of this dissertation.

I am grateful to have the support of my team at R.M engineering consultancy and interior design, who were extremely helpful in managing the workload during the time when I was away working.

I am extremely thankful for my parents and siblings who provided me with endless encouragement and support, and for my Uncle Rashid Hamdan who was tremendously helpful.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF ABBREVIATIONS

HCL	Human centric lighting
IESNA	Illuminating Engineering Society
CIBSE	The Chartered Institution of Building Services Engineers
E_V	Horizontal illuminance
E_V	Vertical illuminance
SCN	Suprachiasmatic nuclei
CS	Circadian stimulus
EML	Equivalent Melanopic Lux
C_L	Circadian light
ADEC	Department of Education and Knowledge
ipRGCs	Intrinsically photosensitive retinal ganglion cells
LRC	Lighting Research center
CCT	Correlated color temperature
E_H	Horizontal illuminance
Ev	Vertical illuminance

CHAPTER ONE
INTRODUCTION

Chapter 1 Introduction

1.1 Background Information

Light counts as one of the life fundamentals; it helps humans to interact with the environment in terms of visualizing. Thorough light, people explore the details of spaces, buildings, and the environment. As it is known, visible light is a narrow band of the electromagnetic spectrum that expand from 370nm to 780nm (NASA 2020) as shown in Figure 1.

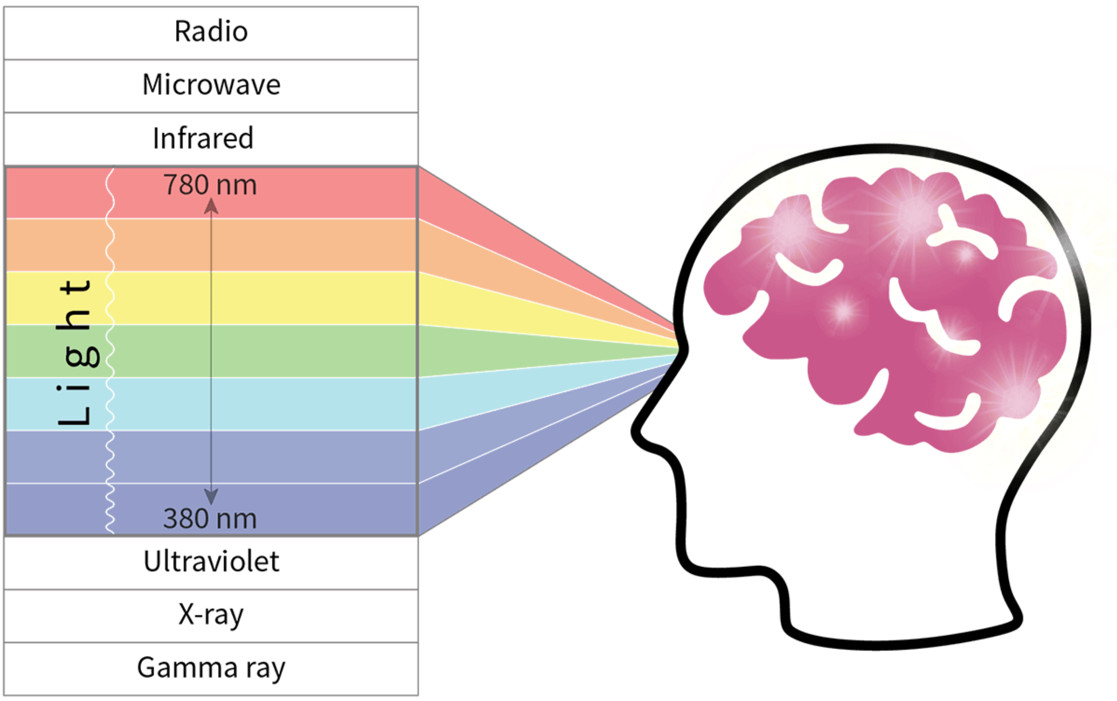


Figure 1: Visible light spectrum (Lighting Research center 2020)

The use of light in buildings has been studied from different aspects such as architectural, aesthetical, and functional. Moreover, light has an essential role in any building environmental footprint where the use of electrical light can affect the overall building energy consumptions. Building function can define the lighting design role, such as educational buildings, where delivering a healthy and productive environment is important.

Recently, it’s been discovered that the range of 446-583nm (Cajochen et al. 2019) can affect human health directly and indirectly. This spectrum has blueish color shades, where it triggers the human biological system that includes the circadian rhythms. Circadian rhythms control the human sleep cycle, where it repeats itself every 24.2 hours and work as a biological clock. Light is the main regulator of this rhythm, and any insufficient changes in light can desynchronize this clock—this effect known as the non-visual effect of light. Therefore, many studies explore how light could affect human health and how to measure it. Measuring the non-visual effect of light can be done through using the new metrics that been developed recently, such as Circadian stimulus and Equivalent Melanopic Lux. Although these metrics been used in all previous researches, yet there are no internationally agreed standards. These metrics depend strongly on the vertical light illuminance, not the normal obtained horizontal lux on the working planes. Pointing out there is limited studies that focused on obtaining the vertical illuminance of light in the spaces and how it could affect the building’s occupants.

In this research, electrical lighting design will be studied in depth in a classroom space in order to deliver an optimal circadian lighting design that will help to increase students’ productivity and performance without affecting their sleep cycle. It will be focused on studying the vertical illuminance from artificial light and obtaining the circadian stimulus value across a typical classroom.

1.2 Importance of lighting design in classrooms

School's lighting design needs to provide a lit environment suitable for students, achieving lighting that allows students and staff to easily and comfortably carry out their particular activities in an attractive and stimulating environment. Natural and artificial lighting plays an important, if not a leading role in providing a good school design and environment that give an impression of liveliness, attractiveness, and pleasure. In addition, lighting design affects the satisfaction of students and wellbeing. Moreover, it has a contribution of alertness and encouragement in fulfillment of the school activities. It is important to mention that the effect of light on the circadian rhythm has a significant effect on children and adolescents compared to adults, making lighting design for classrooms important for delivering good circadian entrainment for students. Baeza Moyano, San Juan Fernández, and González Lezcano (2020) conducted a study to analyze the effect of blue light on the retina through analyzing publications in this field, use this information to explain and evaluate the LED luminaries spectral composition and irradiance, besides evaluating the light emitted by electronics devices on adolescents. They found that the blue light emitted from the luminaries is higher than that emitted by the electronic devices, concluding the importance of providing a good lighting design in classrooms in order to maintain a good circadian rhythm for the students.

1.3 Lighting level requirements in classrooms

According to CIBSE code of interior lighting for public and education buildings, a value of 500 lux is recommended for demanding task areas, whereas, on the surrounding area, the lux should not be less than one-third of that in tasks area to avoid distraction and excessive contrast. Figure 2 below shows the recommended illuminance values from CIBSE for different areas in schools. (Mohamed, Ismail & Ahmad 2020)

		Standard Maintained Illuminance lux	Uniformity Ratio	Limiting Glare Index
1.	General Teaching Spaces	300 *	0.8	19
2.	Teaching Spaces with close and detailed work (eg, art and craft rooms)	500 *	0.8	19
3.	Circulation Spaces:			
	corridors, stairs	80 - 120	-	19
	entrance halls, lobbies & waiting areas	175 - 250	-	19
	reception areas	250 - 350	-	19
4.	Atria	400 *	-	19

Figure 2: Illuminance, uniformity ratio and limiting glare index for schools.(CIBSE 2018)

Similarly, the Illuminating Engineering Society of North America (IESNA) in the IES handbook recommended a horizontal illuminance value of 300 lux to 500 lux for a typical classroom as shown in Figure 3. (Mohamed, Ismail & Ahmad 2020)

Figure 10-9. Determination of Illuminance Categories*

Orientation and simple visual tasks. Visual performance is largely unimportant. These tasks are found in public spaces where reading and visual inspection are only occasionally performed. Higher levels are recommended for tasks where visual performance is occasionally important.

A	Public spaces	30 lx (3 fc)
B	Simple orientation for short visits	50 lx (5 fc)
C	Working spaces where simple visual tasks are performed	100 lx (10 fc)

Common visual tasks. Visual performance is important. These tasks are found in commercial, industrial and residential applications. Recommended illuminance levels differ because of the characteristics of the visual task being illuminated. Higher levels are recommended for visual tasks with critical elements of low contrast or small size.

D	Performance of visual tasks of high contrast and large size	300 lx (30 fc)
E	Performance of visual tasks of high contrast and small size, or visual tasks of low contrast and large size	500 lx (50 fc)
F	Performance of visual tasks of low contrast and small size	1000 lx (100 fc)

Special visual tasks. Visual performance is of critical importance. These tasks are very specialized, including those with very small or very low contrast critical elements. Recommended illuminance levels should be achieved with supplementary task lighting. Higher recommended levels are often achieved by moving the light source closer to the task.

G	Performance of visual tasks near threshold	3000 to 10,000 lx (300 to 1000 fc)

* Expected accuracy in illuminance calculations are given in Chapter 9, Lighting Calculations. To account for both uncertainty in photometric measurements and uncertainty in space reflections, measured illuminances should be with ± 10% of the recommended value. It should be noted, however, that the final illuminance may deviate from these recommended values due to other lighting design criteria.

Figure 3: The recommended a horizontal illuminance from IESNA. (IESNA 2017)

1.4 Research motivation

Health is a vital aspect of human lives as having good health helps us be productive, attentive to others, and to the environment around us, creative, and helps us maintain a better psychological wellbeing.

As circadian rhythm plays an important role in human health both psychologically and physically, it was subject to many researchers, which showed that maintaining a healthy circadian rhythm has a positive impact on human health and productivity.

Circadian light is one of the very interesting subjects that researchers advocate for to maintain a good circadian rhythm, which will improve the wellbeing of the population. Since most of the studies were done on natural light effects on circadian rhythm, and since we have a lot of knowledge gaps in the overall subject, it was chosen to be studied.

In the field of human centric lighting, there are many gaps and questions that need further studies and investigation and gaps in defining the parameters that could affect the human body. Moreover, linking the body anatomy to measurable metrics need a link between the researchers in the medical field, lighting designers, engineers, and manufacturers.

In this research artificial lighting was elected because the knowledge is scarce when it comes to the effect of different types of lighting on circadian rhythm. As maintaining good mental and physical health is vital to the growing population, the study is done for classrooms to include the young population and to see if there is a positive effect from this kind of lightning, which will greatly impact their attention, productivity, and overall wellbeing.

1.5 Research aim and objectives

The aim of the dissertation is to investigate in and evaluate different LED luminaire types in term of circadian light for a typical classroom.

The objectives of the research can be summarized as follow:

- To simulate different types of luminaires in a typical classroom and analyze their impact on the vertical illuminance within a space.
- To conduct a comparison between the different simulation results
- To understand how different lighting types and light beam distribution affects the vertical illuminance.
- To recommend a guidance that helps lighting designers and architects to select luminaires in term of circadian lighting
- To draw future recommendations in the field of artificial circadian light.

1.6 Research focus and limitations

The research focuses in developing a list of recommendations and guidance for architects, interior designers and lighting designers in selecting the appropriate luminaires type for classrooms with taking in consideration delivering the recommended circadian light as well as the recommended light levels. Based on the previous studies a list of parameters that affect the circadian light will be studied in this research.

On the other hand, the study has some limitations that should be addressed. One of the mental limitations in the field of circadian light is that all the metrics that researchers uses and developed so far is measuring only the level of melatonin segregation, although more considerations have to be taking into accounts such as the time and the duration in which the human exposed to the light and the photic history of the human. Moreover, the used metrics uses to measure the effect of only one hour of light exposure. In addition, most of the previous studies was done by the same group of researchers, which result in having the same ideas and thoughts for most of the studies in that field.

Collecting the data needed to conduct the simulation is one of the limitations of the study, where it was impossible to keep the value of the horizontal illuminance value constant for all the scenarios, while fixing the number and arrangement of the luminaries. Moreover, finding all type of luminaires with different light beam distribution was limited especially in the case of indirect linear light.

1.7 Dissertation structure

The dissertation is divided into five chapters as follow to meet the objectives of this study;

Chapter 1 is an introduction that provides background information about lighting, the importance of lighting design in school environment, and an overview of human centric lighting. Moreover, the research motivation, limitations, aim, and objectives are covered in this chapter.

Chapter 2, the literature review chapter, includes the definition of the human circadian system, an explanation of the circadian light, the non-visual effects of light. In addition, it highlighted the circadian light metrics, how it was used in previous studies, and how to design for circadian light in classrooms. Besides, it is to provide a clear review of the background of the research and identify the gaps.

Chapter 3, research methodology, highlights the different methodologies that were used in previous studies in the field of circadian light such as literature review, computer simulation, lab experiment, field experiment, and mixed-mode method. Moreover, the selected methodology, the framework, the variables of the study and, the simulation model are explained in this chapter.

Chapter 4, Results and discussion, which covers the results and the discussion of the different cases. Discusses the difference between the results and find the optimum luminaire in term of the circadian stimulus.

Finally, in chapter 5, a summary of the research findings, an overview of the simulation results was discussed. In addition, it identifies the limitation of the research and draws recommendations for future work studies.

CHAPTER TWO
LITERATURE REVIEW

Chapter 2 Literature review

2.1 Introduction

This chapter provides an overview of the current knowledge and research that we have on Human-centric lighting and identifies the gaps of knowledge that we have on this subject. The chapter will start with an explanation of Human-centric lighting concept, followed by the concept of circadian rhythm and how it is influenced by light. It will cover the non-visual effects of light on humans, provides an explanation on circadian light, it's metrics, and applicable standards and codes.

This chapter will provide an overview of lighting design in classrooms and how to design artificial lighting in classroom while taking circadian light into consideration.

2.2 Human Centric lighting

Human Centric Lighting (HCL) is a popular new term. It represents the sum of visual, biological and emotional effects of light on human as illustrated in. (Schulz 2018)

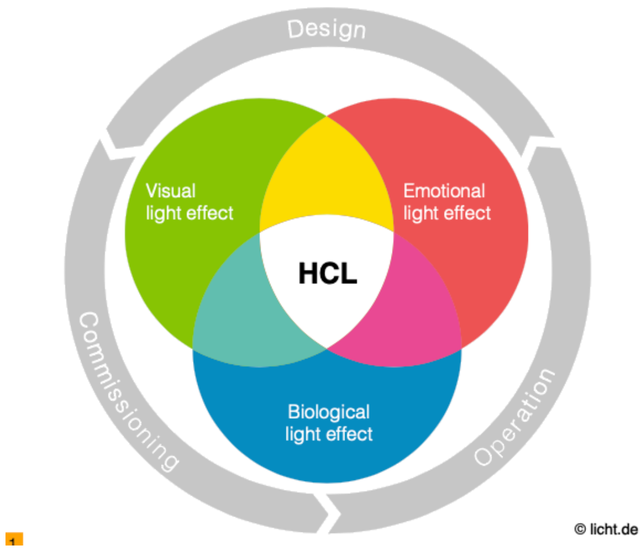


Figure 4: Human Centric Lighting dimensions. (licht 2018)

We need light not only to see things but also it plays an important role in setting our biological clock. Moreover, light has various non- visual effects on our bodies. Multiple researchers showed that the majority of people spend most of their lives indoors; therefore, understanding the effects of light on human health, wellbeing, and functionality is of extreme importance. Human-centric lighting has a lot of interesting areas for further research, and studies such as its effect on human health and well-being. A lot of researches are investigating these effects.

Light can affect the human brain in two ways. The first one is the visual path that interprets the visual images to the brain, and the second one is the circadian path where the ganglion cells (photoreceptors in the retina) are present, these cells when exposing to blue light, are affected by its quantity. The biological clock is set by these cells and synchronizes the human body with surround cycle of night and day. The production of melatonin hormones (which is basically sleep hormones) is the major output of this biological clock system. During daytime melatonin secretion rate is minimal, and at night, its production rate is high, therefore helping Human beings to rest and be more alert in the mornings. Cortisol, which is the stress hormone, is also released during the daytime making us more alert and active. Both of these hormones (Melatonin and Cortisol) work in synchrony to regulate human function in relation to time. (Cupkova et al., 2019)

The wellbeing and inner state of people are influenced by multiple factors. For instance, color is basically wavelengths of light that are absorbed by human eyes. There are six spectrums in which light can be decomposed: orange, yellow, blue, green, violet, and red. The shortest wavelength is of violet, and the longest one is of red color. There are specific effects of some wavelengths on the human body. The researches show that the shortest wavelength can affect the human circadian rhythms most. The brain's cognitive performance can be enhanced using blue lights. The meaning of colors that the human brain can determine is known as color psychology. The retina converts the light waves into electrical impulses, which is processed at the control center of the human's biological clock known as hypothalamus. Emotions and mood can be made or altered with the biological clock. According to psychologists, the colors that have the most impacts on humans include blue, green, violet, red, orange, pink, and black. Psychological impacts of color include both positive as well as negative impacts. To raise the pulse, simulate the body, and represent physical courage, and it can also give a feel to the person that time passes faster than the real one red color can be used. Blue color represents intelligence and trust. Yellow color represents optimism, encourages confidence, and also has positive effects on mood. Artificial light can be used to maintain the right color and brightness for the surroundings. A pleasant atmosphere can be created with a positive impact on humans' health, wellbeing, and productivity by using the right lighting conditions. (Cupkova et al., 2019)

Taking circadian rhythms into consideration, the night blue light can affect the normal flow of hormones: Mood (specific light colors given above have different impacts on mood, emotions, and cognition), Visual acuity (the visual acuity can be improved by adding more blue color in light, in other words, we can say that it can give clarity of vision), Perception (it can help human in perceiving the amount of energy that is required to do a specific task at a different time of the day or the year which can change the course of the work), Sustainability (the carbon footprints can be reduced and amount of energy can be preserved by dimming and Kelvin changing the LEDs system), Productivity (To increase the production and wellbeing high correlated color temperature LED lights should be a beneficial intervention). There is so many things that can be discussed in the human-centric lighting field and many more, which is still unknown, including how this thing is affecting human health. The lighting engineers for their occupants designing and lighting buildings. The technology is getting better day by day, and know they are doing their jobs differently but still working on this mechanism to understand it thoroughly so that to fully utilize this concept for the sake and betterment of humanity. Things are adding and improving the capabilities that allow them to use this technology and use human-centric lighting differently. However, when we come to wellbeing and light, we can say that we humans are still in the learning phase.

2.3 The circadian system and light

Circadian rhythms is part of the biological cycle in all living organisms. It repeats itself on an average of 24.2 hours, and it is affected by environmental signals. The Light-Dark cycle is one of the most important regulators of the circadian rhythm. Any change in the pattern of light and dark can lead to a change in the circadian rhythm as light stimulates the suprachiasmatic nuclei (SCN) in the hypothalamic region of the brain and results in the production of neural signals, in turn, it enhances the synchronization of the biological clock in our brain to the solar day in a process called the circadian phototransduction, helping us to do the right things at the right time of the day (G. Figueiro, Gonzal es, and Pedl er, 2016). In addition, physical activities, social activities, and meal schedule play a big role in regulating the circadian rhythm, therefore regulating the secretion of hormones, body temperature, blood pressure, and sleep and wake cycle. (Thayer 2020) Moreover, research has shown that human alertness and SCN timing can be affected by light stimulus characteristics, amount, and spectral properties. For example, short-wavelength light like blue light can raise alertness and stimulate melatonin hormone release, helping the body relax at night. On the other hand, long-wavelength light such as red light can provide similar alertness while not effecting the secretion of melatonin. (Jarboe, Snyder & Figueiro 2019)

As mentioned previously, the average time period of the circadian system is 24.2 hours while the solar day time period is 24 hours; so in order to maintain the circadian entrainment, a cue of light and dark is a must to further the circadian system by 10 to 15 minutes and therefore keep up resetting the biological clock. (Thayer 2020)

When the human eye contacts light, the light enters the retina first, and it stimulates photoreceptors, mainly rod and cone cells, which help us see the light, and it stimulates retinal ganglion cells as well, which play a significant role in circadian rhythm. Retinal ganglion cells (ipRGC) use melanopsin, which is a type of photopigment to absorb light energy. Melanopsin belongs to a sensitive part of the human retina, which means that it is also sensitive to light. The structure of the human eye is shown in Figure 5. IpRGC connect inner plexiform layer of retina with amacrine cell. Hypothalamus usually receives information of light from ipRGC via Retina Hypothalamic Tract (RHT) and Suprachiasmatic Nucleus (SCN). (Brown, 2020)

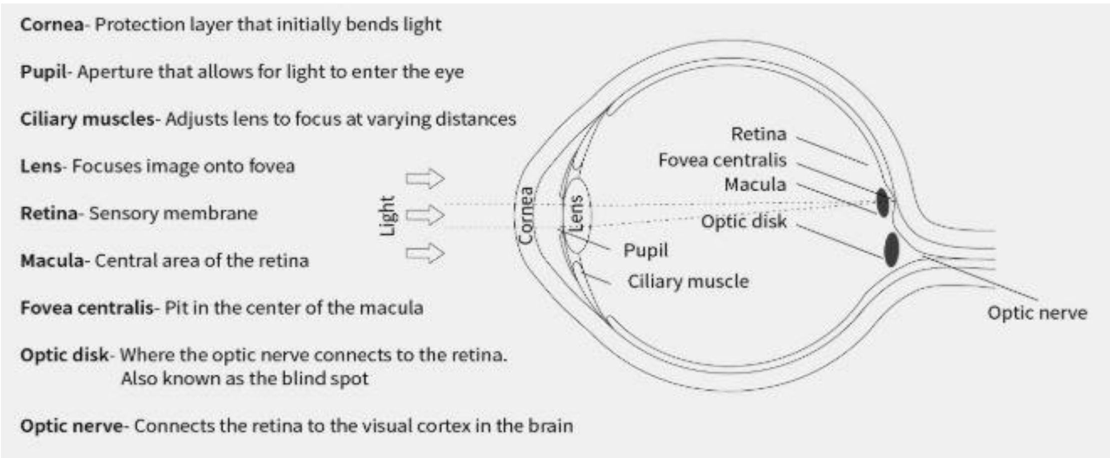


Figure 5: The structure of the human eye. (Brown 2020)

The function of ipRGC is different from that of rods and cones cells, and even when it is separated from other parts of the retina, the ipRGCs maintain its sensitivity, and it can be sensitive to other parts of the light spectrum. IpRBG is sensitive to as low as 1-lux. However, in order to reduce melatonin secretion, 2500-lux is required. Figueiro, Nagare

& Price,(2017) showed that IpRGCs are not sensitive to long-wavelength light but highly sensitive to short-wavelength light.

The main part of the Suprachiasmatic Nucleus (SCN) shows most neurons that are sensitive to light. When circadian contacts with light, some specific genes are used to regulate the rhythm of circadian. When light contacts circadian, the NMDA receptors present in SCN are altered and reset, and that is how entrainment occurs. PER1 and PER2 are the genes that are present in entrainment.

Entrainment is profoundly affected by day and night light; entrainment is not fully studied yet, and research is ongoing. Research has shown that when light is exposed to contact entrainment, it creates a curve in response to the exposure. The exposure of light to entrainment in daylight increases the circadian rhythm, whereas it decreases the circadian rhythm at night. If the circadian rhythm increases, the human usually wake up early, whereas if the circadian rhythm is decreased, the human will wake up late. Time-givers for the circadian clock is shown in Figure 6

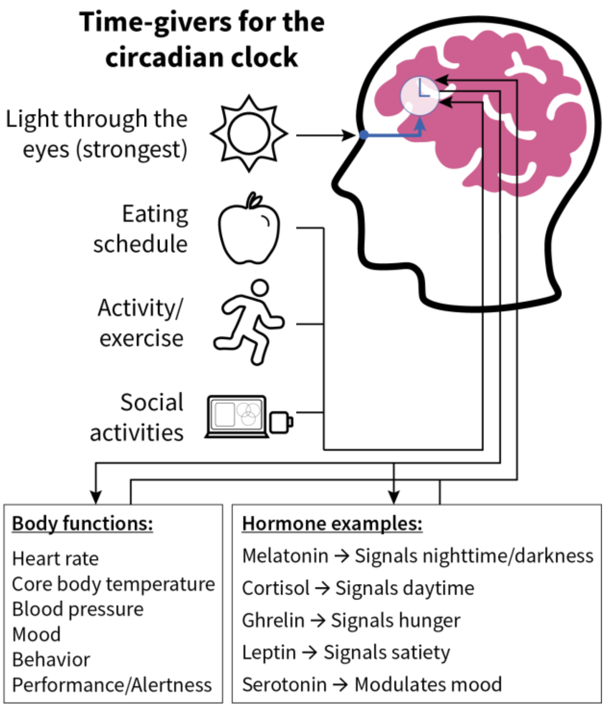


Figure 6: Time givers for the circadian clock. (Thayer 2020)

Melatonin and other hormones are affected by light and, in turn, send signals to the nervous system. Then these signals are used to control blood sugar levels in the human body and give the required energy that the body needs. During wake hours, cortisol level increases to enhance human alertness and activities, and it decreases as the day passes to reach a minimum at nighttime during sleep. At night, melatonin level increases to help the human body relax and get a good night sleep. The increment and decrement of hormones in the human body are usually influenced by the natural principle of earth light and dark. (Tähkämö, Partonen and Pesonen 2018)

Entrainment is directly proportional to light exposure. If the exposure time is high, then the effect will be greater than that of short exposure. The Bright light has a more significant effect on entrainment when compared to dim light, and similarly, little/dim light has a greater effect on entrainment than darkness.

An experiment was done on two groups of people where lights with different wavelengths were used.Group1 was placed under 460nm, and group 2 was placed under 550 nm. The group which was placed under a wavelength of 460nm showed less sleepiness as compared to the other group. The same experiment showed that the heart rate of the group, which was exposed to 460nm was higher over 1.5 hours of time as compared to the group, which was placed under 550nm wavelength of light. Another experiment was done to investigate the intensity of light on delta waves. Results showed that high light intensity 1700lux shows low delta waves, whereas low light intensity 450lux shows high delta waves. The human retina is sensitive to light, which has short wavelengths. Most importantly, melanopsin is very sensitive to blue light, which has almost 480 nanometers wavelength. This type of wavelength has some severe effect on melatonin production, which can lead to increased alertness, continuously changing circadian rhythm, and can cause difficulties in melatonin production. (Adamsson, Laike, and Morita, 2016)

We have discussed some of the direct effects of light on circadian rhythm. Now let us discuss the indirect effects on circadian rhythm. We know that in autumn and winter, the length of the day is shorter, which can affect the circadian rhythm and increase the rate of depression; this is known as a seasonal affective disorder. Some research shows that there is a connection between depression and the length of the day. Light has a therapeutic effect on humans, and the exposure to light for a specific time regularly can regulate the sleep-wake cycle.

Changes in the length of day affect the circadian rhythm, which can affect mood, learning, and memory in humans. Melanopsin also plays a vital role in the growth of cancer or unwanted tumors in the body. There is research that was done on rats, which showed shocking results. When the production of melanopsin was lower at nighttime, the tumors in rats increased in a small period, which was of four weeks.

The excessive use of artificial light or electric light also has some serious health problems on humans. The research showed that the workers who work on night shifts usually have excess progestogens and androgens. Humans who are exposed to morning light have less quantities of progesterone and androgens. When a human is exposed to light the level of alertness is also increased. A relationship was found between changing intensity of light and the hypothalamus, which can disrupt circadian rhythm as light also affect our metabolism.

The melanopic ratio was resolved concerning the light source and melanopic light intensity of the images. Light, the unit used to transmit light and measure the light, teaches the circuit of spectral power distribution. Light intensity and melanopic lux of the five optical images, weighted depending on each image's optical thickness.

Learning boundaries require light modes that can be connected to daylight have melanopic lux equivalent to 125 in any situation, 75% of work areas during an event, four hours off each day, or soft lights continue to appear. Comfort level proposal in Table 3 of IES-ANSI RP-3-13. WELL Standards also provides guidance on circulation copying on multifamily properties. In order to properly return to normal planets, light customers should have the option of setting time for study and sleep. The same type of 250 melanopic lux should be observed at the time of day between the time of sleep presented and two hours before the time of sleep. The time of day from two hours before bedtime is presented until bedtime is required for melanopic lux 50 or less. As well as the indicated activation time, melanopic lux should increase from 0 to 250 for each condition for 15 minutes. (Burnett, D., 2012)

While many scientists believe that light is the most powerful source of controlling the entertainment, it is not the main factor that accompanies circadian rhythm. Different components can increase or reduce the possibility of entertainment. For example, repetition and other physical actions cause intense reactions to entertainment to some extent. For example, various factors, such as the music and organization of exactly the coordinates of the neurohormone planet, have shown a comparable effect. Several different elements also influence the entertainment. These include temperature, custody schedules, pharmacology, mobility, sexual orientation, stress, and social communication.

2.3.1 The non-visual effect of light in human health

The effect of light on the circadian rhythm demonstrates the importance of lighting design, not only in terms of its visual performance and horizontal illuminance in the working plane but also in terms of its non-visual effect on human health. To understand how it affects human health, first, we must understand natural light effects on humans. Many researchers have shown the effect of natural and artificial light on human health. Both scientific and medical researchers have one common thing in their research: the effect of circadian on human health while sleeping. Sleep is important in the development of humans and can save humans from many diseases. Human memory and learning is directly linked to the quality of sleep as well as the quantity of sleep. Now let us talk about how circadian and rest or sleep is related to natural light and how it affects human health. (Figueiro et al. 2019).

The circadian system in humans is as important as any other system in the human body. Sleep plays a vital role in maintaining different functions of the human body, such as psychological, neurohormonal, biological, and neuronal structures. The quantity and quality of sleep are also crucial as sleep effects last for the entire 24h hours. Sleep provides the human body with enough strength to get rid of different fatigues and gives alertness based on the quantity and quality of sleep. It is called restorative sleep as it restores all the energy and gets rid of fatigue. Restorative sleep works efficiently at nighttime or the darkened hours because of the biochemical changes in the human body and works less efficiently in the daytime. (Price et al. 2019)

Effective sleeping means asleep with good quality and quantity; effective sleep provides a lot of health benefits and maintains resistance from many diseases. To get effective sleep at night , humans must avoid lighted areas at night as it provides alertness, and surround themselves with lighted areas at daytime to avoid sleeping , and to maintain an effective biochemical change in their body. By doing this, humans can improve their memory, productivity, and health. As known, the earth revolves around the sun, so we can easily see the light shifts from blue light in early mornings to red light in the evenings. The human body takes note of the shifted light and acts accordingly. The circadian system works with the biological system as well. Our biological system is earthbound, which means that it is greatly affected by the changes in the surrounding environment. For example, humans tend to sleep during the dark and tend to wake during the daytime. Circadian system changes with biological rhythm daily, weekly basis, or monthly basis. (Fabio et al., 2015)

There is a built-in rhythmic process in our body, which creates a balance between the chemicals in our brain and metabolism. The circadian system in the human body is responsible for prevalent human functions like sleep, wound healing, appetite and urine flow, etc. The circadian system also plays an important role in providing strength to our digestive system as well as immune system. The circadian system is, directly and indirectly, connected to almost every system in our body. It was proven that the ambient electric light environment has the capability to drive the circadian system. (Skeldon, Phillips and Dijk 2017)

2.3.2 Metrics of circadian lighting design

Many metrics help us to measure the non-visual effects of light. Every metric uses a different methodology to measure the non-visual effect of light on humans. Some metrics use photoreceptor sensitivity, some use physiology, and some use the data of hormonal changes in our body when we contact light. The purpose of these metrics is to give clear and precise information about the physiological impact of light on the human body. It is important to mention that these metrics are still not yet included in international standards and codes.

- Equivalent Melanopic Lux (EML)

The circadian system is kept in a state of harmony by using different cues, including light in which the body reacts in a way that stimulates the spinal cord cells (ipRGC) - the photomicrographs of non-image of the eyes. With the use of ipRGCs, high-frequency repeats, and enhanced readiness, while the absence of this signal to enhance, the body reduces the use of the cloud in preparation for relaxation. The natural effect of light on humans can be measured by the Equivalent Melanopic Lux (EML), which is a proposed exchange of stress for ipRGCs rather than cones. WELL standards use the EML metric to evaluate the building in terms of wellbeing. For example, the working space should rate at least 200 equivalent melanopic lux for four working hours every day when the sunlight is at its peak. In the event that sunlight is not taken into account, all works require light with a similar or higher resolution of 150 melanopic lux. Living conditions, which are the rooms, the installation should provide a melanopic lux comfort rate per case 200 during the day and a melanopic comfort factor of less than 50 per night, estimated at .76 meters from high on the finished land. Dining rooms require a standard 250-gallon melanopic lux. (Standard.wellcertified.com. 2020)

- Circadian Stimulus (CS)

One of the most used metrics by researchers is the CS (circadian stimulus), which helps to quantify the light effects in the human circadian system; it is a segregate metric of how much a specific light will affect the human biological clock. The CS is developed by LRC (lighting research center) to measure how different light sources could affect the human, not only by melanopsin and the ipRGCs but also by considering the impact of centric rods and cones in the eyes, which make it more accurate than the EML metric. Figure 7 shows the relation between the circadian stimulus and circadian light (CL_A), which is the amount of the irradiance at the cornea in relation to the spectral sensitivity of the human circadian system, which measured by acute melatonin suppression after a one-hour of light exposure obtained from the measurements of nocturnal melatonin suppression. Moreover, it shows the circadian stimulus levels at different photopic illuminance levels. It is important to mention that the CS is a relative scale derived from the CL_A with a minimum value of 0.1 to 0.7, which is the saturation that is equivalent to nocturnal melatonin suppression in percent after a one-hour exposure to light. (Thayer 2020)

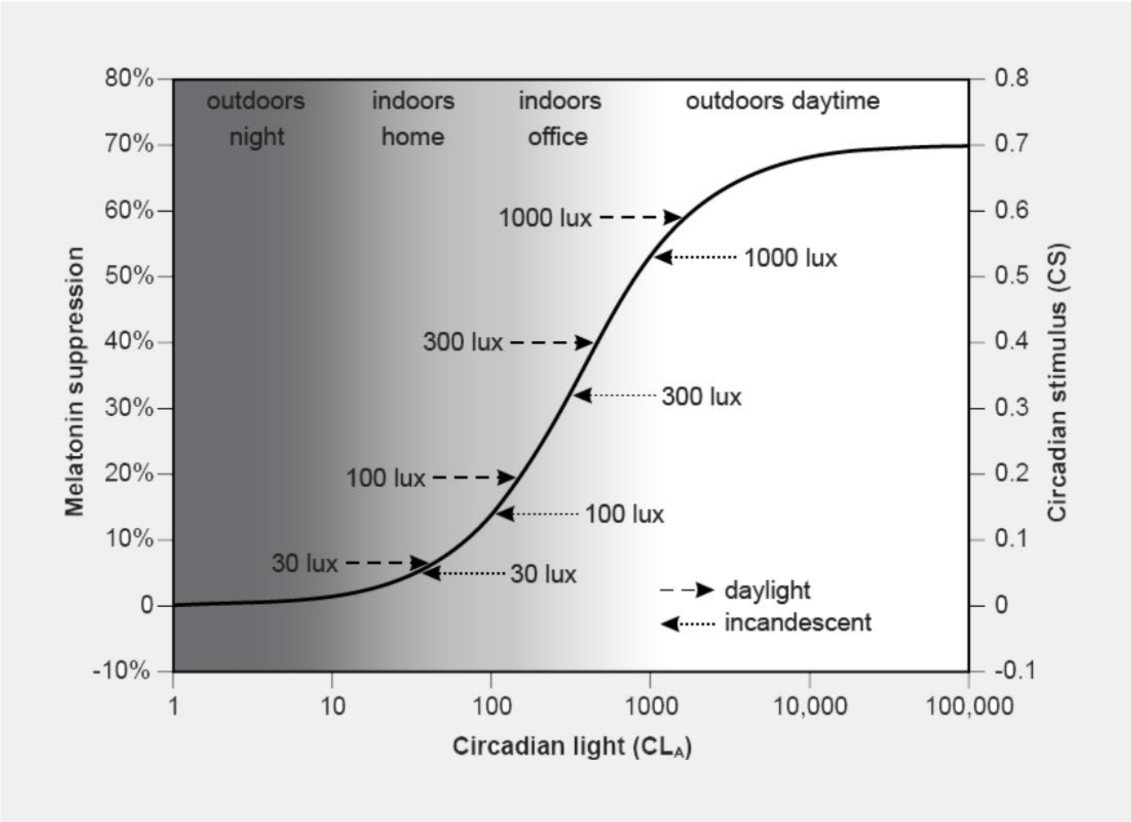


Figure 7: The relation between circadian stimulus and circadian light. (Thayer 2020)

2.3.3 Design for natural circadian Lighting

Although sunlight is abruptly enhanced by a lot of false light when outdoor light levels are shallow, where it is possible to expect sunlight to be the primary source of school light, if properly controlled, daylight is generally invited to be the source of light for all European buildings. Where windows or windows emerge from the north, the sun entering a public space will become softer and more enlarged, with clever changes in the light and surface levels of the period day. With different directions, daylight enhances the overall brightness of the space, with clear regions of intense light. The light structure test is particularly evident in the living rooms, where there is a big difference between the windows and the back of the room. Here there is always a difference between light levels: light near windows and darker backgrounds.

In situations where the shape or size of the classes does not always provide adequate light levels, as well as where the possibility of windows is limited, hand windows are often the best arrangement maker. Where there is no immediate access to heaven due to the built-in floors, light wells may be another successful option.

The issue of the amount and type of natural light present in the workplace has long been a research topic. It is evaluated that how the size of the lenses and the degree of interaction of natural light could affect heat and performance compliance. In their tests, they found that the dimming of the glasses would not affect the level of enthusiasm or customer satisfaction. However, the natural light intensity level could affect employees with windows on the other side of their vision. During the day, light intensities outside can reach illuminances up to 100,000 lux in direct sunlight and 25,000 lux in full daylight (Blume, Garbazza and Spitschan 2019).

They completed a comprehensive survey, aimed at stress assessments, satisfaction levels, and job satisfaction, matching the symptoms and windows. This review, which examined a sample of 100 employees, found a close and rapid relationship between the constant light level in the work environment and the level of satisfaction and overall prosperity. In 2001, the National Survey of Canada (NRC) distributed a credible report on the status of investigations to communicate windows of prosperity to working people. In this account, several areas of research are considered, particularly in the science of environmental psychology. Employees generally turn to the view of indigenous homes outside the window, rather than to the suburbs or cities. This makes it possible to improve the welfare state and the level of greed and job satisfaction; the overall vision will also positively impact patients' recovery time after the medical procedure. In this case, this will also not be limited to expanding employee efficiency and change. An introduction to the artificial light of the staff in an open place of business, clearly intended to give tenants the highest door in natural light.

2.3.4 Design for Artificial Circadian Lighting

Since the topic of circadian light has begun to attract experts and inventors, much research has been done to study the natural light of the interior spaces, often with negative and sometimes positive views of the features of the people around them in artificial light. In that case, there are no questions about which part of the natural light in the workplace is being investigated. These include two recent studies by Andersen et al. in 2012 and Mardaljevic et al. in 2014, who have often tried to identify a work philosophy to evaluate the effect of NIF (No-Image Forming) light on the interior. A spectroscopic observational study by Bellia et al. in 2014, the continuous light in three workplaces is broken into two different periods: winter and summer. The workstations are located on the seventh and final floor of the building in the city of Naples.

The luminaires offer tunable white lighting with a correlated color temperature (CCT) that can vary from 3000 to 5000 K. The 4800 lm light output option was specified for the classrooms, and this option results in a rated light output ranging from about 4600 to 5000 lm and input power can vary from 34 to 45W at full output. The artificial light for indoor areas should always be active, with varying volumes of light and CCT during the day, such as natural light. The light should ensure a short CCT exposure at any time during the two-part of the day: the first part in the morning, and the second part is in the night. (Energy.gov. 2020)

These two positive aspects, ironically, address specific issues in terms of the overall level of internal space in urban buildings. A study of 13,296 employees at a French car agency near Paris examined two staff meetings. The largest conference, consisting of 34.9% of subjects, served in exclusive artificial lighting. In contrast, the next session was spent on the regions of the fragments or generally introducing the natural light. In the main session, a common problem of rest, for example, insomnia and fatigue in waking up, was randomly selected, such as sleep problems. The survey of nonlinear lenses was used in which light was obtained by workers in the workplace. The data collected attributed the immediate connection between the light received during the day and the type of rest for the following nights. It has been shown that they have increasing importance and attention to detail in the days when they had the option of having benefited by extra circadian artificial lighting. If non-natural lighting is properly designed, it can compensate for the absence of natural light in the home, both for private displays and the effects of NIF lighting.

A study done by Jarboe, Snyder & Figueiro in 2019 to investigate how effective the LED lighting in providing circadian stimulus in office spaces while minimizing or avoiding any extra energy consumption, they conducted the study with illuminance of 300 lux and 500 lux for the horizontal working plane for different types of luminaries. They founded that, in the case of 500 lux the CS value reaches 0.3 for most of the CCTs, while in 300 lux case only few was reached the recommend CS. Moreover, they founded that the troffers and linear pendants has the highest value of E_V/E_H which means it is the most effective luminaire in delivering the vertical illuminance.

2.4 Circadian light design for schools

2.4.1 WELL standards for circadian light in schools

WELL standards for educational spaces require circadian light designing guidance, which classified according to the different education levels, including primary, secondary, and adults. Achieving at least 125 EML on the vertical plane of 75% of more of the student's desks at the eye-level. This EML target shall be achieved for at least 4 hours per day throughout the year. Illuminance on the vertical plane of EML should obtain equal or greater than the desired lux in the vertical plane (E_v). It is important to highlight that WELL recommended to change the desired EML according to the room function. For instance, studios in educational spaces should achieve 150 EML form electric light. (Standard.wellcertified.com, 2020)

2.4.2 Circadian Stimulus for Schools

Circadian rhythms and sleep-wake cycles tend to be stable for the children in pre and early elementary schools as they get older (12-14 years); they tend to wake late and morning and sleep late. Therefore, researchers at LRC developed different recommended CS values for students as shown in Figure 8.

Teens (6th-12th grade)	
Time	**CS**
Wake - 12:00 PM	0.4
12:00 PM - 1:00 PM	0.4 → 0.3
1:00 PM - 3:00 PM	0.3
3:00 PM - 4:00 PM	0.3 → 0.1
4:00 PM - Bed	0.1

Pre-teens (K-5th grade)	
Time	**CS**
Wake - 3:00 PM	0.3
3:00 PM - 4:00 PM	0.3 → 0.1
4:00 PM - Bed	0.1

Figure 8: CS recommended for classrooms. (Thayer 2020)

As mentioned earlier, humans need to have a higher CS at early morning and lower light exposure and CS as time passes; therefore, they divided the recommended value according to the time. For example, 0.4 CS value is recommended in early morning to 12 PM, while only 0.1 CS value is recommended from 4 PM to bedtime.

2.4.3 Designing for Circadian Light in schools

The light became an essential link between our circadian clock and local time. Fluorescent lighting systems are the most prevalent sources of illumination in schools. However, living and working in existing circumstances has changed our preconceived notions of natural light. Circadian disruption is caused by an unpredictable encounter or insufficient light / light cycle, leading to negative health outcomes. In addition, exposure to the rich conditions of the surrounding light properties greatly improves well-being, and also provides alert effects, improves learning outcomes and improves productivity.

Electric light sources manufacturers have maintained the quality of vision by enhancing the characteristics of the LED sources that constantly keep other sources of light. Technological research has overcome the development of LEDs that produce an increasing amount of light activity, while expanding the potential for light flux, cost, performance, and unmatched use of light sources in the past. One of the most controversial changes made to the proposed design of the light entering interior spaces of the electric bulbs in the areas in almost a hundred years, they perform better visual recognition ability, and not create problems for the health of customers. It must be said, however, that almost no one presented, until a few years ago, some basic research on compilation, from a physical state, regardless of whether the light was in the interior can cause problems, especially when there is little compromise on natural light. People who get enough levels of circadian light in the first half of the day have a normal, higher quality rest than those without it. In addition, exposure to circadian light during the whole day improves people's mood planning and reduces their tendency to depression.

Each of these sections provides design guidance for circadian lighting system, for the redevelopment and construction of the structure, to establish the tenants of circadian light, which can be natural light, as suggested by WELL standards.The combination of each of these elements makes the circadian light system a subject of investigation, and cannot be more predictive of the interior lighting design. However, more important aspects than current indicators can be considered. In the case of low light artificial circadian lighting should be used, regardless of whether this requires more power than focused light in the view. However, we can identify key features of a light that should be seen as a circadian is described in the coming paragraphs.

The artificial light for indoor areas should always be active, with varying volumes of light and CCT during the day, such as natural light. The light should ensure a short CCT exposure at any time during the two part of the day: the first part is the morning and the second part is the night. During cold CCT lighting, high levels of light should also be used. For relaxation and before night, warm CCT with low light levels should be used. From now on, without explicit principles, the measurement of CL_A characteristic or light-dependant circadian rhythm and the resulting CS, should be possible by repairing. The insertion of light circadian should be very large to consider the first part of the day and absent in second part (night). Using vibrant LEDs, LMS, and kits, the light level expansion can be monitored in a practical way due to the maximum efficiency of light sources and intelligent control. The conscious light system should include the use of sensors that can recognize the quality of light around and near humans. In addition, late in the day, packages can also differentiate between position, physical condition, amount and type of light that a person receives during the day.

Devices that use artificial lighting should provide the possibility of modifying the current and the resulting CCT. In addition, they should give them the opportunity to manage the path of light, in order to shift the ratio between rapid and intense light, thus promoting visual comfort. All light structure results should be related to LMS or possibly a good homepage to the Product Network. Finally, we must remember that the light effects of NIF add to circadian effects through melatonin remodeling, but in addition to other direct consequences of the nervous system, we must highlight the importance of a person at the heart of the design related to environment. Light circuits that people experience during the day can alter their muscular tone and negatively affect the duration and type of rest in the coming days, in terms of well-being and production. The age of the person should be considered in the structure. To be sure, the light of the elderly and the external disability includes requirements that exceed those of ordinary people. SPD light amount and symptoms can affect the ability of people to observe significant attention and activity in the daytime, as well as at night time if they work at night. The measurement of the effect of light on the circadian should be done at the level of light that appears normal to the eyes of the customer. The effect of the internal condition should be taken into consideration by the actual CCT of light reaching the eyes, generally lower than those of the light sources presented. Light areas can influence the individual's assessment of lighting, while people's favorite light sources also display generous personalities for particular species. This way, it is great to have a feature that allows you to adjust the lighting. (Konis, 2016)

On a day with cloudy skies, the normal light was clearly high and SPD against the mean sky and this was confirmed by the estimates. Specifically, eye illuminance measurements were at 5-281 lx, typically 87 lx. CCTs were estimated at intervals between 3,629 and 5,246 K very close to the CCT for the same period. The reason for the upgrade in CS ranged from 0 to 0.5, with a normal 0.11, much lower than the base edge to complement the circadian system. (Tidbury, Czanner and Newsham, 2016) During cold CCT lighting, high levels of light should also be used. For relaxation and before night, warm CCT with low light levels should be used. From now on, without explicit principles, the measurement of CL_A characteristic or light-dependant circadian rhythm and the resulting CS, should be possible by repairing. The insertion of light circadian should be very large to consider the first part of the day and absent in second part (night).

The artificial lighting system in the study room depends on the LED with CCT 3,000 K. Although the measurements were made in the eye level, the CCT was consistently below 2,553 K, with normal stimulation for all. The four parallel positions with three head shifts equal to 2,525 K, due to the simpler images between the inner surfaces hitting the CCT. It should be noted that there is not a large proportion of even the brightness range of 300 and 400 lx in accordance with the European standard for interior lighting EN 12464-1: 2011. The reason for updating CS is recorded in large numbers 0 to 0.21, with a standard deviation of 0.08, well below the base edge to indicate circadian fitness. In this case, the development cycle of CS is recorded flat place between 1 and 0.53, the standard 0.31, slightly above the cutoff fundamental base considered to be effective promotion of the circadian system thereby achieved natural light and a clear sky.

2.5 Summary of chapter 2

Table 1 summarized the findings from the literature review.

Table 1: Summary of the research papers used for literature review. (Author 2020)

Literature Section	Findings	Author	Year of Publication
Introduction	An overview of the definitions and application of HCL. Moreover, designed a system using artificial intelligent based on Human centric lighting, which detect human face and emotions therefore change the light color. They found that design lighting according to HCL can improve human productivity and health. Moreover, when they used the developed system, they found that how changing the lighting color could influence in the mood and emotion of people.	Dominika Cupkova, Erik Kajati , Jozef Mocnej, Peter Papcun, Jiri Koziorek and Iveta Zolotova	2019
	Developed a device with three light sensors and the algorithm created permit a precise location of kind of light, intensity of light and timing for full obvious and circadian light, with concurrent observing of a few circadian marker rhythms which will encourage to investigate light synchronization in populace gatherings while they keep up their ordinary way of life. By testing the device using field experiment and statistical analysis they have proven the sensitivity of the device.	Arguelles-Prieto, Bonmati-Carrion, Rol and Madrid	2019

	In this research, they developed tristimulus color calibration procedures for high dynamic range photography, in order to measure the circadian lighting. Moreover, the accuracy of the camera color was evaluated using CIE trichromatic, which shows a strong linear relationship between the camera recordings and a scientific grade Colorimeter. The results proved the relationship, which mean that the data can be used as a physical quantity of circadian illuminance, therefore, it can be used as a guideline and metrics to improve circadian lighting design.	Jung and Inanici	2018
Background	In this research, they analyzed the data of different laboratory studies which measure the melatonin suppression and the alerting response of human toward the circadian by using melanopic illuminance metrics to predict the response to light. Therefore, provide a validation in the use of melanopic illuminance as a metrics to measure the melatonin segregation.	Timothy M. Brown	2020
	The aim of the study is to Summarize the effect of light on the alertness and how to promote circadian entrainment using light.	Figueiro, M., Nagare, R. and Price, L.	2017

	Research has shown that the circadian light shows lower wavelength to sensitivity as compared to sensitivity on cone receptor.		
	The paper shows that the increment and decrement of hormones in the human body are usually influenced by the natural principle of earth light and dark and by measuring melatonin levels circadian rhythm can be determined.	Tähkämö, L., Partonen, T. and Pesonen, A.	2018
	The aim of the present study was to report on the natural pattern of diurnal and seasonal light exposure and to examine seasonal variations in the circadian change of melatonin.	Adamsson, Laike and Morita	2016
The non-visual effect of light in human Circadian System	Light have effect on both visual and as well as non-visual system. The data in this paper agreed the fact that light exposures, when applied properly can help increase the circadian entrainment and increase alertness.	Figueiro, M., Steverson, B., Heerwagen, J., Yucel, R., Roohan, C., Sahin, L., Kampschroer, K. and Rea, M.	2019
	The circadian system in humans is as important as any other system in the human body. Sleep plays a vital role in maintaining different functions of the human body, such as psychological, neurohormonal, biological, and neuronal structures.	Price et al.	2019

The non-visual effect of light in human Circadian System	The target of this paper is an overview on researches which is developed in this field to compare general approaches and measurements protocols: the weak point of this research is represented by the scant information of the physiological mechanisms, as well as the lack of methodologies and tools which are shared.	Fabio et al.	2015
	Circadian clocks emerged as a response which is adaptive to the daily cycles of environment, for example light-dark cycle, that is associated with the Earth of the rotation. It is assured by the circadian system that biochemical, physiological, and behavioral processes, such as sleeping time and wake, occurs at some specific time of day.	Skeldon, Phillips and Dijk	2017
Human Circadian System	The new discovery has shown that as few as 1 to 3% of the total of 1.3 million tumor cells in the each eye are more susceptible to the symptoms of non-visible light.	Burnett, D.	2012
Natural Circadian Lighting	This paper investigate in the effect on daylight in human circadian system in how it could play an effective role in human sleep and mood. In addition, the effect of artificial light from smart phone and the use of Light therapy devices which can be used for medical conditions.	Blume, C., Garbazza, C. and Spitschan, M.	2019

Artificial circadian lighting	The effect of the internal condition should be taken into consideration by the actual CCT of light reaching the eyes, generally lower than those of the light sources presented. Light areas can influence the individual's assessment of lighting, while people's favorite light sources also display generous personalities for particular species.	Konis	2016
	They investigate in how effective the LED lighting in providing circadian stimulus in office spaces while minimizing or avoiding any extra energy consumption using a photometric simulation and a focus group. It was founded that troffers and pendent with direct lighting are the most effective in terms of delivering CS with lowest energy consumption.	Jarboe, Snyder & Figueiro	2019
Metrices of Circadian Lighting Design	Reviewed different methods for the metrics of Circadian Lighting Design. The research developed an argument for applying circadian stimulus as a metric for evaluating light in indoor spaces.	Rea, M. and Figueiro, M.	2016

CHAPTER THREE
METHODOLOGY

Chapter 3 Methodology

This chapter will review the different research methods that were used to investigate the circadian lighting design in term of daylight and electrical light, in addition to the parameters that affect the circadian light. Since the circadian light is related to human health and well-being, A lot of research has explored and studied the circadian light effects, parameters and how we can maximize it and minimize it throughout the day. Therefore, many research methodologies were used in order to fill the knowledge gaps such as literature review, computer simulation, field and lab experiments and finally, the mixed mode method where a combination of method can be used.

Moreover, A selection of the research methodology that will be used in this research and the method framework will be highlighted in this chapter.

3.1 literature review

The literature review used as a research methodology mainly to provide answers using previous researches, to evaluate and examine the accuracy of a theory and to investigate the relations between variables for a certain topic. In addition, literature review can be used to evaluate the knowledge and to identify the gaps for a specific topic.(Snyder 2019) In the circadian lighting field Rea & Figueiro (2016) based their research on literature review about using the circadian stimulus as a metric for measuring the light effect in the circadian rhythm in architectural spaces, discussing the previous studies that investigated modelling the circadian stimulus and the mathematics behind it. In addition, analyzing the mathematical equation of circadian stimulus with respect to circadian light CL_{A}. Through this study, they concluded that there is a big knowledge gap in understanding the human circadian system which needs to be clarified . As well as, the limited s about other characteristics of lighting that could affect the circadian stimulus metrics such as the photic timing, duration, distribution and history.

Figueiro (2017) focused on the disruption in circadian rhythm which caused by light at night (LAN), discussing the reasons behind the lake of researches that link between the LAN and melatonin suppression and to understand these connections, measuring and controlling the light stimulus should be in both day and night. The study reviewed different papers in the field of circadian disruption and LAN, discussing and specifying the aim and limitations. After all, recommended different approaches to make the future studies in circadian disruption more accurate such as the use of calibrated device to measure the light effect in circadian system directly Instead of measuring the visual system.

Figueiro, Nagare & Price (2017) maintained a literature review of how alertness and entrainment can be affected by the light. Started with a deliberation of circadian rhythm, followed by the characteristics of light that could affect the circadian rhythm and the metrics that has been used according to their light sensitivities and spectral. Moreover, described the related applied and field researches among different populations such as adolescents, adults and elderly , the different devices and technique that can be used in that field to maintain accurate results for circadian system. In addition, a deliberation of how the real-life settings were applied in the reviewed papers. Finally, conclude the review with the expected path for the research in the field of circadian lighting for the next 50 years, in maintaining the circadian entrainment, avoiding the circadian disruption and improving the health and well-being of human.

(Price et al. 2019) argued on how to improve the scientific evidence in circadian light and wellbeing by investigating a literature review in daytime indoor work and its negative impact on circadian rhythm and nightshift work and its effect in the short and long terms health. In addition, highlighted the shift work and light exposure metrics gaps and limitations in the existing papers. Moreover, remarked the laboratory and field experiment investigation method in term of circadian rhythm, highlighting the advantages and disadvantages in the different methods and how we should combine the methods to get the best results which will give a better understanding in circadian light field.

LOWRY, G. (2018) Conducted a literature review to discuss and compare between the different metrics for circadian lighting and its fundamental such as circadian action factor, melanopic sensitivity, Melatonin Suppression Index, circadian stimulus and finally the correlated color temperature. Moreover, discussed WELL Building Standard criteria and argued in how effective the EML in measuring the circadian rhythm cycle.

3.2 Computer simulation

Computer simulation as a research method, can help researchers to simulate real-life conditions in order to investigate new aspects in a faster manner, using less resources and with the advantage of controlling different parameters.

Acosta, Leslie & Figueiro (2016) conducted a study to find the percentage of days all over the year in which a patient in the hospital rooms would receive a minimum CS value according to WWR, surface reflectance and latitudes. DAYSIM were used which is a lighting simulation program to calculate the average illuminance values to determine the CS values by taking advantage of controlling the parameters such as sky condition, Surface reflectance values and WWR in shorter time and less cost. As a result, an illustration was developed as a guide for the optimum window size based on the target percentage of ds throughout the year for 0.35 CS value or higher for London and Madrid city.

Acosta, Molina & Campano (2017), used the same approach to deliver the proper circadian stimulus in residential rooms by finding the optimum window size for four different locations to test the impact of changing latitudes and weather conditions.

Brennan, M., AIA & Collins, A. (2018) as well, conducted a study using DAYSIM and Radiance simulation of vertical illuminance, that helped them to achieve the goal of the study by taking into consideration the impact of climate, CCT, view, the color of the walls and orientation in order to determine the minimum EML according to The WELL Building Standard on the basis of daylight and electrical light. The study used different parameters and metrics to build a composite understanding of predicate hours of circadian light in offices. Moreover, a further validation is applied using LARK spectral lighting plugin, in order to simulate and test the impact to EML from 6500 K CCT of electrical light that reflected from different wall paint colors with total of 24 views and 90 different furniture layouts. The study shows that the Evaluation of parameters such as views of all occupants, the window orientation, light source, the different SPD, CCT and surface reflectance value is a must in order to achieve 200 EML value annually. Moreover, they founded that the higher the CCT value of the source the more energy you can save by reducing the usage of task light. Overall, the results highlight the importance of maximizing the daylight, using high CCT value for the light source in the morning and orienting the users toward the light source.The computer simulation was chosen for this study due to its fixability in changing variables, simplicity and time and resources saving. Saiedlue et al. (2019) have used Rhinoceros 3D Modeling programe and ALFA plugin to collect data regarding the non-visual effect of light by placing sensors on the vertical plane at 1.2 m which is the height of the eye level while seating and on the horizontal plane at 0.76 m the height of the working plane to calculate the illuminance. The simulation helps in investigating how effective the circadian in term of daylight and electric light in indoor spaces, Based on WELL Building Standard, the daylight was examined using different glazing systems with respect to circadian stimulus potential, task performance and visual comfort. It was concluded that the electromagnetic three zones glazing type deliver the best balance among the metrics results comparing to Double IGU clear 63% glass and Electrochromic single zone. While, the electrical light was examined in term of circadian stimulus were LED Blue light achieved a higher value than the minimum EML standard, which stresses that the non-visual system is more sensitive to blue-enriched light.

3.3 Field Experiment

Field experiment maintains a real-life setting for the experiment which means that the findings will be more realistic, Therefore, more reliable. Moreover, researchers should be aware of all obstacles and parameters that could affect the work.

On the other hand, Field experiments are more time and resources consuming . As well as, its difficult to control all the parameters. It’s important to highlight, that it’s hard to repeat the experiment and get the same results because of the changing conditions . In term of circadian light, many variables could affect the results of field experiments such as uncontrolled exposure of light, the users sleeping habits and uncontrolled sky conditions.

Pici & Pieper (2019) conducted a field experiment for an office in Portland to measure how effective is the office space in term of delivering the optimum amount of daylight in order to maintain the circadian rhythm. WELL building standards is the metric used as a baseline to evaluate the results, where Equivalent melanopic lux should be at least 200 should cover 75% or more of workstations. The study had taken 5 days and 20 employees participated in the experiment by wearing sensors on their cloths during working hours to monitor the Equivalent melanopic lux, the data was logged in every five minutes and after collecting the sensors the data was compiled to be analyzed. Spectrophotometer were used to sperate levels of illuminance coming from artificial and daylight in order to measure the current levels of light spectrum, that will help to understand the contribution of the biological effect of lighting on the occupants. Three reading were taken from the Spectrophotometer in different location in the office at 8 AM, 1 PM and 5 PM Moreover, a camera was used in time-lapse technology to monitor when the occupants will use the sunshades and compare it to the data collected from the sensors to highlight any decrease in circadian caused by the sunshades . The results of the study shows that in the sunny days more than 80% of the workspace had reach the recommended value of EML from WELL standards, whereas in overcast and partly only 10% and 41% of the occupant meet the recommended value Leading them to conclude that the highest impact of EML caused by the sky conditions, in addition to sunshades.

Konis (2018) have investigated in the effectiveness of daylight in circadian for dementia care facilities at the peck time of circadian resetting period which is between 8 AM to 10 AM by field experiment. Moreover, determine how are the view orientation and the location in the space will affect the circadian stimulus potential. The study conducted over a period of 13 weeks to collect eye level light exposures in 9 daylight spaces and 4 non-daylight spaces ,a of 579 measurements using digital charge coupled device spectrometer were collected an analyzed by mounting the spectrometer on a mobile cart and positioned on a vertical plane at 1.07 m from floor level. In addition, a high dynamic range (HDR) enabled camera is also included in the cart to deliver a visual record of scene.

3.4 Lab experiment

Lab experiments can be applied in a highly controlled environment therefore, the researcher can set the causes and effects. Lab Experiments can be repeated under the same conditions which makes the verification of the results easier. Morover, it needs less time and resources when implementing than the field experiment. On the other hand, the results can be affected by human and instruments errors.

Using a lab experiment Jain et al. (2019) conducted to analyze the variations in CCT and circadian lighting metrics of the daylight and artificial light in interior spaces by applying time lapse high dynamic range image. The experiment lasted for 14 days and located in a mid-latitude area with sunny climate. The calculations of the different CCT and circadian lighting metrics were calculated using an automated time-lapse HDR photography apparatus with vertical illuminance sensor, and a spectrophotometer attached. Moreover, the tubular daylight device TDD were calibrated against the spectrophotometer to ensure the accuracy before taking the measurements. The research concluded that the CCT values for the daylight using TDD is much higher than the electric light, Moreover, they founded that the CCT of the daylight vary throughout the day. Finally, recommended future work to determine the effect of this behavior in the occupants of the space.

3.5 Mixed-mode study

Mixed mode methodologies is one of the most used method in the field of circadian light. It is mainly a mix of quantitative and qualitative research method, where the researchers answer the research question or validate the results of the first method by applying a second method or more. Moreover, it will help to eliminate the weakness of using one method.

In the field of circadian light, Acosta et al. (2019) applied a mixed mode method between computer simulation and field experiment to conduct a study to find the suitable window size in order to achieve the proper CS value for a typical classroom space from daylight, in addition assessing the effect of electrical light in circadian system. The study took place in three different locations in London, Madrid and Paris to evaluate the CS among different SPD and luminance values. Moreover, they examined the impact of changing the surface reflectance values on the CS value. The study applied in a virtual classroom 8x8x3 m using two different reflectance values for walls, ceiling and floor, In addition to two different position for the window centered in the wall and with 1.5 m height of sill, the windows were examined in two different orientation north and south in order to analyze the best and worst case scenarios. It is important to mention, that when eye receive the light two important factors are effecting the amount of light, the spectral distribution of the sky and the reflection of the light on the surface, therefore in this study three different desk finish were used white, light blue and brown, in order to find the resulting SPD perceived by the subject. They also, calculated the CS based on the CCT of the electrical light luminaries, since it could the circadian rhythm using Dialux software, whereas DaySim 3.1 software was used to calculate the dynamic metrics for daylight, Moreover, An equation developed by previous study were used to calculate the CS value in term of daylight and electrical light. In addition to the first calculation methodology, a further field experiment was carried out to validate and compare the results. Several findings were concluded from the study after applying different scenarios and variables. First, In order to achieve a minimum CS value regardless of the widow size and orientation, A white finish can be applied to the working plain surface can increase the CS by 30% for a space with 60% window to wall ratio and up to 50% in the case of

30% window to wall ratio. Second, in term of changing the location and sky conditions they concluded that the weather conditions has a higher impact in promoting good CS than the latitude. Finally, the results from analyzing the electrical light in term of CCT showed that using a cool color temperature light requires less illuminance level than using a worm color to have the same amount of CS.

Figueiro et al. (2018) as well used a mixed mode methodology to conduct a study about the circadian effective light and how it could impact the alertness in offices. They started the study with a field experiment in four different offices to demonstrate the effect of using circadian effective lighting, where CS value is 3 or above. Moreover, examine whether this lighting design would rise the alertness and reduce the sleepiness. They implanted the experiment in three days, the first day without changing any lighting conditions to set it as a baseline and the other two days the intervention in lighting design take a place by adding desktop or overhead luminaries that can provide an effective circadian light. In order to measure the CS value through the experiment they used a pendant mounted Daysimeter device among the three days and the data showed that the intervention days has a higher level of CS compared to the baseline day. The other part of the study evaluated the alertness where they used a questioners among the three days to inquire about the sleep habits, the stress levels and the vitality and energy feelings and results showed that the sleepiness score were less in the intervention days, In addition they reported more feeling of vital and energy. As a result, they concluded that using a circadian effective light system can reduce the sleepiness and increase the alertness.

In the same manner Figueiro et al., (2017) conducted a study in 5 office building to evaluate the impact of daytime light exposures on sleep and mood in office workers for 109 participants in summer and winter. Daysimeter were used to measure and collect the data of light and motion, the data were analyzed and divided based on the CS value, where CS ≥ 3 is high and CS ≤ 0.15 counted to be low. Moreover, 5 different self-reported questioners were completed by the participants for 7 days in order to measure mood and sleep. After analyzing the results, they concluded that workers who received a high CS level in the morning has a lower sleep onset latency, higher phasor magnitude, better sleep quality and less depression compared to workers who received a low CS, this effect seems to be more obvious in winter. Similarly, Figueiro et al., (2019) conducted a field study in office space followed by questioners along 3 weeks. They used desktop luminaire and changing the CCT according to the time of the day, the CS was monitored using Daysimeter and the alternance was examined using the questioner. Moreover, they tracked the sleep habits for the participants and compared it to the baseline, they found that the participants had an earlier sleep time by 1 minute and a difference of 21 minute in sleep end time.

A further study done by Jarboe, Snyder & Figueiro (2019) to investigate in how effective the LED lighting in providing circadian stimulus in office spaces while minimizing or avoiding any extra energy consumption using a photometric simulation and a focus group. The simulation studies 144 different lighting conditions for an open plan office, as a result of evaluating 6 luminaires types, 2 luminous intensity distribution, 6 spectral power distribution and 2 horizontal illuminance surfaces, in order to deliver Circadian stimulus of 0.3 to the calculation points in the occupant eye level. Moreover, the discomfort glare was evaluated for the types with highest lumen output, smallest aperture and at the higher horizontal illuminance value for direct luminous intensity distributions. AGi32 software were used to model and simulate the space, which assisted in examine how to maintain the energy consumption by changing the luminous intensity distribution and the spectral power distribution of the luminaires while maximizing the circadian stimulus. In the cases where the CS value didn't reach the desired value a desktop luminaire with blue light was added, and in order to check the practicality of using it in term of comfort and glare a focus group of 20 participants in an average age of 33 and they asked them to do computer task then evaluating their experience. To evaluate the results CS/LPD ratio were used, where LPD is a metric that measures the lighting power density by calculating the sum of the electric lighting watts per square foot. The higher the CS/LPD ratio, indicates that the lighting strategy is more energy efficient. The results of the study shows that, the CS/LPD had minimal effect by the different SPD.

Yao et al., (2020) proposed an equation in their study to prove the relation between the corneal illuminance and daylighting design parameters such as WWR and surface reflectance. They validated the accuracy of the equation by conducting a lab experiment using a scaled model in an artificial sky lab, they tested different room surface reflectance, WWR and locations which resulted in a total of 90 different combinations. The results of the lab experiment prove the accuracy of the equation and showed that the room reflectance has the highest impact in achieving a high value of corneal illuminance. A further validation is applied in the perspectives of daylight-enabled CS across the room, through a simulation analysis using Radiance lighting simulation software, in addition, Honeybee and Ladybug plugin to perform the analysis. The simulation showed that the room surface reflectance has a big role in improving the daylight-enabled CS, especially in the winter. Concluding the accuracy and practicality the of the proposed equation in estimating the circadian daylighting.

3.6 Summary of research approaches

Among the different research papers that were studied, Table 2 summarized the most significant studies.

Table 2: Summary of research papers (Author 2020)

Publication	Journal title	Year	Authors	Aim of the study	Method used
Lighting Research & Technology	Light as a circadian stimulus for architectural lighting	2016	MS Rea and MG Figueiro	An argue of how effective the CS metrics in interior space	Literature review
Lighting Research & Technology	Disruption of Circadian Rhythms by Light During Day and Night	2017	Mariana G. Figueiro	Discuss the effects of the exposing to light at night	Literature review
Lighting Research & Technology	Non-visual effects of light: How to use light to promote circadian entrainment and elicit alertness	2017	MG Figueiro R Nagare and LLA Price	Summarize the effect of light on the alertness and how to promote circadian entrainment using light.	Literature review
Building and Environment	Daylight, manual sunshade use and occupant-centric circadian lighting stimulus in an open office	2018	Prof. Kyle Konis	To nvestigat in the effectiveness of daylight in circadian for dementia care facilities at the peck time of circadian resetting period	Field Experiment
Earth and Environmental Science	Circadian lighting in a space daylit by a tubular daylight device	2019	Sneha Jain1Luis Fernandes,Cynthia Regnier, Vishal Garg	To analyze the variations in CCT and circadian lighting metrics of the daylight and artificial light in interior spaces by applying time lapse high dynamic range image	Lab experiment
Solar Energy	Daylighting design for healthy environments: Analysis of educational spaces for optimal circadian stimulus	2019	Ignacio Acosta, Miguel Ángel, Russell Leslie, Leora Radetsky,	To find the suitable window size in order to achieve the proper CS value for a typical classroom space from daylight	Mixed Mode
Lighting Research & Technology	The effectiveness of light-emitting diode lighting for providing circadian	2019	C Jarboe , J Snyder and MG Figueiro	Investigate in how effective the LED lighting in providing circadian stimulus	Mixed Mode

	stimulus in office spaces while minimizing energy use			in office spaces while minimizing or avoiding any extra energy consumption	
Lighting Research & Technology	Circadian-effective light and its impact on alertness in office workers	2018	MG Figueiro , M Kalsher , BC Steversonc, J Heerwagen , K Kampschroerc and MS Rea	Conduct a study about the circadian effective light and how it could impact the alertness in offices	Mixed Mode
Lighting Research & Technology	Impact of daytime light exposures on sleep and mood in office workers	2017	Mariana G. Figueiro, Bryan Steverson,Judith Heerwagen, Kevin Kampschroer, Claudia M. Hunter, Kassandra Gonzales, Barbara Plitnick, RN a, Mark S. Rea	Study in 5 office buildings to evaluate the impact of daytime light exposures on sleep and mood in office workers	Mixed Mode
Energy & Buildings	Efficient circadian daylighting: A proposed equation, experimental validation, and the consequent importance of room surface reflectance	2020	Qi Yao , Wenjing Cai , Min Li , Zhiguo Hu , Peng Xue , Qi Dai	proposed an equation in their study to prove the relation between the corneal illuminance and daylighting design parameters such as WWR and surface reflectance.	Mixed Mode
Lighting Research & Technology	Analysis of circadian stimulus allowed by daylighting in hospital rooms	2016	I Acosta, RP Leslie and MG Figueiro	To find the percentage of days all over the year in which a patient in the hospital rooms would receive a minimum CS value according to WWR, surface reflectance and latitudes.	Computer simulation
International Journal of Engineering and Technology	Analysis of Circadian Stimulus and Visual Comfort Provided by Window Design in Architecture	2017	I. Acosta, J. F. Molina, and M. A. Campano	To deliver the proper circadian stimulus in residential rooms by finding the optimum window size for four different locations	Computer simulation

3.7 Research method and justification

After reviewing different methodologies used in previous researches in circadian light, a computer simulation methodology was chosen to implement this research aiming to investigate different luminaire types with different beam distribution and multiple CCTs and compare them in term of circadian light. Due to the variation in the variables in this research, computer simulation is the most appropriate methodology, it will give an advantage of controlling the variables, and it will save money since there are around 40 luminaires that need to be tested. Moreover, computer simulation will guarantee faster and accurate results by avoiding human and instruments errors.

3.8 Methodological framework

Figure 9 shows an illustration of the methodological framework of this research, which starts with a literature review to set the requirements and find the gaps in this field, and to choose the proper luminaires that could be used in classrooms. Followed by setting the permanent and variable parameters of the research, then simulate the different luminaires, compare between them, and find the optimum luminaire type. Finally, suggest future recommendations.

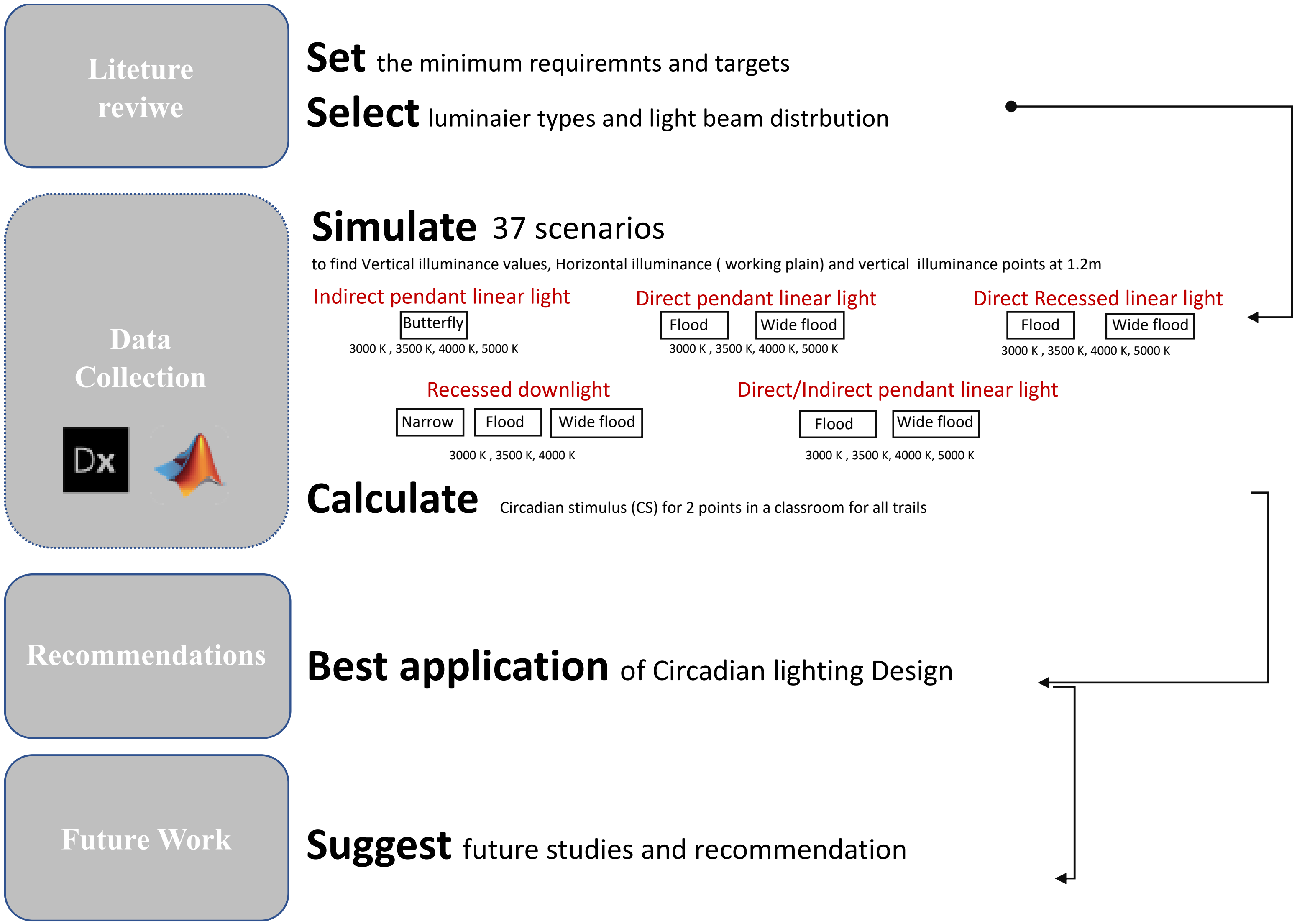


Figure 9: The methodological framework. (Author 2020)

3.9 List of variables

- **Luminaire type**

Classroom lighting should always be designed to meet the student's requirements; selecting the luminaire type has a key role in defining the space atmosphere and light level. Moreover, multiple variables shall also be considered, such as; Watts and lumen values. Five luminaires type in this research were selected based on the most popular and applicable lights in the educational environment like recessed downlight, direct and indirect pendant linear light, direct/indirect linear light, and direct recessed linear light.

- **Correlated color temperature**

As mentioned earlier, the correlated color temperature is one of the variables that could affect circadian lighting. To measure this effect, different CCTs were selected according to the preferable color temperatures range in schools 3000 K – 5000 K. Table 3 shows the selected CCTs to be studied in this research.

Table 3: The color correlated temperatures and its appearance. (Author 2020)

<table>
<tr><th>CCT</th><th>Appearance</th></tr>
<tr><td>3000 K</td><td>Warm white (Reddish)</td></tr>
<tr><td>3500 K</td><td rowspan="3">Neutral white</td></tr>
<tr><td>4000 K</td></tr>
<tr><td>5000 K</td></tr>
</table>

- **Light beam distribution**

Light beam distribution or light distribution curve can give useful information about the light, where designers and architects can select the best choice according to the space function and the light level required on the work plane. There are wide ranges of beam angles that are available and applicable to use in the classroom environment. In this research, a narrow beam (25-30-degrees), flood (>45-dgrees), and wide flood (>80-dgree) ware used in order to distinguish between their effects on both horizontal and vertical planes.

3.10 Software selection and validation

There are different software that can be used to design for electrical light, such as AGi32, IES, Revit, DIALux 4.13, and DIALux Evo. In this research, DIALux 4.13 was selected for the simulation due to its fixability, variation of luminaires selection, and the ability to export the detailed data of vertical calculation. The author is familiar with DIALux 4.13, which makes the simulation smooth and fast, therefore saving time. Moreover, DIALux 4.13 was validated by previous studies. (Mangkuto 2015), (Chen, Zhang & Du 2020), (van Hoof et al. 2009),

In order to present the data in a clear and easier way to understand, MATLAB software was selected to generate 3D plots using a special script as shown in Figure 10 to present the vertical calculation surfaces.

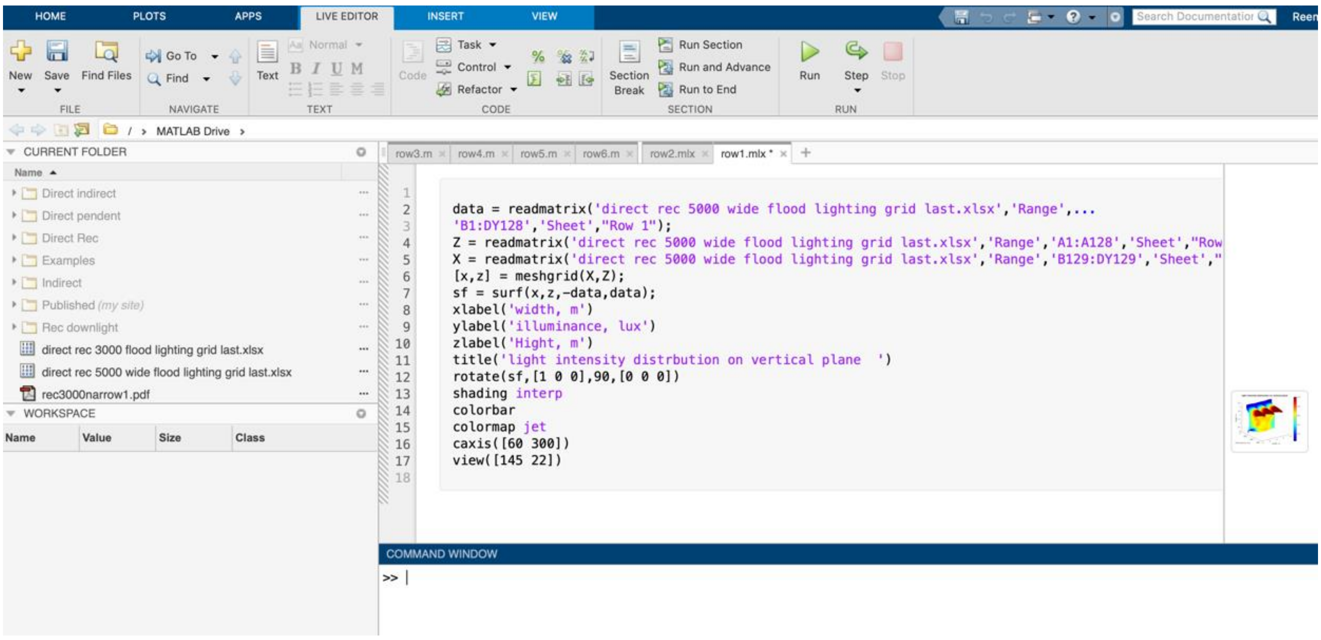


Figure 10: MATLAB script for 3D plot. (Author 2020)

3.11 Simulation model

The simulation model was conducted for typical classroom space for 30 students, measuring 10 m long and 8 m wide with celling Hight of 3.6 m, according to ADEC. The desks were arranged in 5 linear rows, and each row has six desks with a total of 30 desks in the space, modeled using DIALux 4.13 software as illustrated in Figure 11. The reflectance values were assigned to be 20%, 50%, and 80% for the floor, walls, and ceiling, respectively.

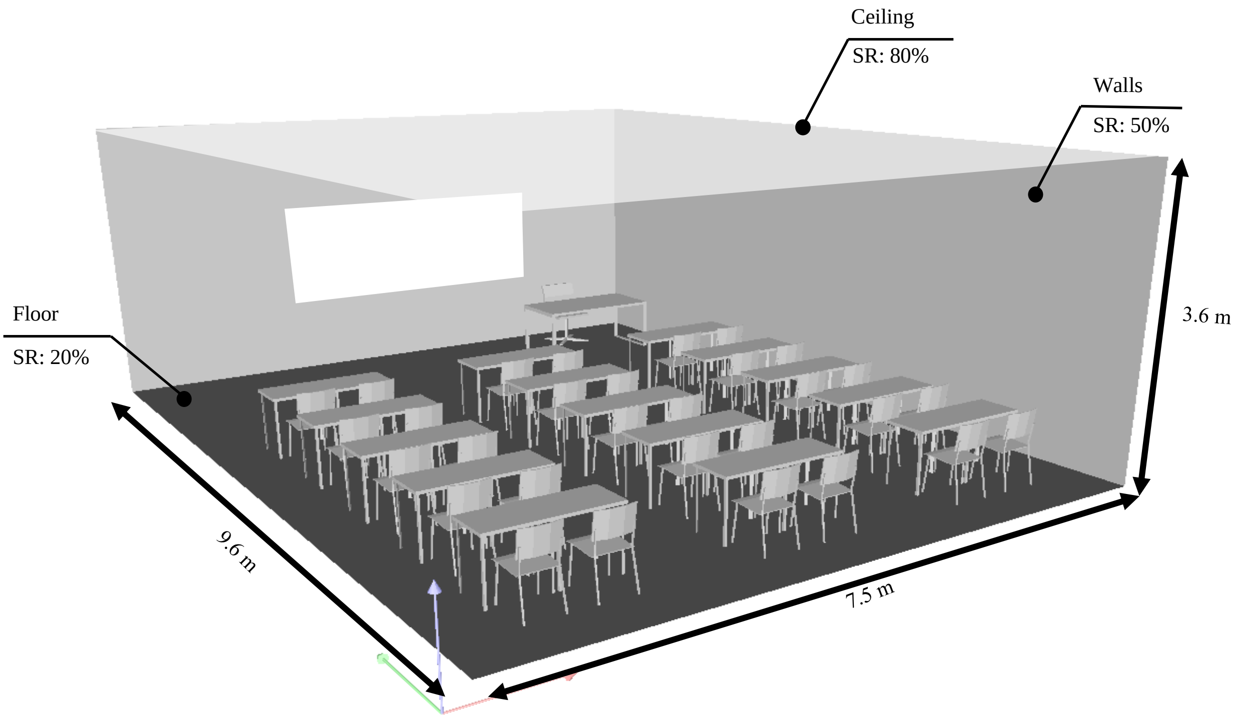


Figure 11: Classroom 3D model with furniture and reflectance values. (Author 2020)

3.11.1 Horizontal calculation surface

The calculation surfaces were added to measure the illuminance levels in the space, a horizontal calculation surface using 128X128 grid, on the working plane at 0.76 cm above finished floor level as shown in Figure 12 in order to maintain an average of 500 lux, which is the recommended E_H value in classrooms.

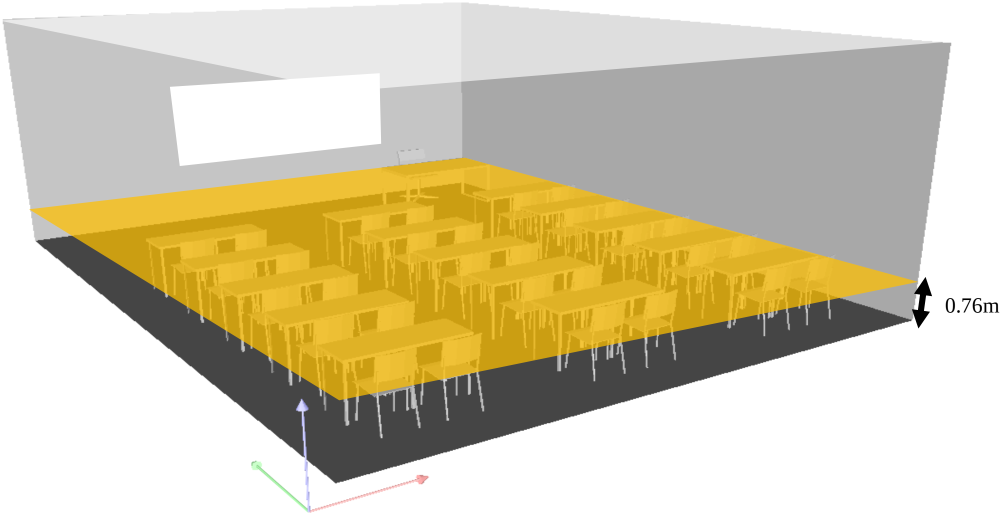


Figure 12: The horizontal calculation surface at 0.76m height. (Author 2020)

3.11.2 Vertical calculation surface

The research aims to study the effect of vertical illuminance on the occupants rather than the working plane; therefore, a total of 6 vertical calculation planes were placed according to the students' position and covering the full height of the space. The vertical calculation surfaces have a 128X128 calculation grid to obtain accurate and praised values. It was positioned to measure vertical illuminance values towards the teacher and the students' viewing angles as illustrated in Figure 13 and Figure 14.

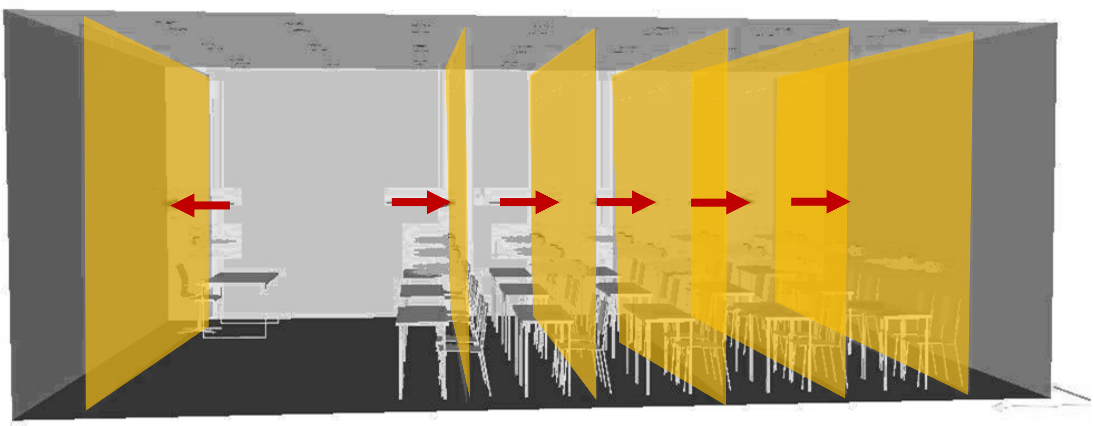


Figure 13: The vertical calculation surfaces showing the side of calculation. (Author 2020)

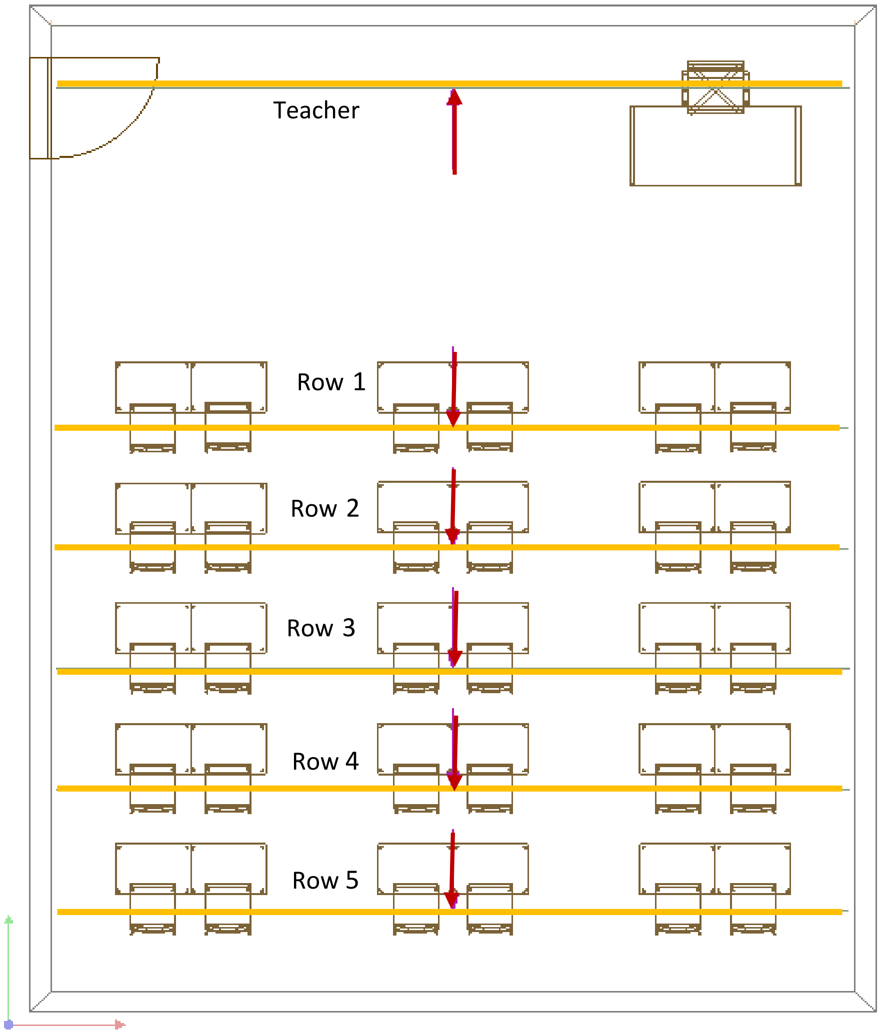


Figure 14: Plan view of the vertical calculation surfaces. (Author 2020)

3.11.3 Vertical Calculation points

Vertical calculation points were set at 1.2 m (The eye level) in order to measure the vertical illuminance in lux received by students' eyes. The calculation points were positioned in every chair in the classroom to demonstrate how the light will affect the students according to their position. Moreover, a total of 13 calculation points for each position were obtained with an interval of 15 degrees to give a full understanding of students' different viewing angles toward the whiteboard as shown in Figure 15.

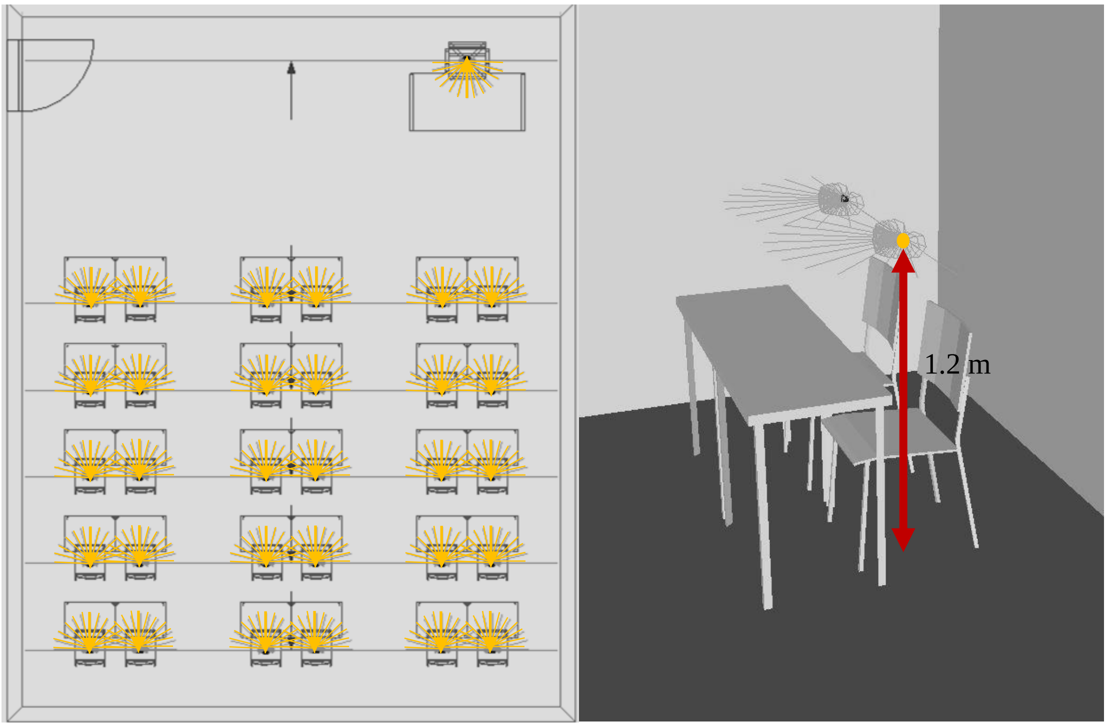


Figure 15: The calculation points distribution in the classroom at 1.2 m (eye level) height. (Author 2020)

3.12 luminaires arrangement and selection

In order to select the best type of luminaires, five different types were examined: recessed downlight, direct pendant linear light, indirect pendant linear light, direct/indirect linear pendant light, and direct recessed linear light. The luminaires were arranged to be in a fixed position in all the cases according to the furniture layout as shown in Figure 16. Each type of luminaire could have different inputs in terms of CCTs and light beam distribution according to market availability. The main criteria for selecting the luminaires depended on achieving the recommended value on the horizontal plane (working plane), which is 500lux. To achieve the recommended value, Watts and lumen values were selected accordingly to meet the target. It was notable that some manufacturers were changing the lumen value of the luminaires to change their CCTs while others kept the same lumen value regardless of the change in CCTs.

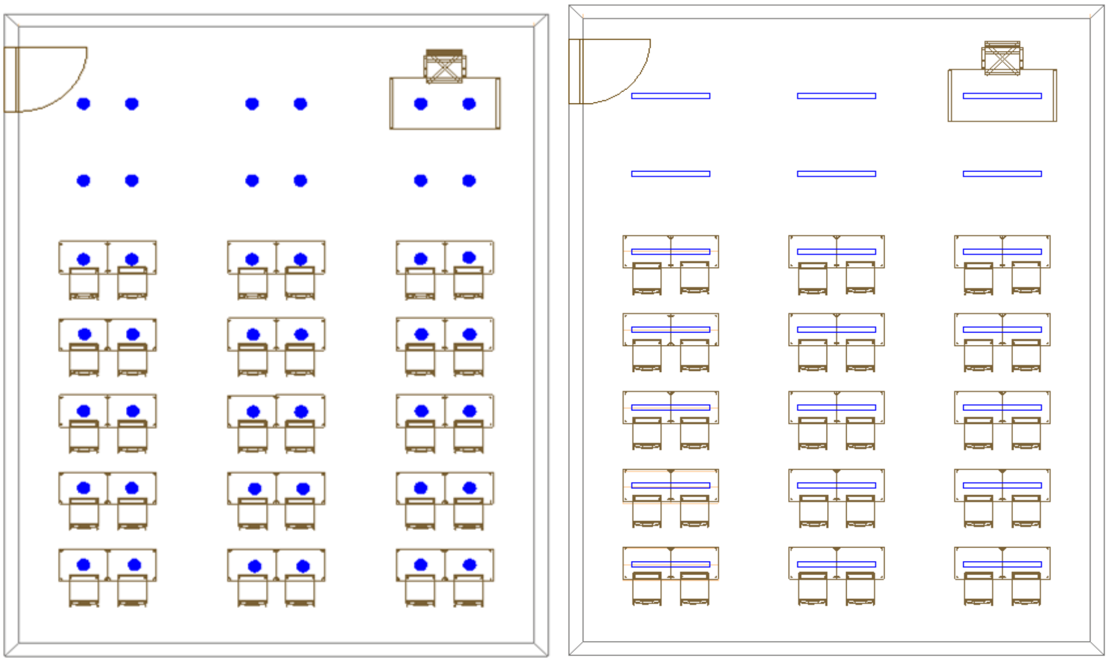
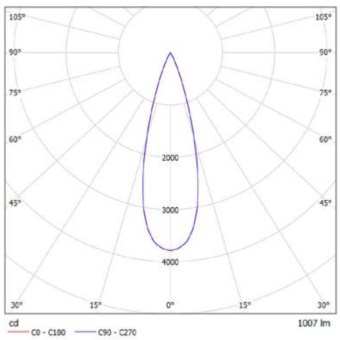


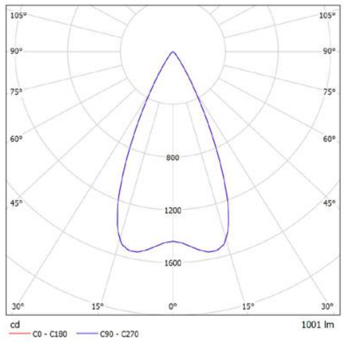
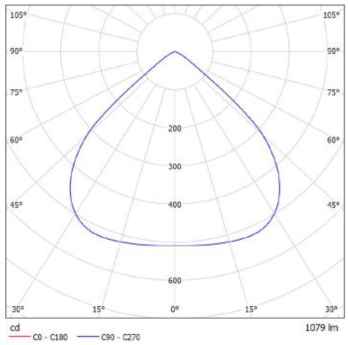
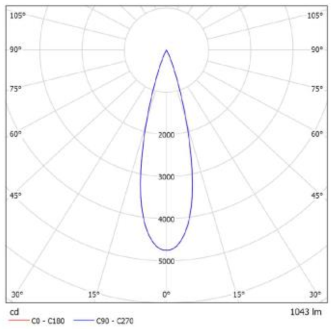
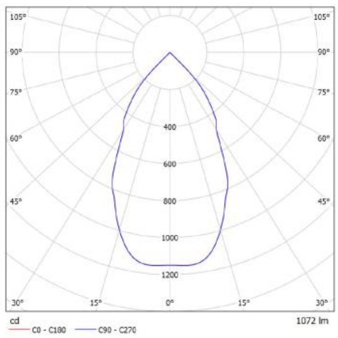
Figure 16: The different lighting distribution reflected ceiling plans for the classroom mode, from left to right (a) downlight distribution, (b) linear light distribution. (Author 2020)

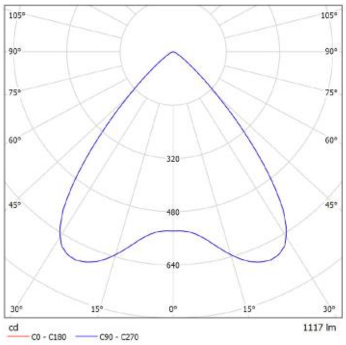
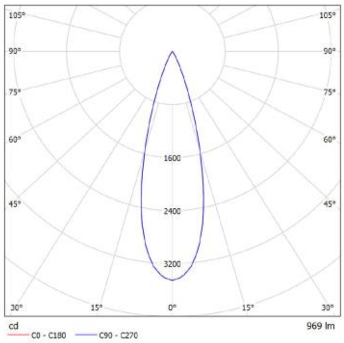
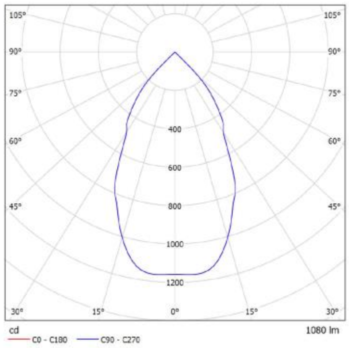
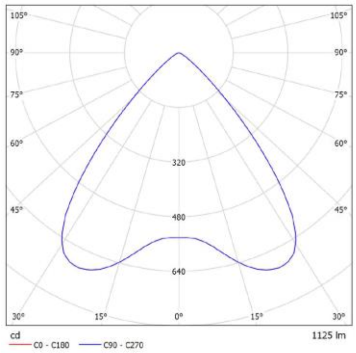
3.12.1 Recessed downlight

Recessed downlight is one of the most popular luminaires types that been used in classrooms. These luminaires are fixed on the ceiling to provide a light that falls directly into the working plane. In order to examine the effect of different correlated color temperatures on the circadian light, three main CCTs were selected (3000 k, 3500 k, 4000k). However, for each CCT three different light beam distributions were examined which are listed in Table 4.

Table 4: The Recessed downlight cases. (Author 2020)

Recessed downlight		
CCT	**Light beam distribution**	
3000 k	**Narrow**	

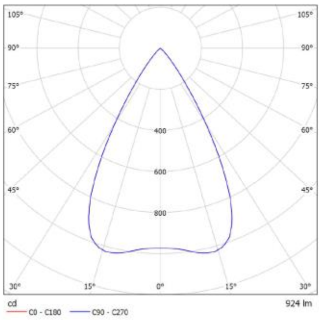
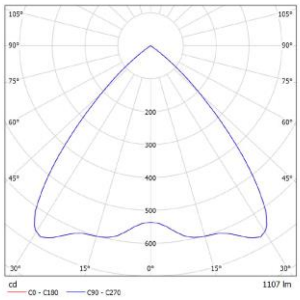
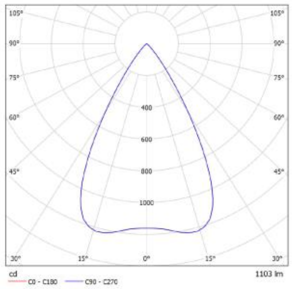
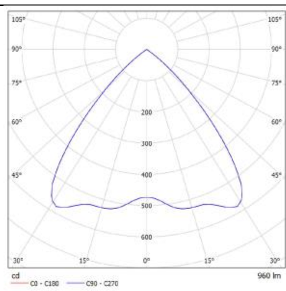
<table>
<tr><td rowspan="2"></td><td>Flood</td><td>
</td></tr>
<tr><td>Wide Flood</td><td>
</td></tr>
<tr><td rowspan="2">3500 k</td><td>Narrow</td><td>
</td></tr>
<tr><td>Flood</td><td>
</td></tr>
</table>

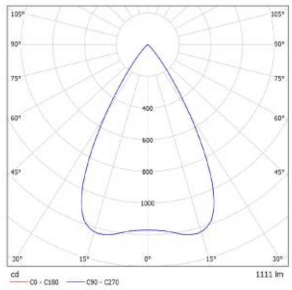
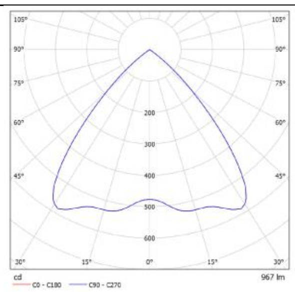
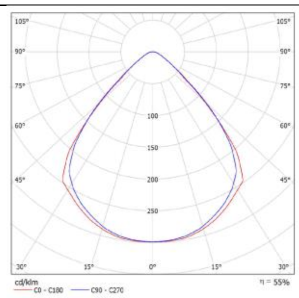
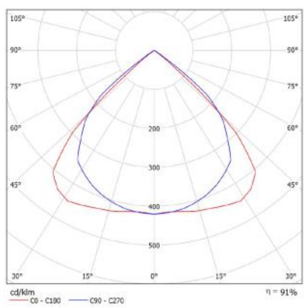
	Wide Flood	
4000 k	**Narrow**	
	Flood	
	Wide Flood	

3.12.2 Direct pendant linear light

The direct pendant linear light was examined and suspended at a height of 2.6 m for four different CCTs, which are 3000 K, 3500 K, 4000 K, and 5000 K. In term of light beam distribution, only flood and wide flood were tested because there is no narrow beam for this type of luminaries, Table 5 shows the different cases for direct pendant linear light.

Table 5: The direct pendant linear light cases. (Author 2020)

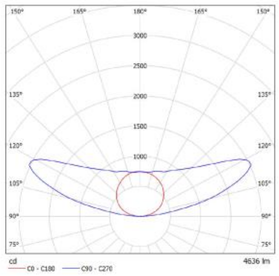
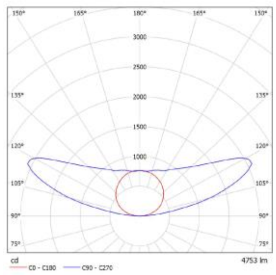
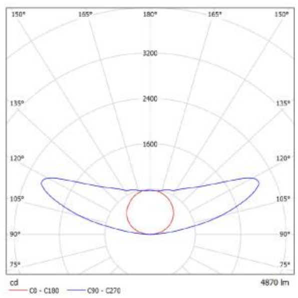
Direct pendant linear light		
CCT	**Light beam distribution**	
3000 k	**Flood**	
	Wide Flood	
3500 k	**Flood**	
	Wide Flood	

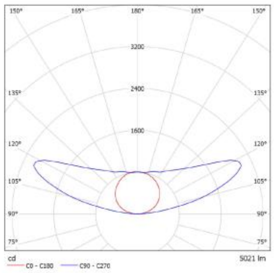
4000 k	Flood	
	Wide Flood	
5000 k	Flood	
	Wide Flood	

3.12.3 Indirect pendant linear light

For this type of lighting, the work plane received the reflected light indirectly from the ceiling and the walls to deliver a diffuse lighting effect, free of glare and uniform. The butterfly light beam distributions were simulated for the indirect pendant linear light in 3000 K, 3500 K, 4000 K, and 5000 K and suspended at a height of 2.6 meter, summarized in Table 6.

Table 6: Indirect pendant linear light cases. (Author 2020)

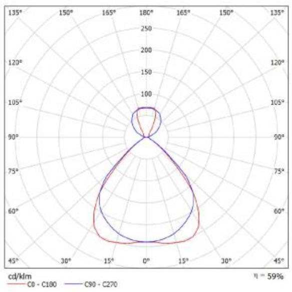
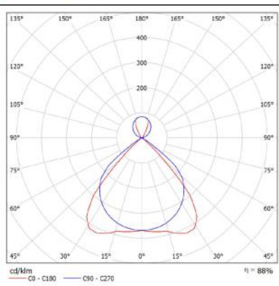
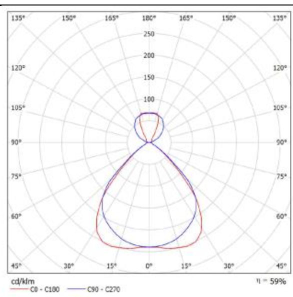
Indirect pendant linear light		
CCT	**Light beam distribution**	
3000k	**Butterfly**	
3500k	**Butterfly**	
4000k	**Butterfly**	
5000k	**Butterfly**	

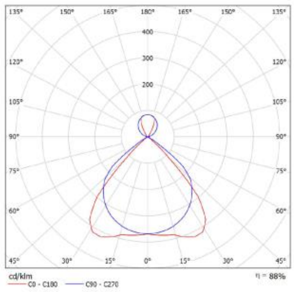
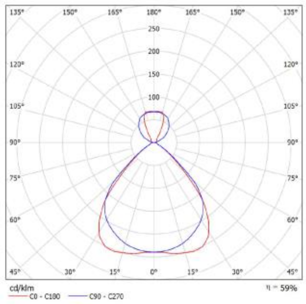
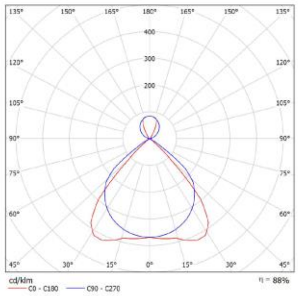
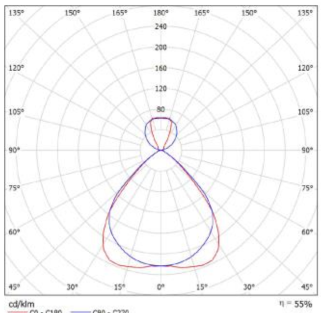
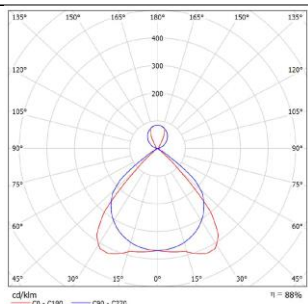
		

3.12.4 Direct / indirect linear pendant light

The direct/indirect light illuminates the work plane directly and indirectly, which creates a pleasant visual environment in the classrooms, making this type one of the highly acceptable types by users. In this research, four CCTs were selected with two types of light beam distributions (flood and wide flood) with a suspension height of 1 meter as shown in Table 7.

Table 7: Direct / Indirect pendant linear light cases. (Author 2020)

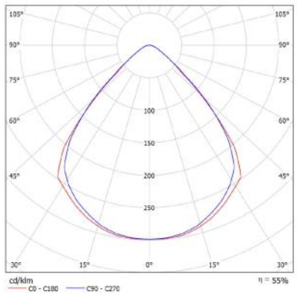
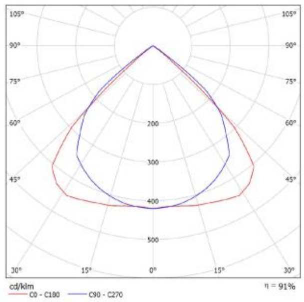
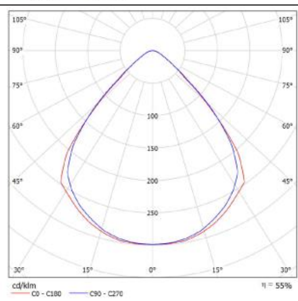
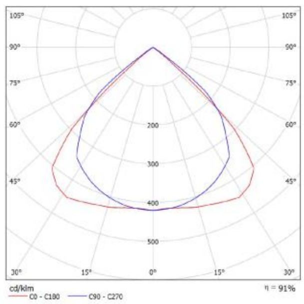
Direct/Indirect pendant linear light		
CCT	**Light beam distribution**	
3000 k	**Flood**	
	Wide Flood	
3500 k	**Flood**	

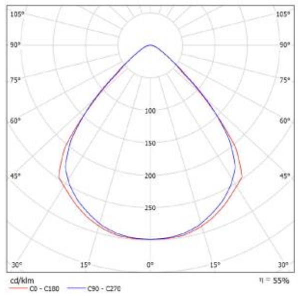
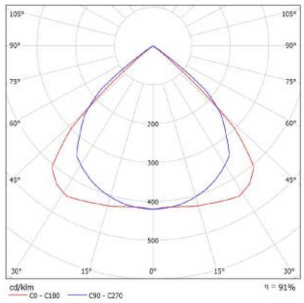
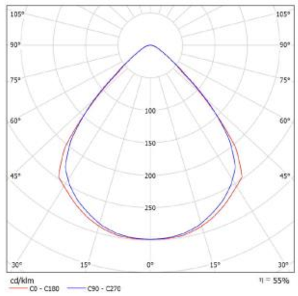
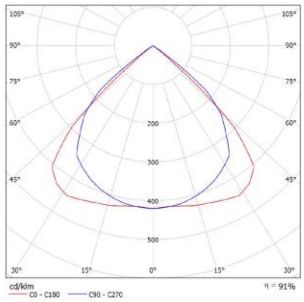
	Wide Flood	
4000k	**Flood**	
	Wide Flood	
5000k	**Flood**	
	Wide Flood	

3.12.5 Direct recessed linear light

The different cases for the direct recessed linear light are listed in Table 8 including four CCTs and two light beam distributions.

Table 8: Direct recessed linear light cases. (Author 2020)

Direct Recessed linear light		
CCT	**Light beam distribution**	
3000 k	**Flood**	
	Wide Flood	
3500 k	**Flood**	
	Wide Flood	

<table>
<tr><td rowspan="2">4000 k</td><td>Flood</td><td></td></tr>
<tr><td>Wide Flood</td><td></td></tr>
<tr><td rowspan="2">5000 k</td><td>Flood</td><td></td></tr>
<tr><td>Wide Flood</td><td></td></tr>
</table>

3.13 Summary of chapter 3

Chapter 3 reviewed previous studies done in the field of circadian light to explore the different research methodologies that were used, the pros and cons of each methodology, and discussed the selected research methodology for this research, which is computer simulation and the justification of this selection. Moreover, it provided a full view of the research's methodological framework, which started with a literature review and ended with recommendations for future studies. The list of variables was discussed with the reasons behind considering them, which are luminaries' type, CCTs and, light beam distribution. In addition, validated the use of DIALux 4.13 software in lighting simulation and MATLAB, which was chosen to create 3D plots that present the vertical illuminance data exported from DIALux 4.13. Finally, Reviewed the simulation model, set the permanent parameters, and explored all simulation cases that will be examined.

CHAPTER FOUR
Results and discussion

Chapter 4 Results and discussion

4.1 Introduction

The aim of this research is focused on examining and evaluating different luminarie types in their ability to deliver the recommended CS value in classrooms, as well as analyze their impact on the vertical illuminance. As mentioned previously, computer simulation was used in this research to model and produce the data needed to make a comparison between the luminaries that have different CCTs and light beam distribution. This chapter discusses and compares vertical and horizontal illuminance results obtained from DIAlux, and the 3D plots of the vertical illuminance distributed in the classroom that plotted using MATLAB to give a clear view of how light affects the vertical illuminance. Moreover, a CS calculator developed by LRC (Thayer 2020) will be used to find the CS value delivered by the different types of luminaries.

4.2 Simulation results and discussion

4.2.1 Recessed downlight

- **Recessed downlight, Narrow beam distribution**

The rendered 3D perspective simulation of the recessed downlight with a narrow beam is shown in Figure 17 where it is noticeable that the light is low near to the walls comparing to the tables. To achieve the recommended 500 lux on the working plane a luminaire with 1007 lumen and 12 Watt was used in the case of 3000 K as shown in Figure 18 (a) result in 513 lux as an average illuminance on the horizontal plane (E_H). It is clearly noticeable that the light is concentrated as expected where the luminaires are distributed since the narrow beam light has an angle of 30 degrees. Moreover, compared to the case of 3000K, 3500K and 4000K have a slight change which was noticed in the horizontal illuminance value (E_H) of 491 lux and 467 lux respectively as shown in Figure 18. It is important to highlight that the luminaires' Wattage and lumen have been changed in both cases in order to achieve the recommended E_H as following; for 3500 K (535W, 1043 lm) while for 4000 K (489W, 969 lm). In general, lighting manufacturers change the lumen values from luminaire to another in order to change the CCTs. To study how this light affect the students, a 3D plots to show the vertical illuminance value with respect to height (Z-axis) and width (Y-axis) of the classroom were used, the results of the vertical surfaces calculations for 6 vertical planes (1 teacher row and 5 student rows), Figure 19 shows the 3D vertical illuminance for downlight cases with different CCTs, where it is noticeable that all the CCTs perform in the same manner, with a higher vertical illuminance in the case of 3500K because the luminaire used in this case has a higher lumen value. Therefore, the case of 3000K will be presented in depth as a representative for 3500K and 4000K. Figure 20 and Figure 21 shows that the maximum vertical illuminance (E_v) value in the vertical calculation surface reached up to 262 lux at a height of 2.2 m then it start to decrease until it reaches around 200 lux at 1.2 m.

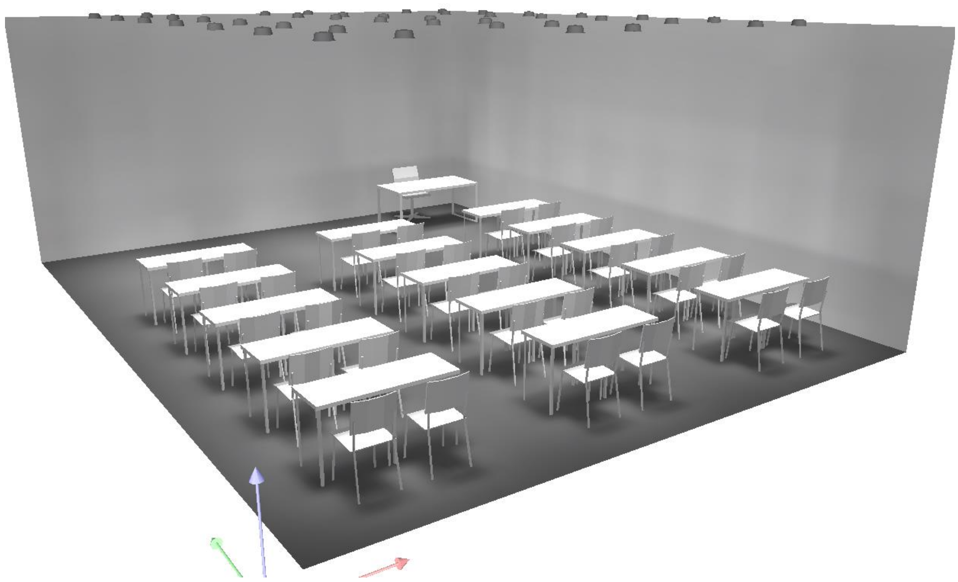
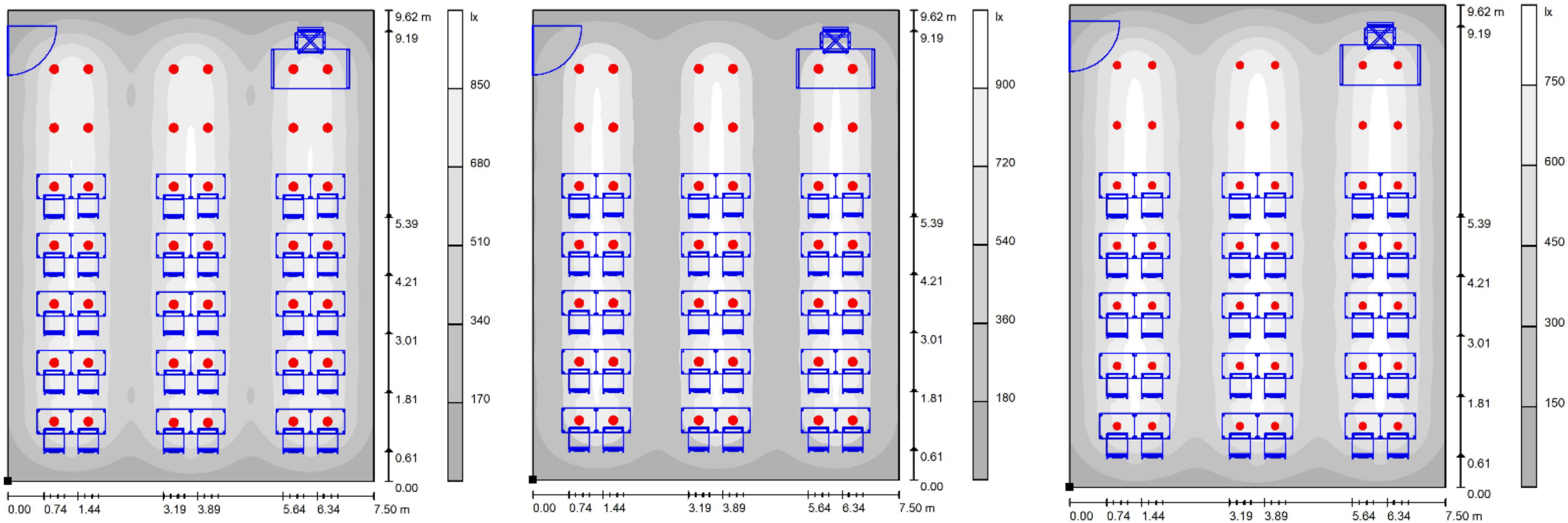


Figure 17: 3D perspective for recessed downlight with narrow beam. (Author 2020)



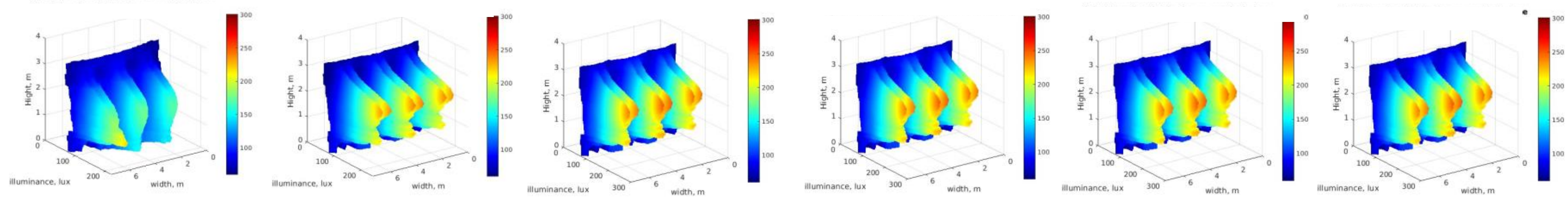
3000 K

3500 K

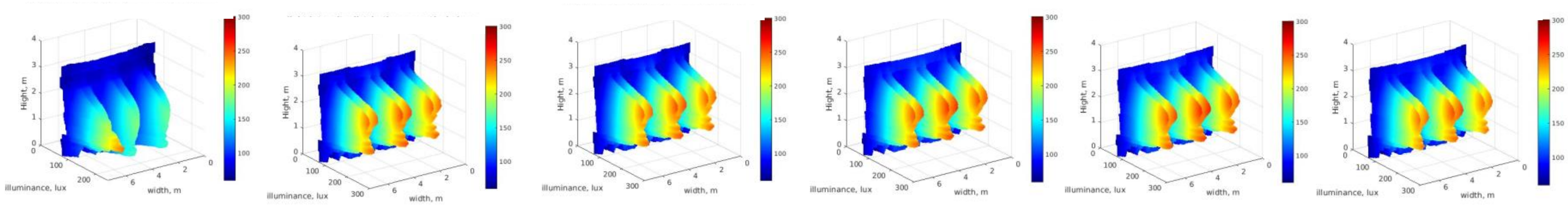
4000 K

Figure 18: The horizontal calculation surface at 0.76 m for narrow recessed downlight, from left to right (a) 3000 K (b) 3500 K (c) 4000 k (Author 2020)

3000K – Recessed downlight - Narrow



3500K – Recessed downlight - Narrow



4000K – Recessed downlight - Narrow

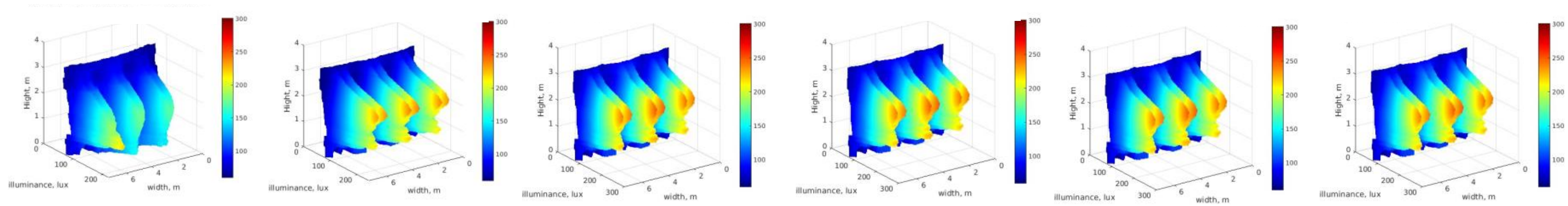


Figure 19: 3D vertical illuminance for 3000 K, 3500K and 4000K in the case of narrow recessed downlight., from left to right (a) Teacher vertical plane (b) Row 1 vertical plane (c) Row 2 vertical plane (d) Row 3 vertical plane (e) Row 4 vertical plane (f) Row 5 vertical plane. (Author 2020)

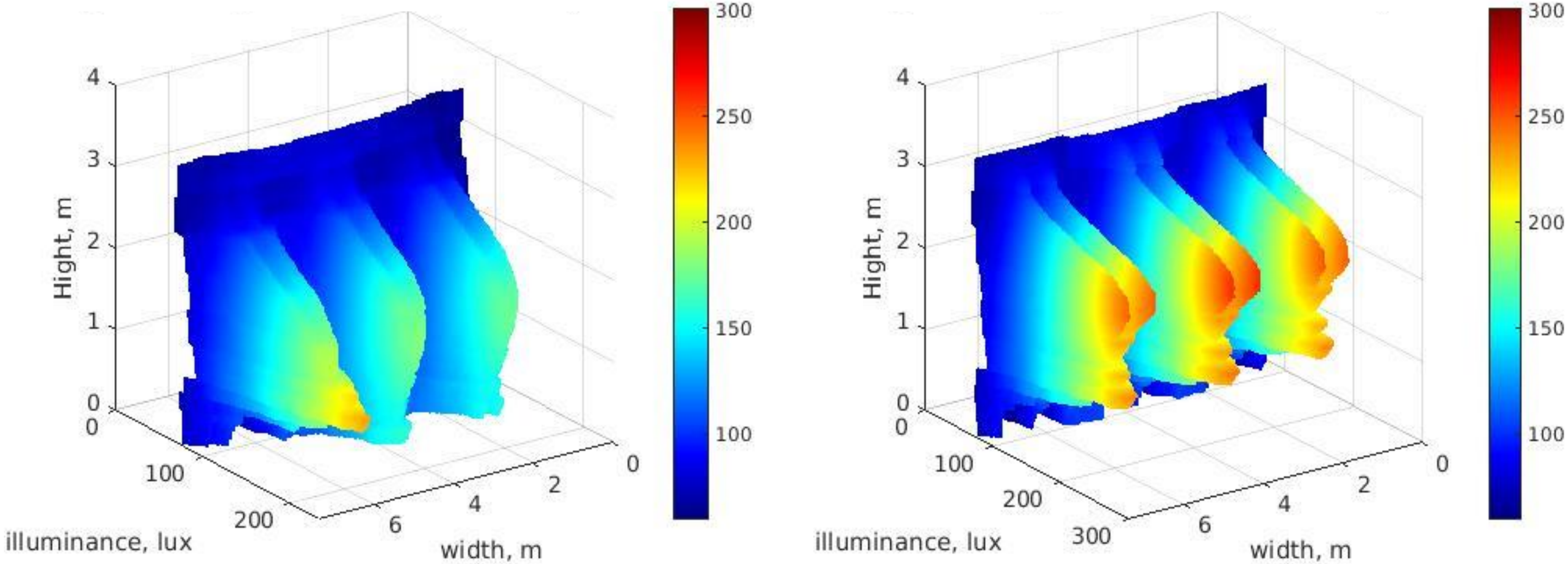


Figure 20: A representative 3D vertical illuminance for 3000 K in the case of narrow recessed downlight, from left to right (a) Teacher Vertical plane (b) representative vertical plane for row 1, 2, 3, 4, and 5 . (Author 2020)

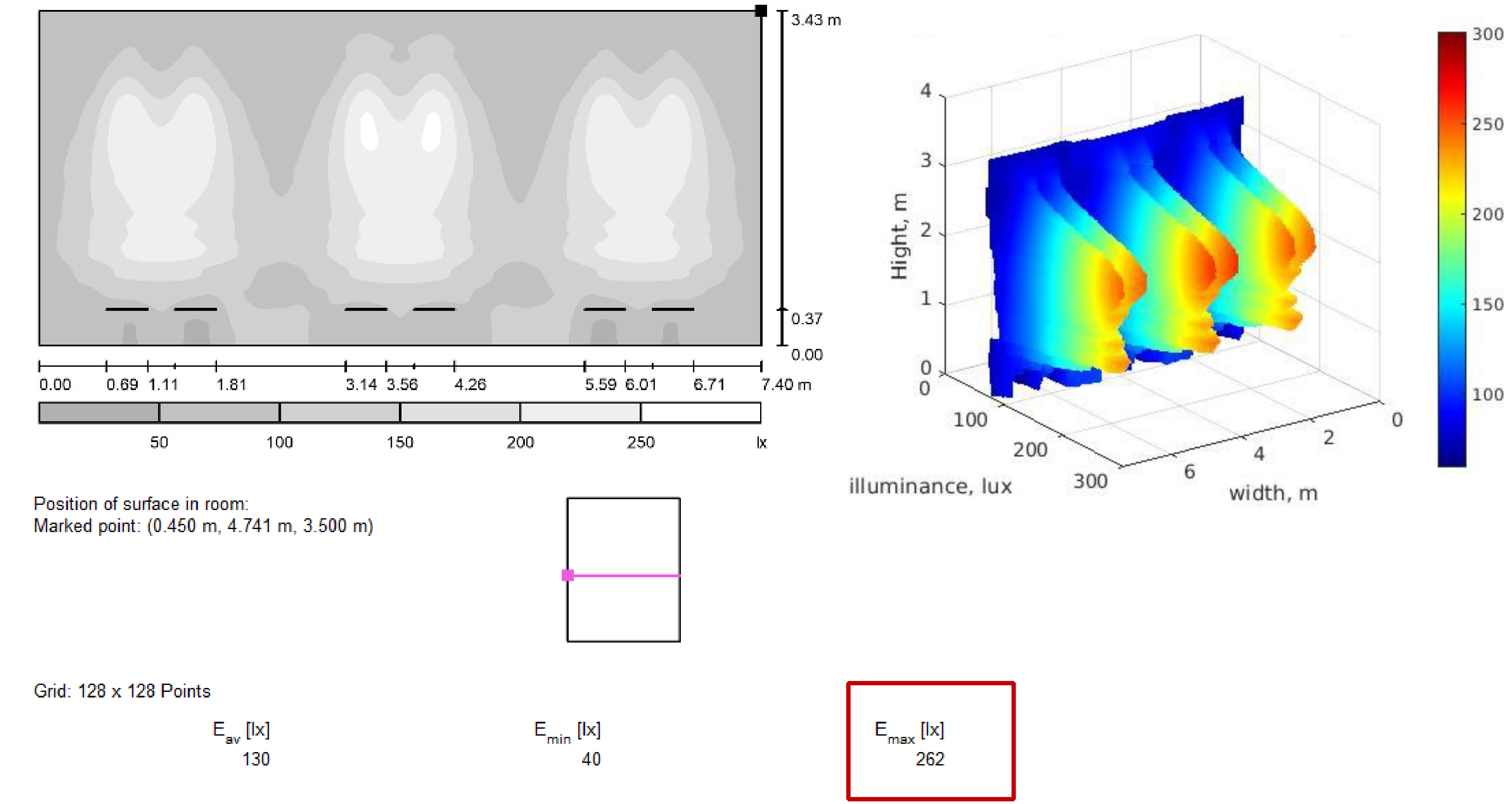


Figure 21: 2D and 3D vertical illuminance for one row of narrow recessed downlight showing the average, minimum and maximum vertical illuminance. (Author 2020)

As mentioned previously, the calculation points were distributed at a level of 1.2 m (eye level) to measure the vertical illuminance for students and the teacher received from the luminaires. All the simulations of the narrow beam with different CCTs perform the same; therefore, only one case will be presented Figure 22 shows the polar diagrams for the calculation points distributed in the classroom.The results from the calculation points clearly reflect the narrow beam behavior which has a small angle of distribution (30 degrees), where its noticed in Figure 23 in which the vertical illuminance values differ from the right to the left viewing angles in both position A and B which results in low uniformity ratio for the vertical illuminance along the different viewing angles. Position A has an average vertical illuminance of 168 lux with a uniformity ratio of 0.5, while B has an average of 162 and 0.4 uniformity ratio.The direct viewing angle toward the whiteboard in the highlighted case has a value of 203 lux for position A and 199 lux for position B, while the minimum value is 88 lux (A) and 67 lux (B) both at 90 degrees to the right side. For both A and B, the maximum value is 215 lux to the left side (at -30 degrees).

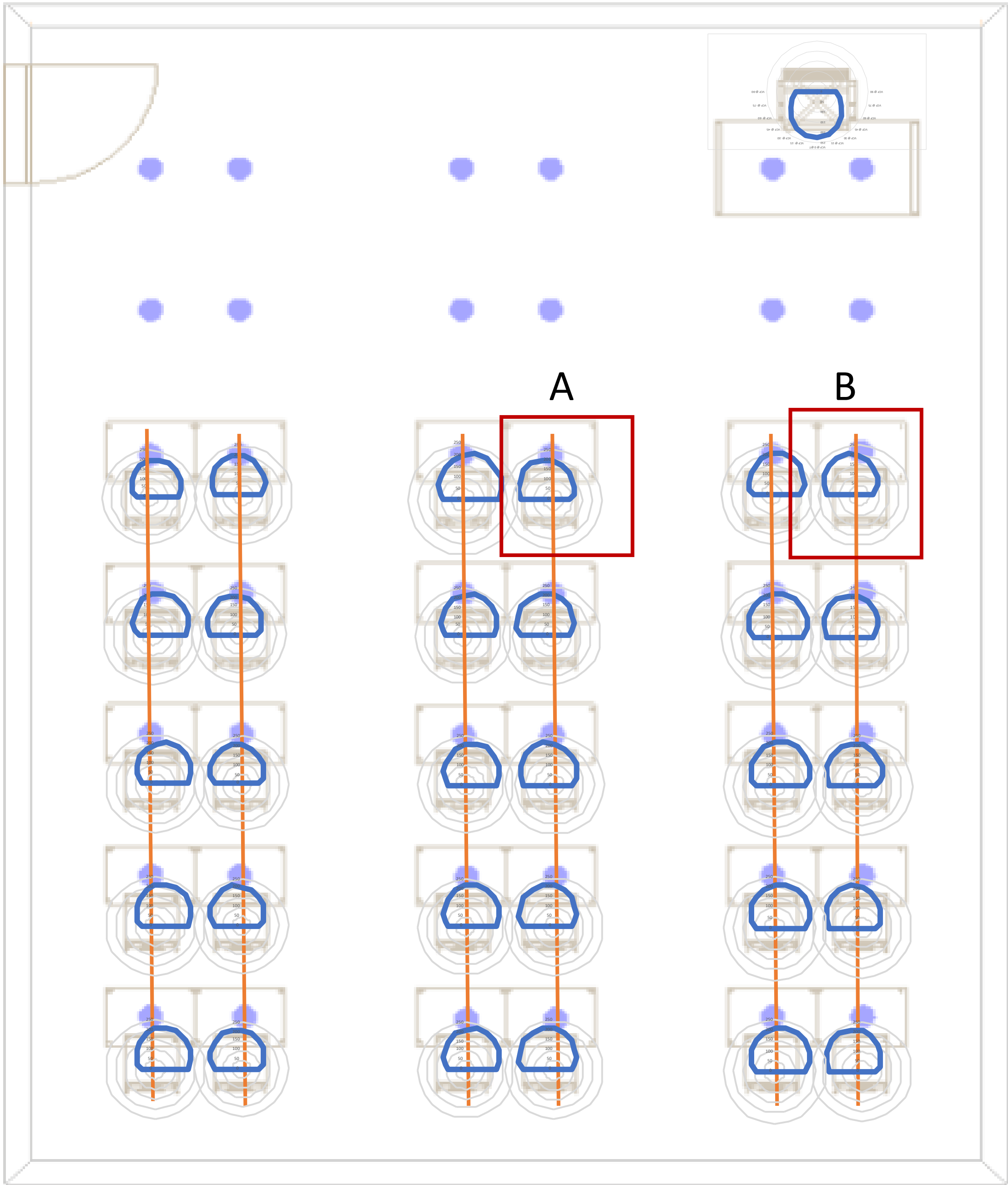


Figure 22: The calculation points polar diagrams of narrow recessed downlight distributed in the plan. (Author 2020)

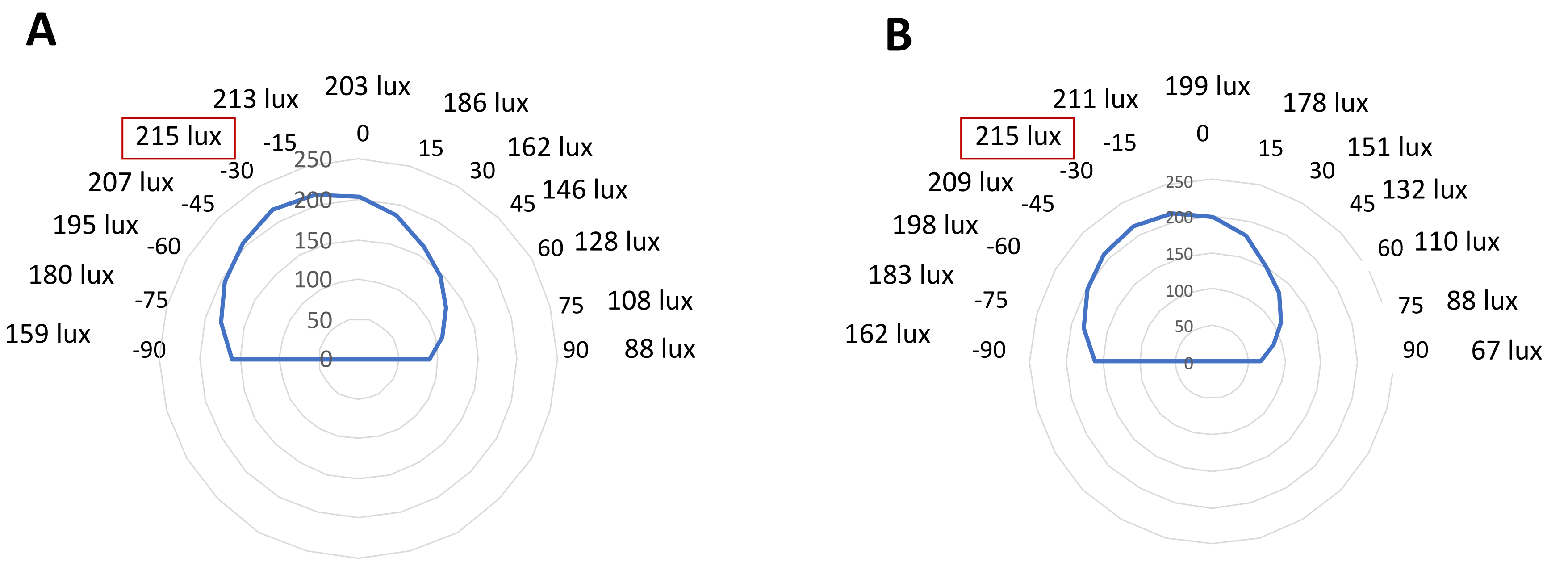


Figure 23: The polar diagram for a calculation points for recessed downlight, narrow beam distribution, 3000K, from left to right (a) At position A,(b)At position B (Author 2020)

- **Recessed downlight, Flood beam distribution**

In the case of the flood beam distribution it is noticeable from

Figure 24 that the light spread more than the case of the narrow beam, where the walls look brighter. Moreover, Figure 25 shows the recessed downlight of flood beam distribution for 3000 K, 3500 K, and 4000 K; it's important to highlight that all of them shows that the light spread in a wider angle than the narrow beam. In addition, both 3500 K and 4000 K have a similar light distribution on the working plane. In these cases, an average E_H of 491 lux, 504 lux, and 508 lux was achieved for 3000 K, 3500 K, and 4000 K, respectively.

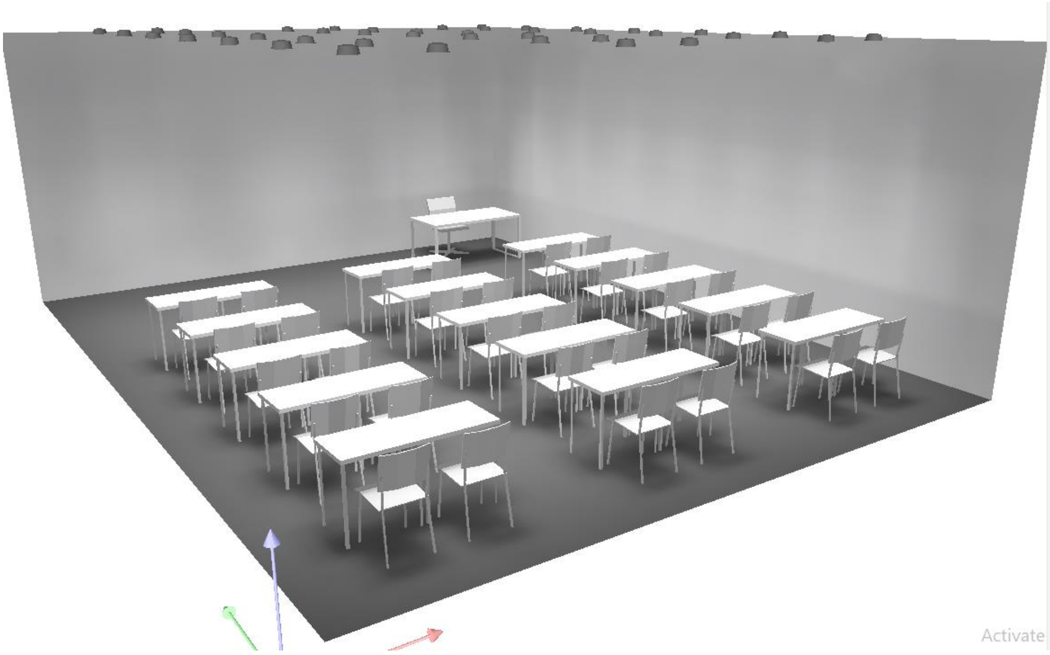
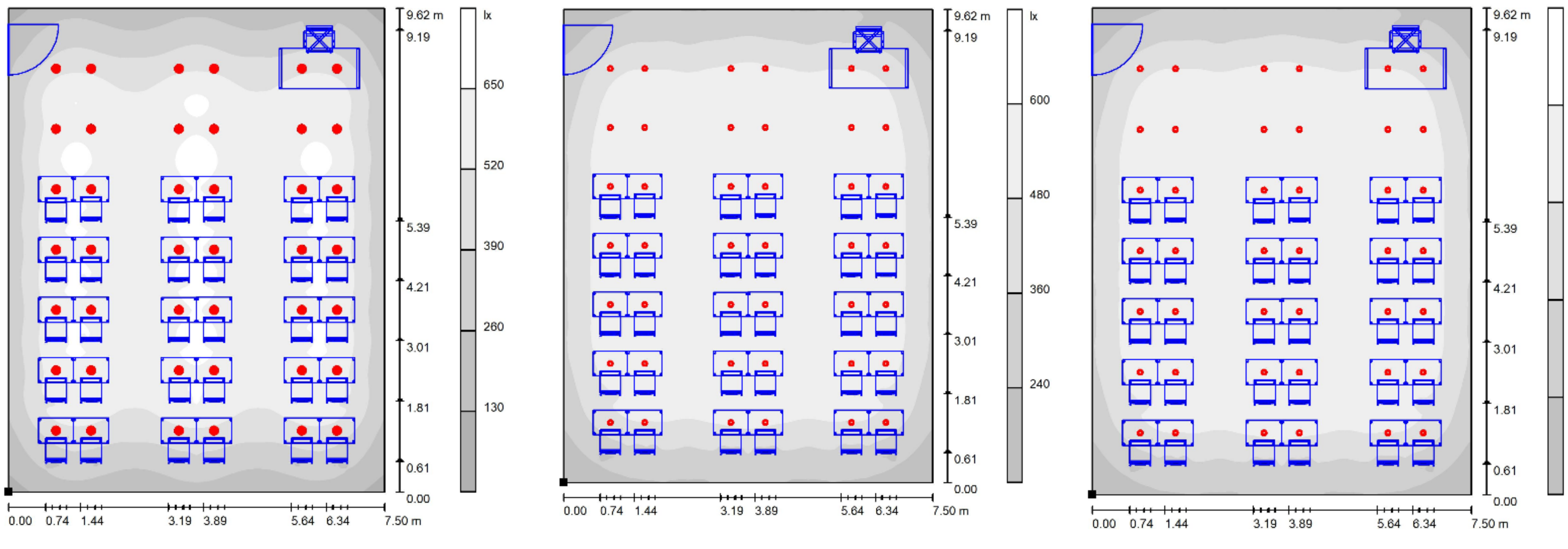


Figure 24: 3D perspective for recessed downlight with Flood beam. (Author 2020)



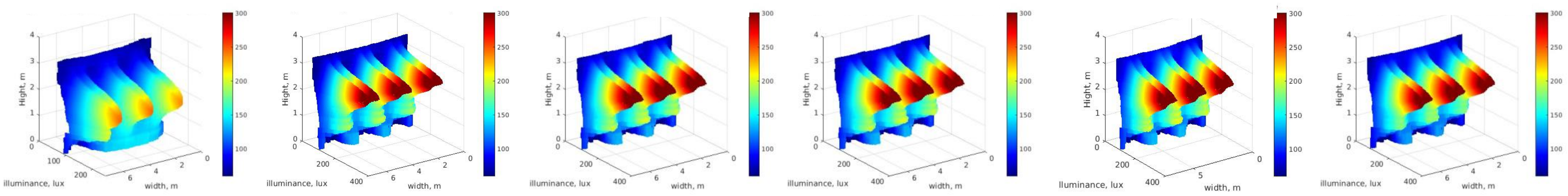
3000 K　　3500 K　　4000 K

Figure 25: The horizontal calculation surface at 0.76 m for flood recessed downlight, from left to right (a) 3000 K (b) 3500 K (c) 4000 k. (Author 2020)

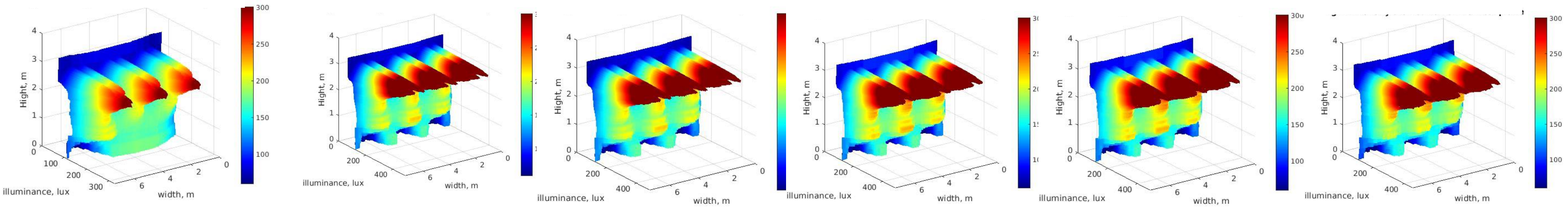
Figure 26 shows the vertical illuminance in a 3D plots, where it is shown that 3000K case results differ from both 3500K and 4000K cases, which seems to be more similar to each other. It is noticeable that 3000K has a lower maximum vertical illuminance (E_v) equal to 351 lux at 2.6 m shown in the detailed results from DIALux in Figure 27, while the cases of 3500K and 4000K have a higher E_v equal to 488 and 492 lux respectively at 3 m height which confirms the similarity of the results also as shown in and Figure 28 and Figure 29. By simulating the calculation points, all CCTs of the flood luminaire have the same performance in the distribution of the vertical illuminance along the different viewing angles, therefore 3000K case will be presented.

Figure 30 shows the calculation points polar diagrams plan, where it is noticed that in each position the semicircle is not symmetrical, therefore the students will receive different flux along the viewing angles. For example, Figure 31shows the values of the vertical illuminance in position A and B, where both of them have the maximum vertical illuminance at -30 degrees and a uniformity ratio of 0.6 and 0.5 for position A and position B, respectively.

3000K – Recessed downlight - Flood



3500K – Recessed downlight - Flood



4000K –Recessed downlight - Flood

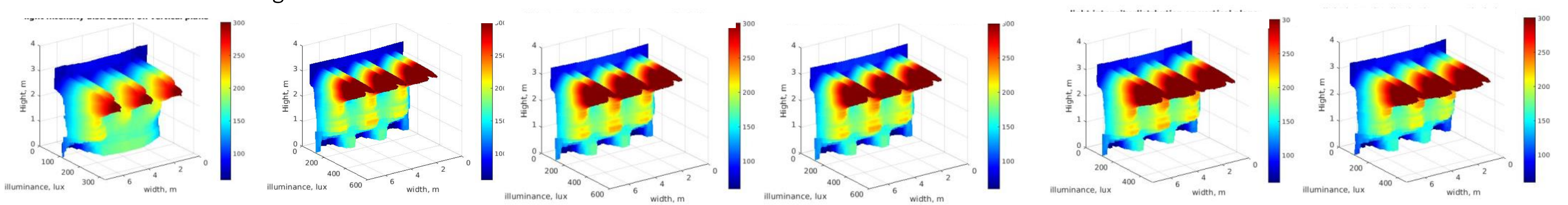


Figure 26: 3D vertical illuminance for 3000 K, 3500 K, 4000 K in the case of flood recessed downlight. from left to right (a) Teacher vertical plane (b) Row 1 vertical plane (c) Row 2 vertical plane (d) Row 3 vertical plane (e) Row 4 vertical plane (f) Row 5 vertical plane. (Author 2020)

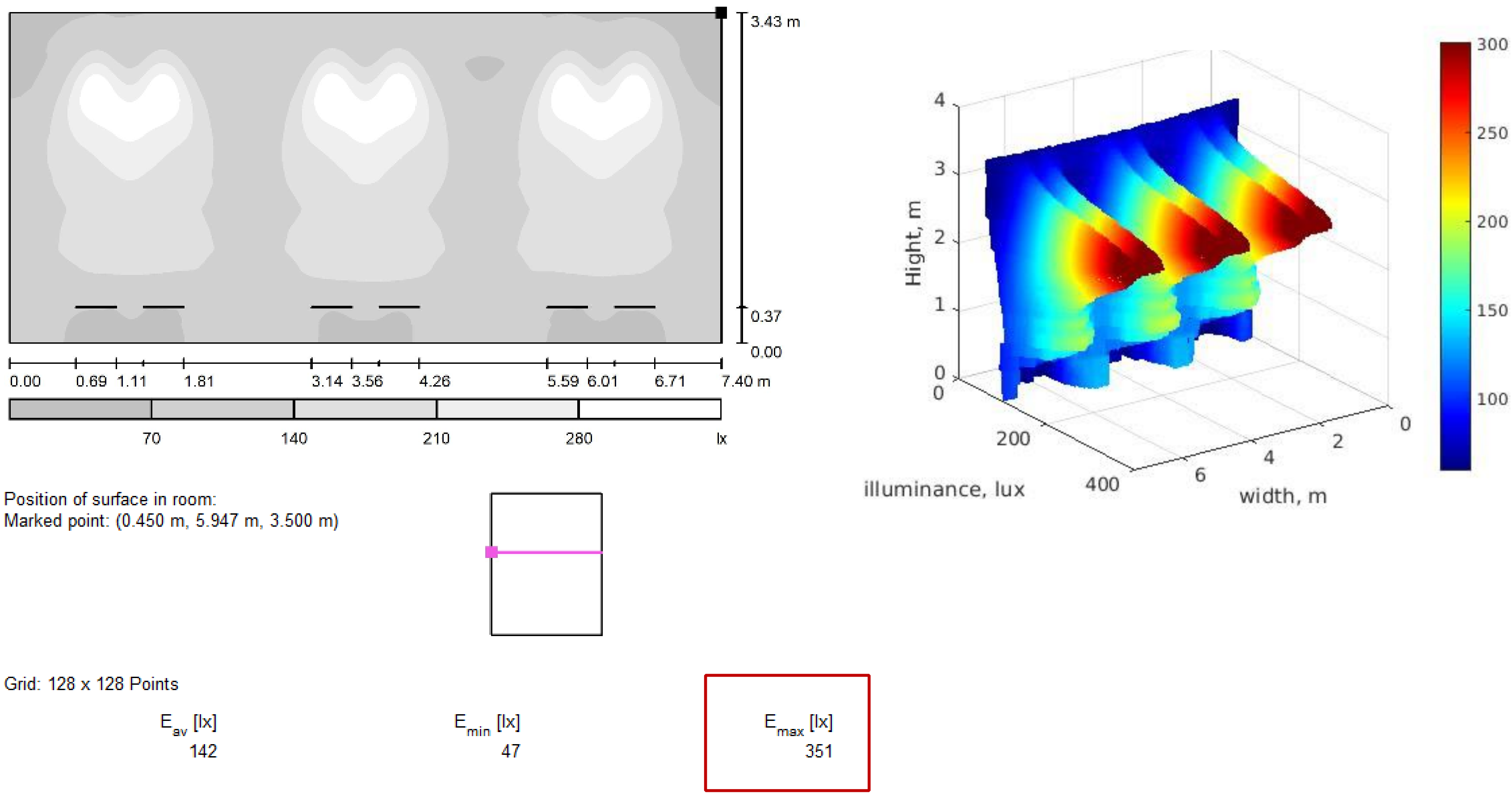


Figure 27: 2D and 3D vertical illuminance for row 1 in the case of Recessed downlight, flood, 3000 K showing the average, minimum and maximum illuminance. (Author 2020)

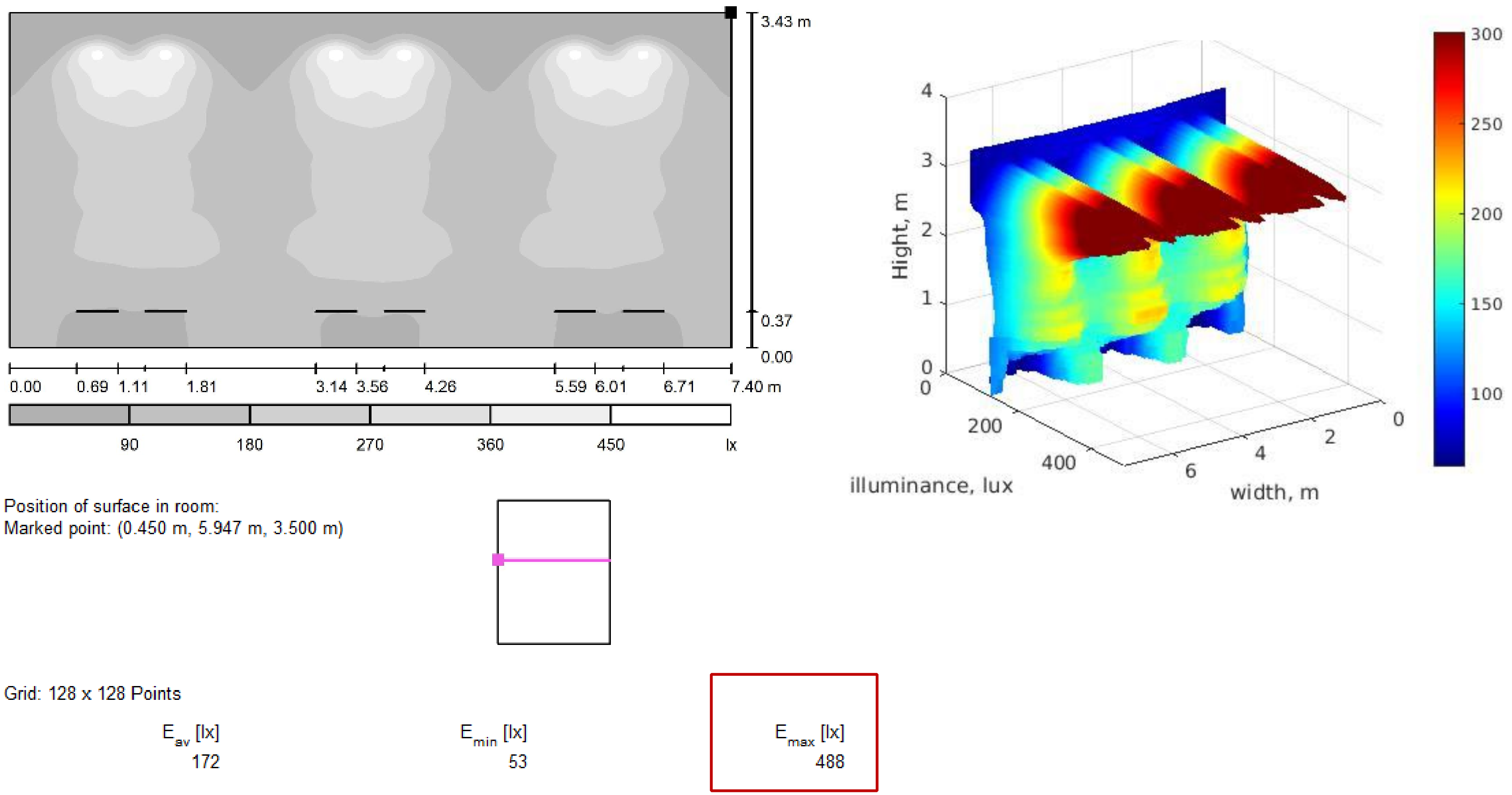


Figure 28: 2D and 3D vertical illuminance for row 1 in the case of Recessed downlight, flood, 3500 K showing the average, minimum and maximum illuminance. (Author 2020)

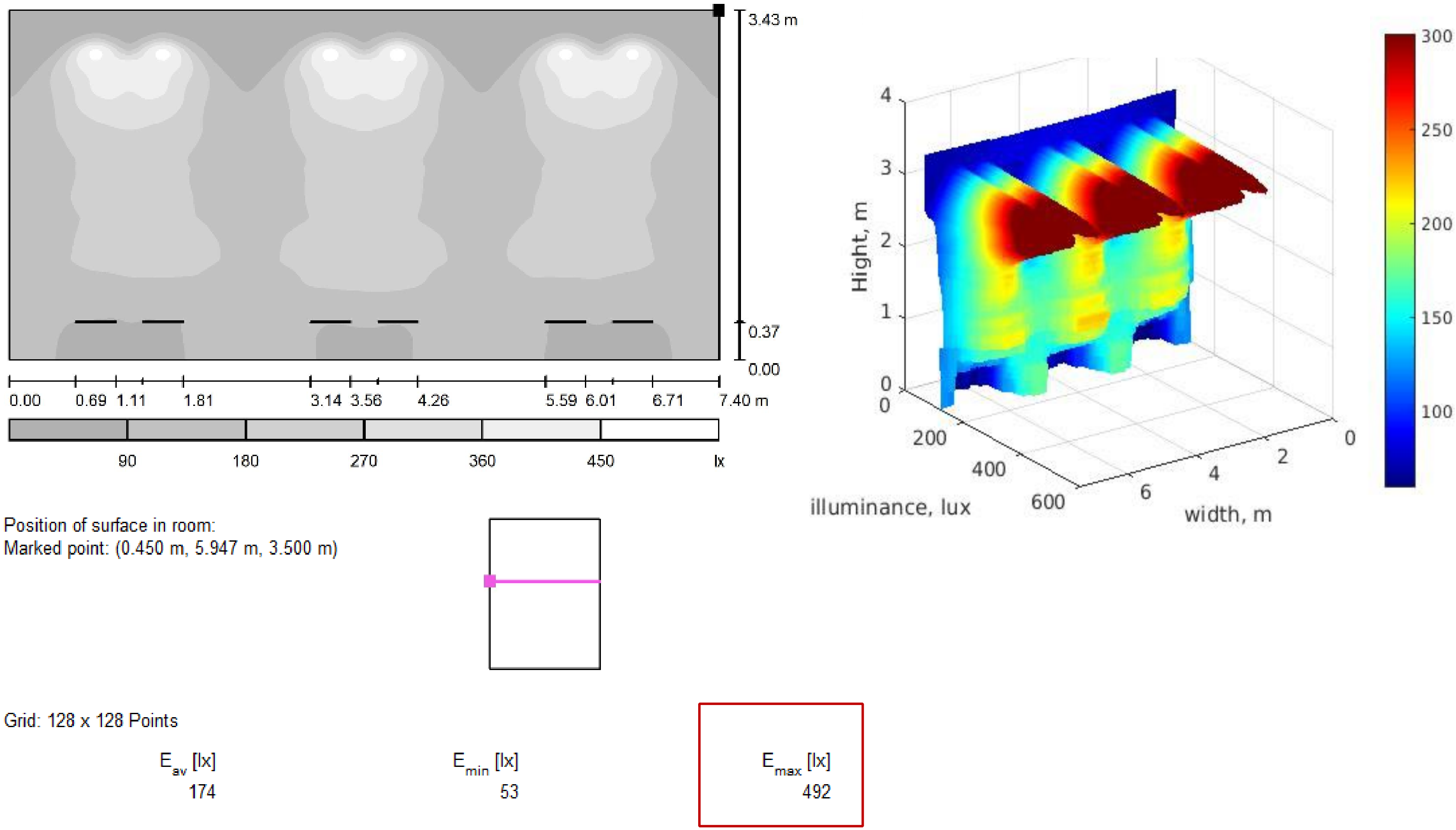


Figure 29: 2D and 3D vertical illuminance for row 1 in the case of Recessed downlight, flood, 4000 K showing the average, minimum and maximum illuminance. (Author 2020)

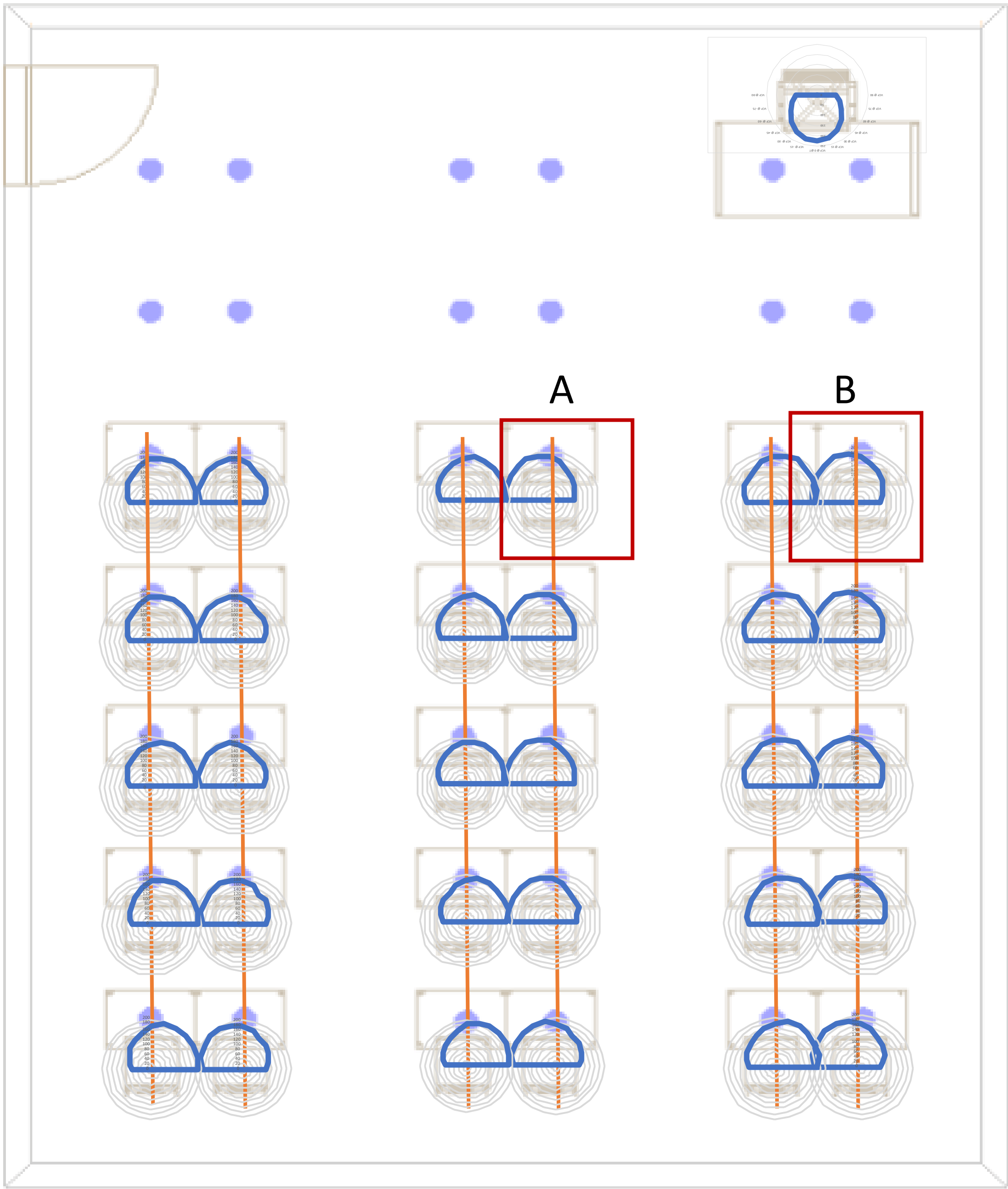


Figure 30: The calculation points polar diagrams of flood recessed downlight. (Author 2020)

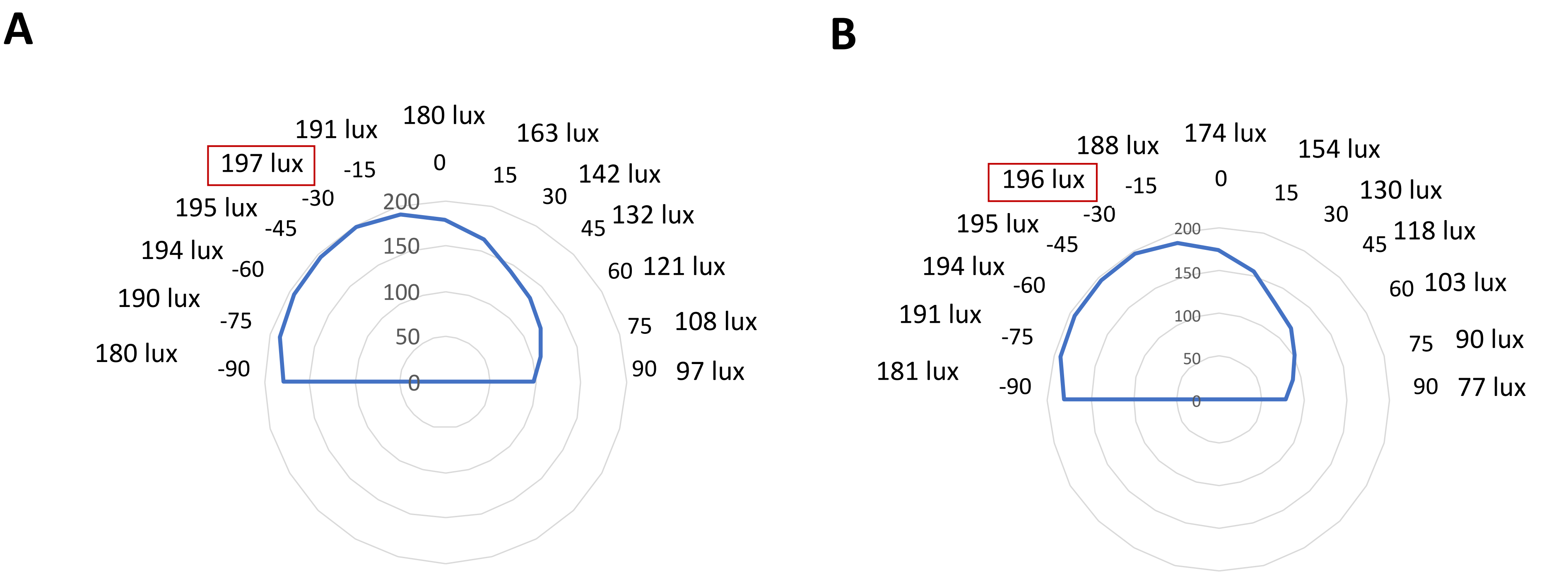


Figure 31: The polar diagram for a calculation points for recessed downlight, Flood beam distribution, 3000K, from left to right (a) At position A,(b)At position B (Author 2020

- **Recessed downlight, Wide Flood beam distribution**

In the wide flood distribution the angle of distribution is more than 80 degrees, therefore the light is spread out in the space as shown in Figure 32. Average horizontal illuminance on the working plane (Figure 33) was achieved in the different CCTs as follows: 467lux, 496, and 499 for 3000K, 3500K, and 4000K, respectively. Figure 34 shows the vertical illuminance of the wide flood recessed downlight for 3000K, 3500K, and 4000K. It is obviously shown that all of the CCTs cases have the same light behavior, where the maximum values of the vertical illuminance are all at a height of 3.2 m. However, a slight change noticed in the case of 3000K where the light reached a higher value at a lower level comparing to other scenarios as shown in Figure 35 and Figure 36. For example, a vertical illuminance at 1.2 m in the case of 3000K has a value of 244 lux, while at the same position in 3500K and 4000K it has a value of 235 and 237, respectively. This may be occurred because of the higher lumens in the case of 3000K comparing to 3500K and 4000K.

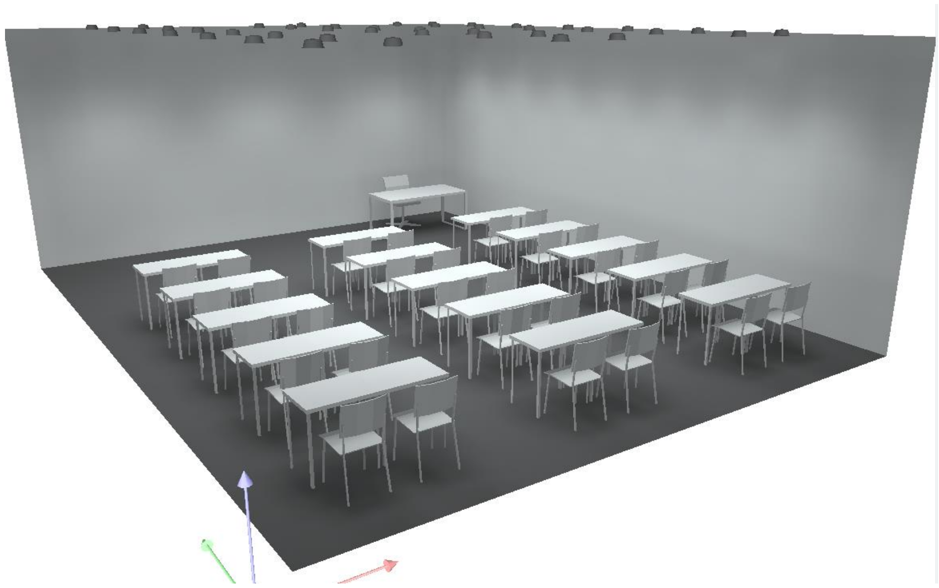


Figure 32: 3D perspective for recessed downlight with wide flood beam. (Author 2020)

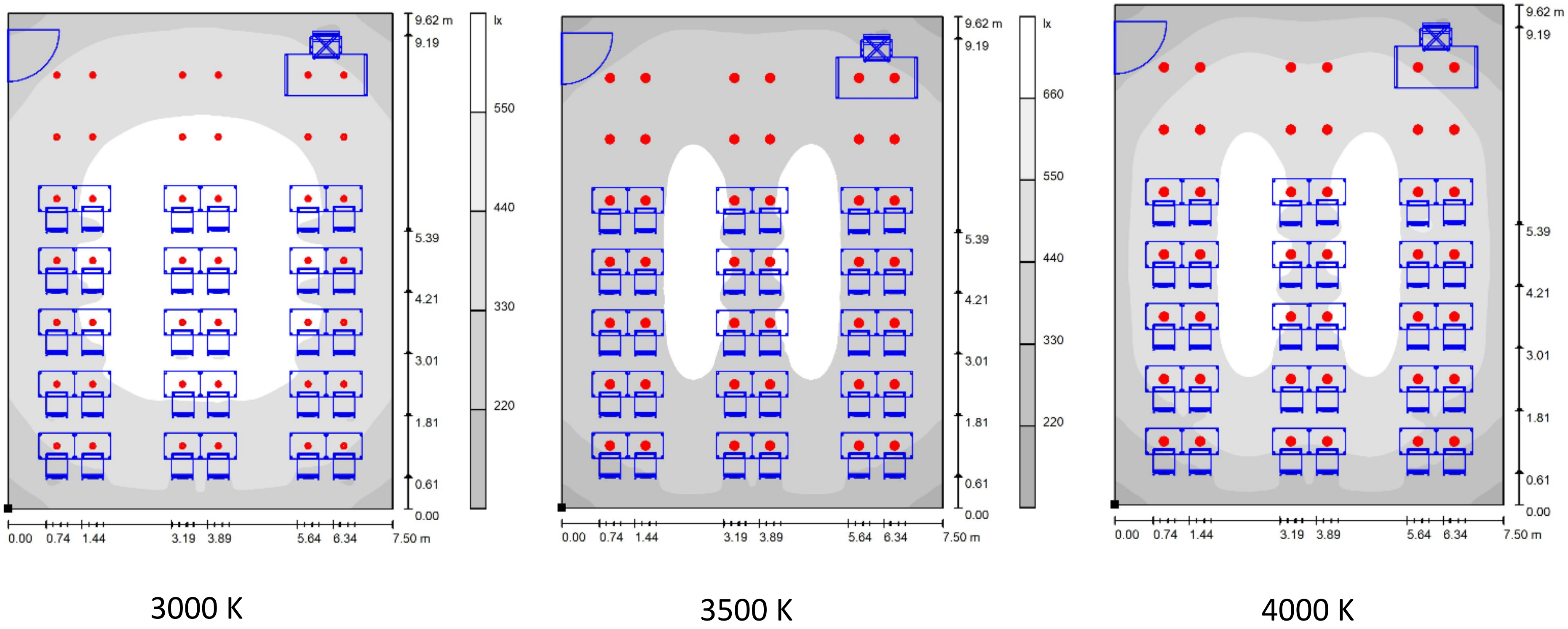
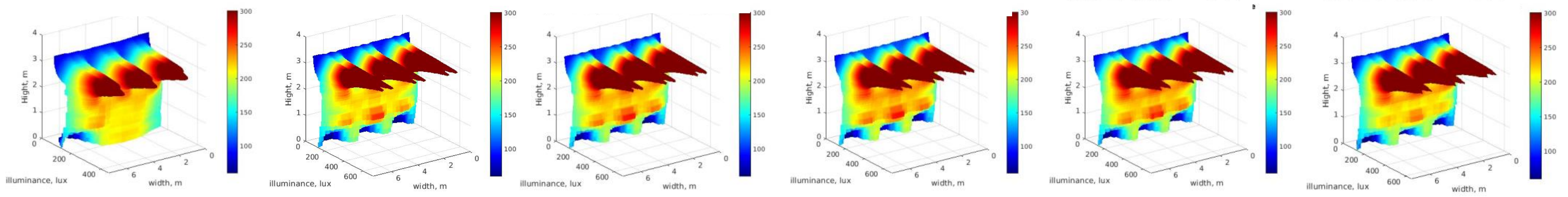
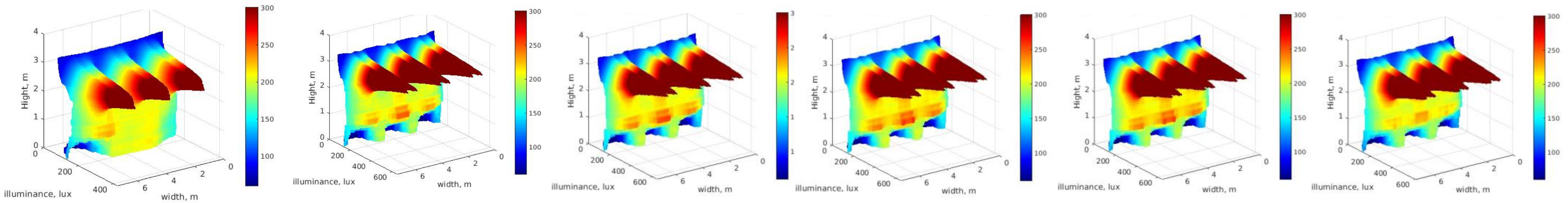


Figure 33: The horizontal calculation surface at 0.76 m for wide flood recessed downlight, from left to right (a) 3000 K (b) 3500 K (c) 4000 k (Author 202

3000K – Recessed downlight – Wide Flood



3500K – Recessed downlight - Wide Flood



4000K –Recessed downlight - Wide Flood

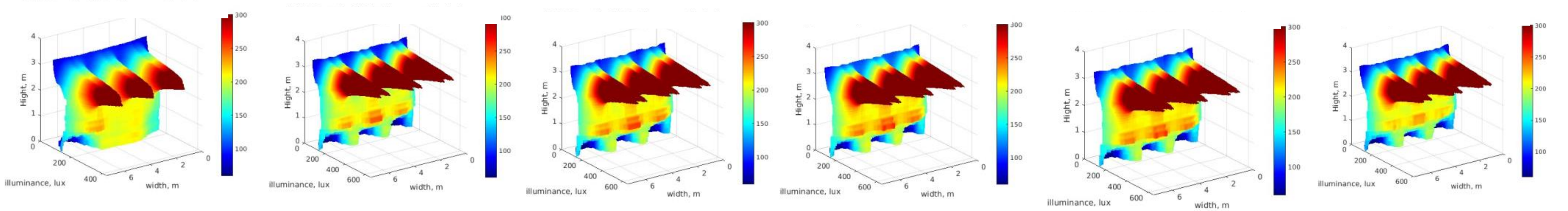


Figure 34: 3D vertical illuminance for 3000 K, 3500 K, 4000 K in the case of wide flood recessed downlight. from left to right (a) Teacher vertical plane (b) Row 1 vertical plane (c) Row 2 vertical plane (d) Row 3 vertical plane (e) Row 4 vertical plane (f) Row 5 vertical plane. (Author 2020)

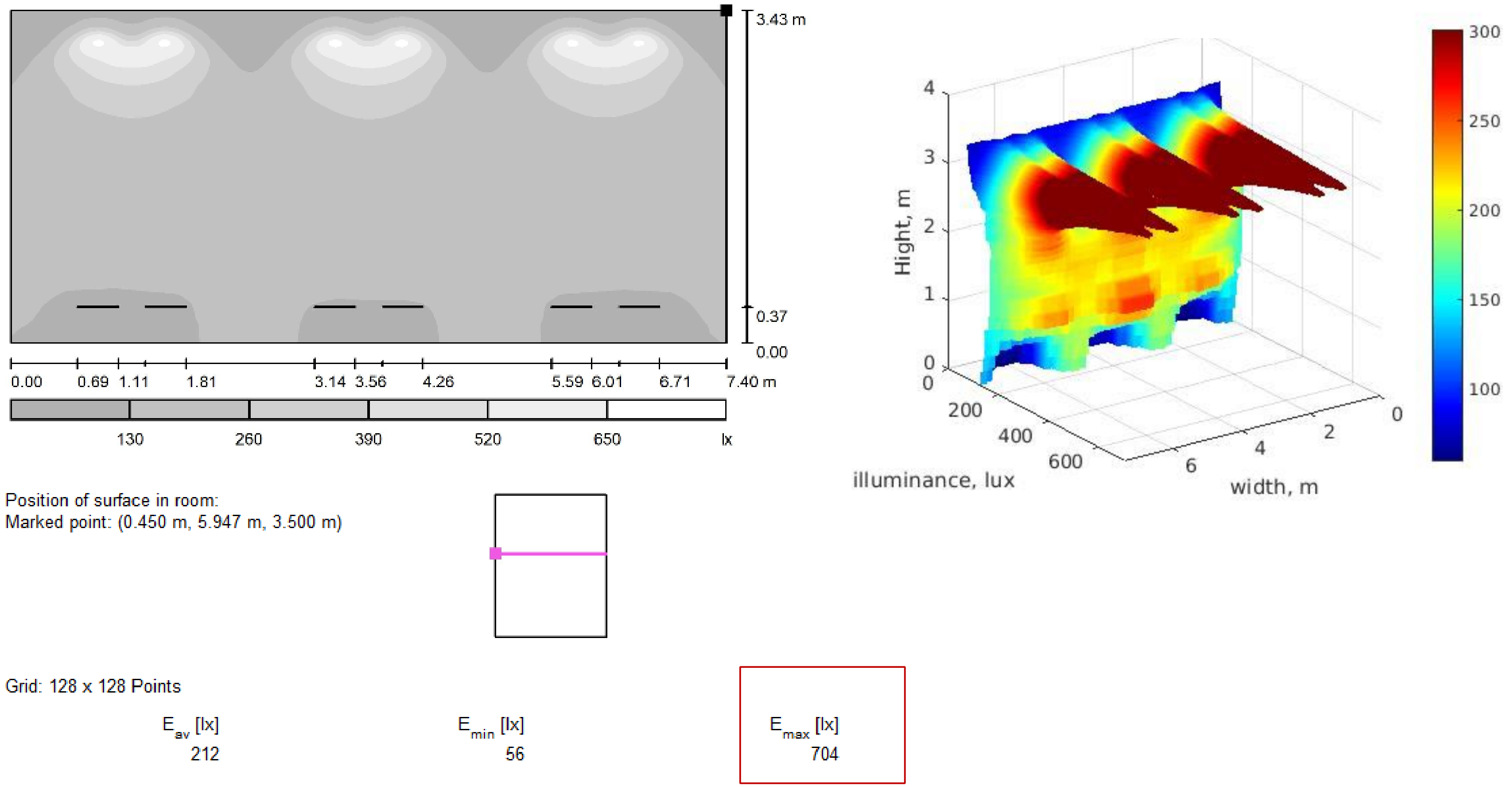
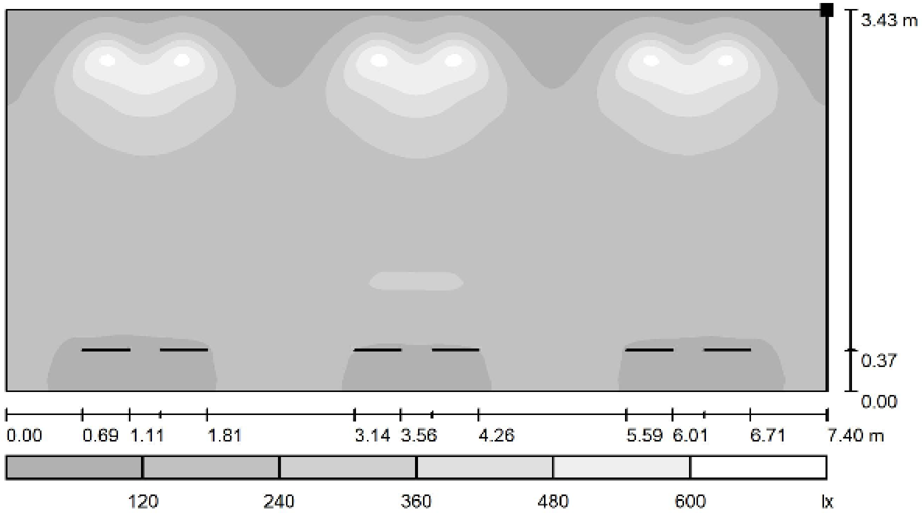
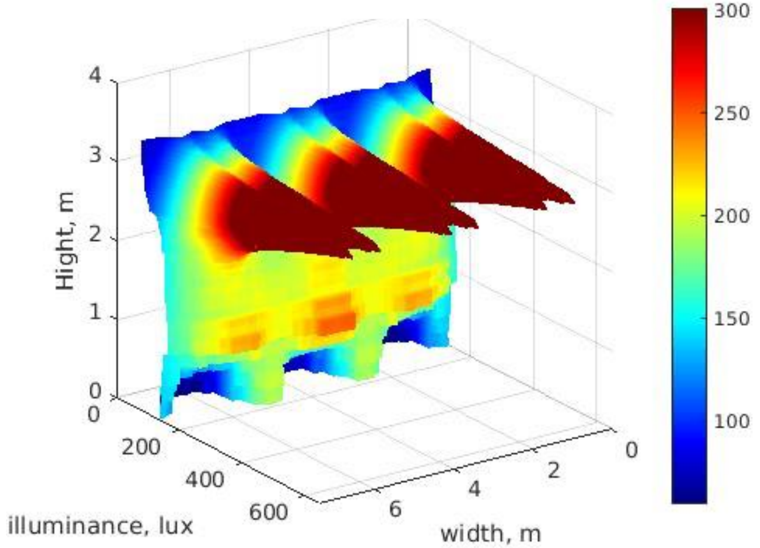
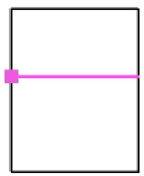


Figure 35: 2D and 3D vertical illuminance for one row in the case of wide flood Recessed downlight, flood, 3000 K showing the average, minimum and maximum illuminance. (Author 2020)





Position of surface in room:
Marked point: (0.450 m, 5.947 m, 3.500 m)



Grid: 128 x 128 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]
206	58	645

Figure 36: 2D and 3D vertical illuminance for one row in the case of wide flood Recessed downlight, flood, 3500 K showing the average, minimum and maximum illuminance. (Author 2020)

Because of the high similarity between calculation points results of all cases 3000K, 3500K, and 4000K, one calculation points plan was chosen to represent the rest (Figure 37). It is noticeable that the vertical illuminance values in the middle area (A) has a symmetrical semicircle where the students in this area receives the same flux from all viewing angles, unlike the corners (B) where there is a shift in the semicircle at the side of the wall. Furthermore, Figure 38 shows the values of the vertical illuminance at position A and B in details, where it is noticeable that A is more uniform with a uniformity ratio of 0.9 among the different viewing angles, while B shows that the high values is shifted to the left side which causes a low uniformity (0.58).

Comparing the calculation points at 3000K at position B of narrow, flood and wide flood distribution as shown in Figure 39 it is noticeable that the narrow beam distribution has the highest difference between the minimum and the maximum of vertical illuminance with a difference value of 148 lux , while both flood and wide flood has a lower difference with a value of 119 lux and 123 lux. Moreover, it shows that in the case of wide beam distribution, the vertical illuminance value at 90-degree is the highest comparing to narrow and flood beam distribution, because the luminaries in the wide flood case has a distribution angle that is bigger than 80 degrees which can cover the sides of the classroom, unlike the narrow beam which has an angle of 30 degrees only where that light is concentrated in a small area. It is important to highlight that the calculation points in the narrow beam distribution case has the lowest uniformity ratio 0.4, while the flood and wide flood has a value of 0.5 and 0.58, where it is shown that the vertical illuminance values have a shift to the left side. Moreover, in position A the wide flood distribution can reach a uniformity ratio up to 0.9, whereas in the case of narrow and flood it is, much less with a value of 0.5 and 0.6 only.

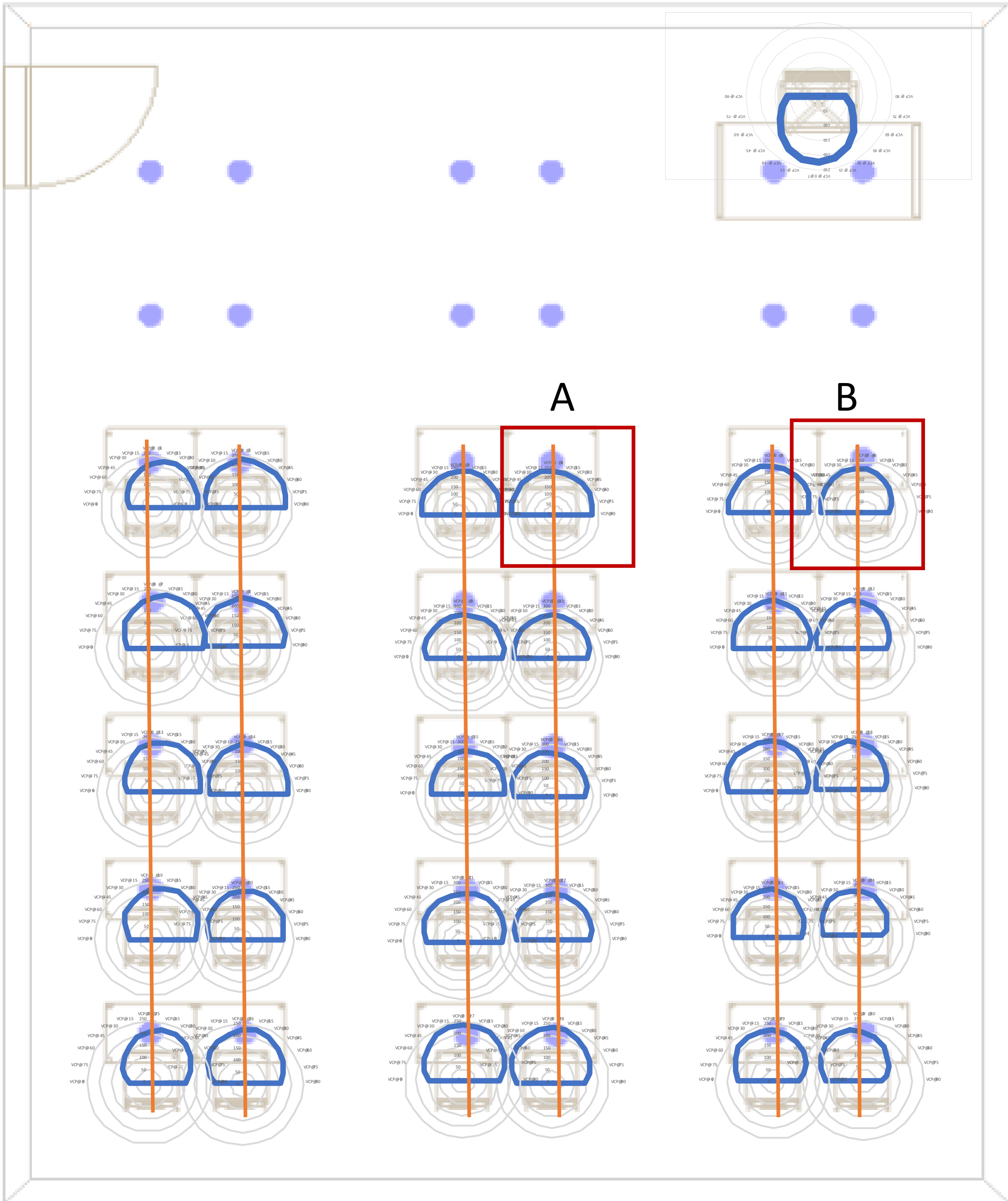


Figure 37: The calculation points polar diagrams plan of wide flood recessed downlight. (Author 2020)

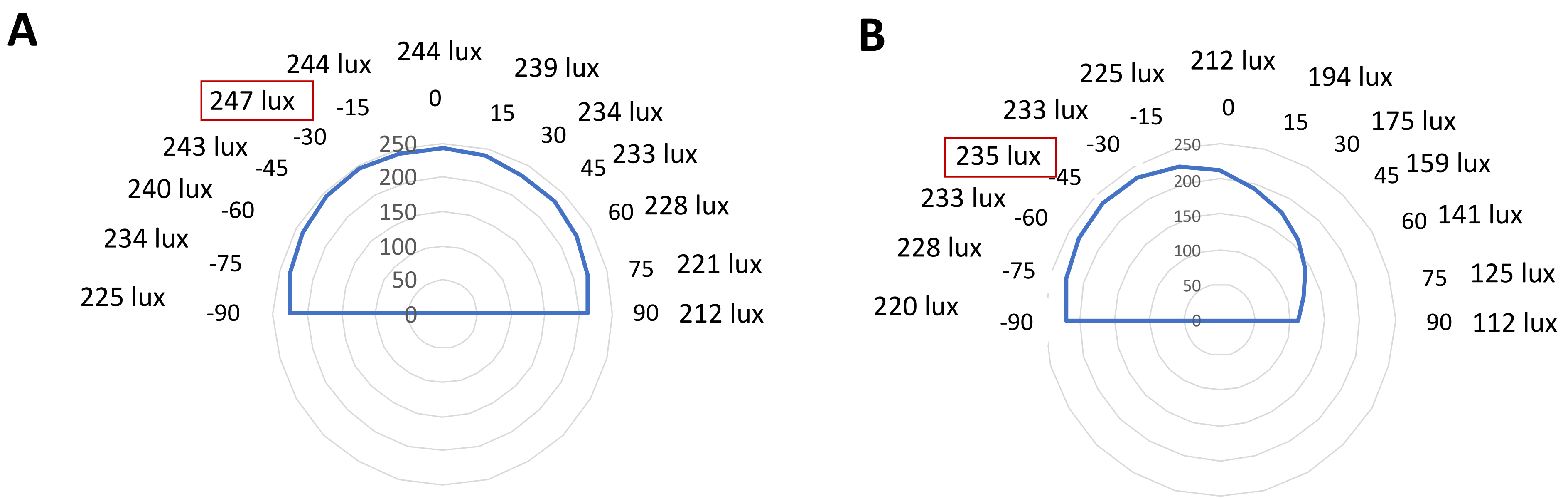


Figure 38: The polar diagram for a calculation points for recessed downlight, wide Flood beam distribution, 3000K, from left to right (a) At position A,(b)At position B (Author 2020

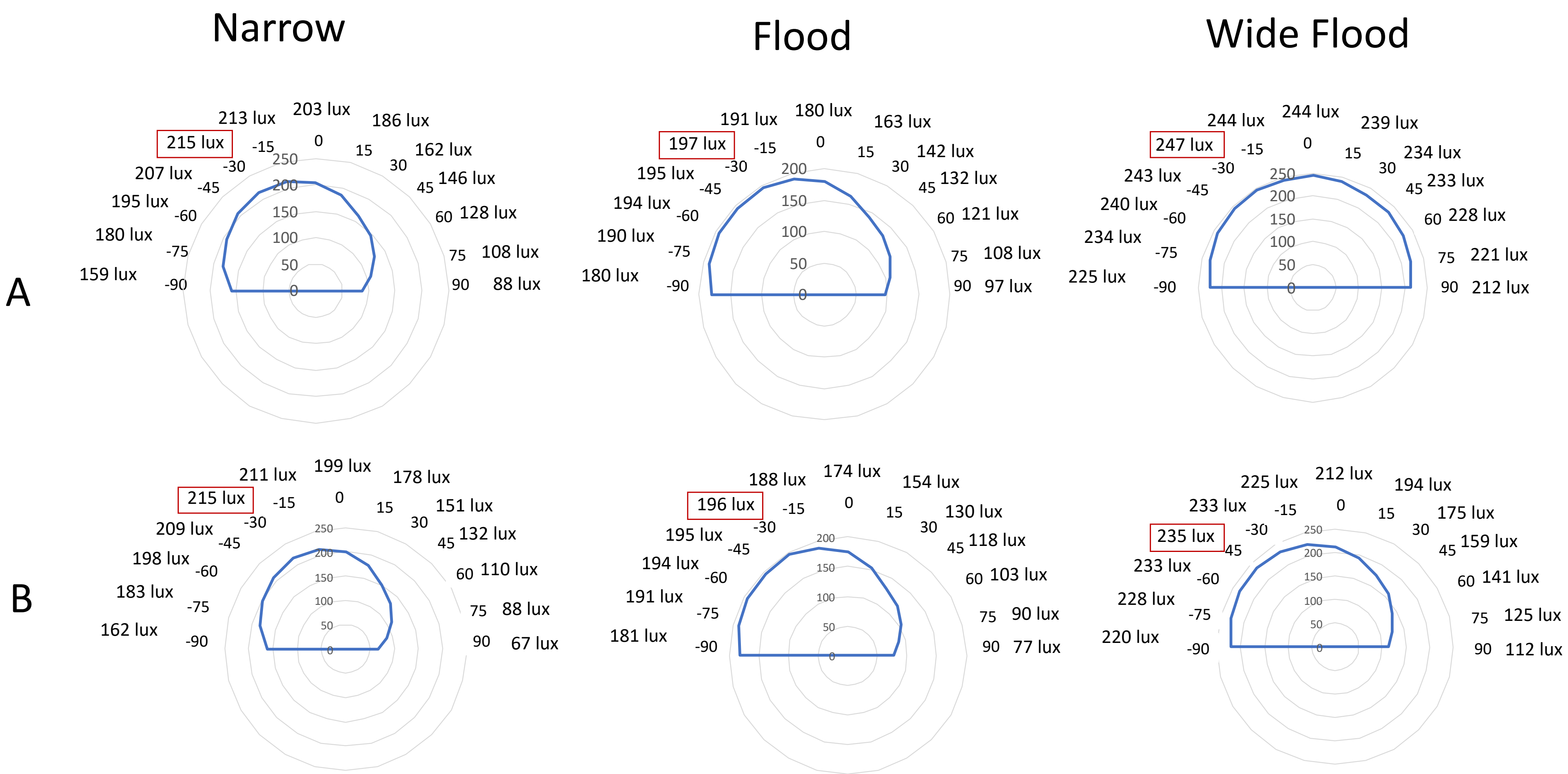


Figure 39: The polar diagram for a calculation points at A and B for recessed downlight, 3000K. From left to right (a)narrow (b) flood (c) wide flood (Author 2020)

4.2.2 Direct pendant linear light

- **Direct pendant linear light, Flood beam distribution**

Figure 40 shows a perspective view of the direct pendant linear light using flood beam distribution, where it is noticeable that the light is concentrated in the lower part of the classroom. By simulating the four CCTs Figure 41 shows the different horizontal plane for 300K, 3500, 4000K and 5000K, taking into consideration that the 3500 K and 4000 K cases have a lot of similarity with E_H of 548 lux and 552 lux, respectively.

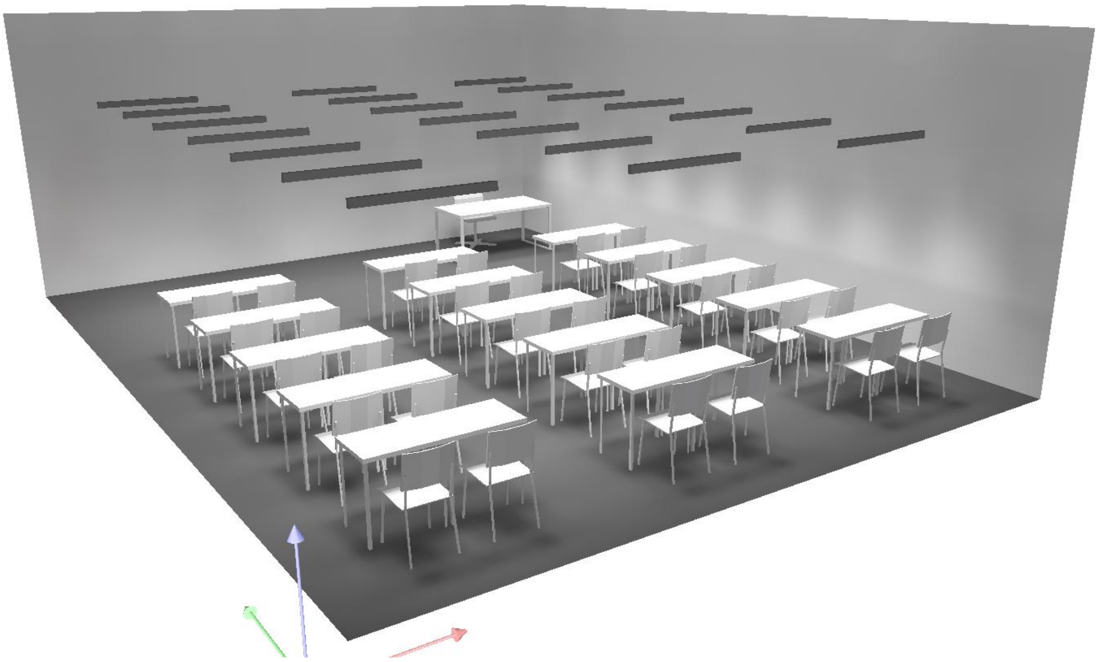


Figure 40: 3D perspective for direct pendant linear light - flood beam distribution. (Author 2020)

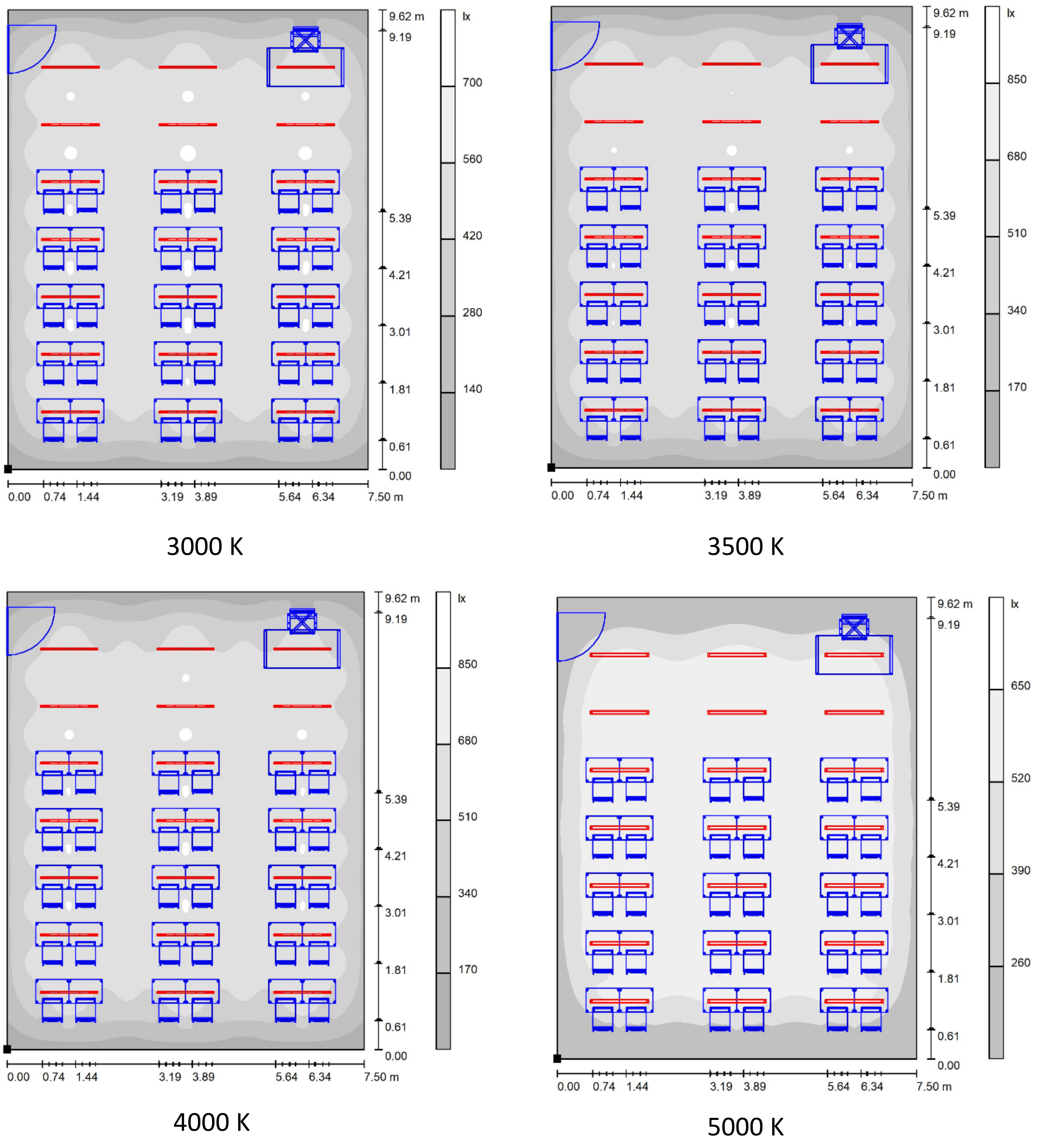


Figure 41: The horizontal calculation surface at 0.76 m for direct pendant light – flood, from left to right (a) 3000 K (b) 3500 K (c) 4000 k (c) 5000 k. (Author 2020)

Obviously noticed in Figure 42 and Figure 43 that the maximum vertical illuminance values in the pendant linear light are in a lower height comparing to the recessed downlight cases, for example the maximum value of the vertical illuminance in 3000K case is 377 lux at 1.7 m height. In addition, it is shown that the vertical illuminance values get higher as the CCT increase, where the lumen is increasing as well. For instance, the maximum vertical illuminance at 3500 K is 450 lux, while it reached up to 462 lux at 4000K and 692 lux at 5000K.

Figure 44 shows the polar diagram for calculation points at 3500K, where it is noticeable that at one position (student) will receive the maximum vertical illuminance in the straight position (at 0 degree), moreover the polar diagram look symmetrical which means that the students in this case will receive almost the same amount of vertical illuminance from left and right side, unlike the downlight cases where it was shown that the student in the corners will receive lower vertical illuminance in the side of the wall comparing to the other side. By comparing between the different CCTs in terms of calculation point in one position (in the left side of the classroom) as shown in Figure 45 it can be found that that 3000K, 3500K and 4000K perform the same, where the maximum value is in the straight view angle and both left and right side have almost the same values, while at 5000K, the maximum vertical illuminance comes from -30 degrees and a clear shift is observed to the left side that means the students will receive a vertical illuminance from the left side around 2.5 times from what can be received from the right side (The wall). It important to mention that 3000K, 3500K and 4000K has the same uniformity ratio of 0.7, while 5000K has a 0.5 uniformity ratio, which means the students receives more uniform light among the different viewing angles at 3000K,3500K and 4000K cases.

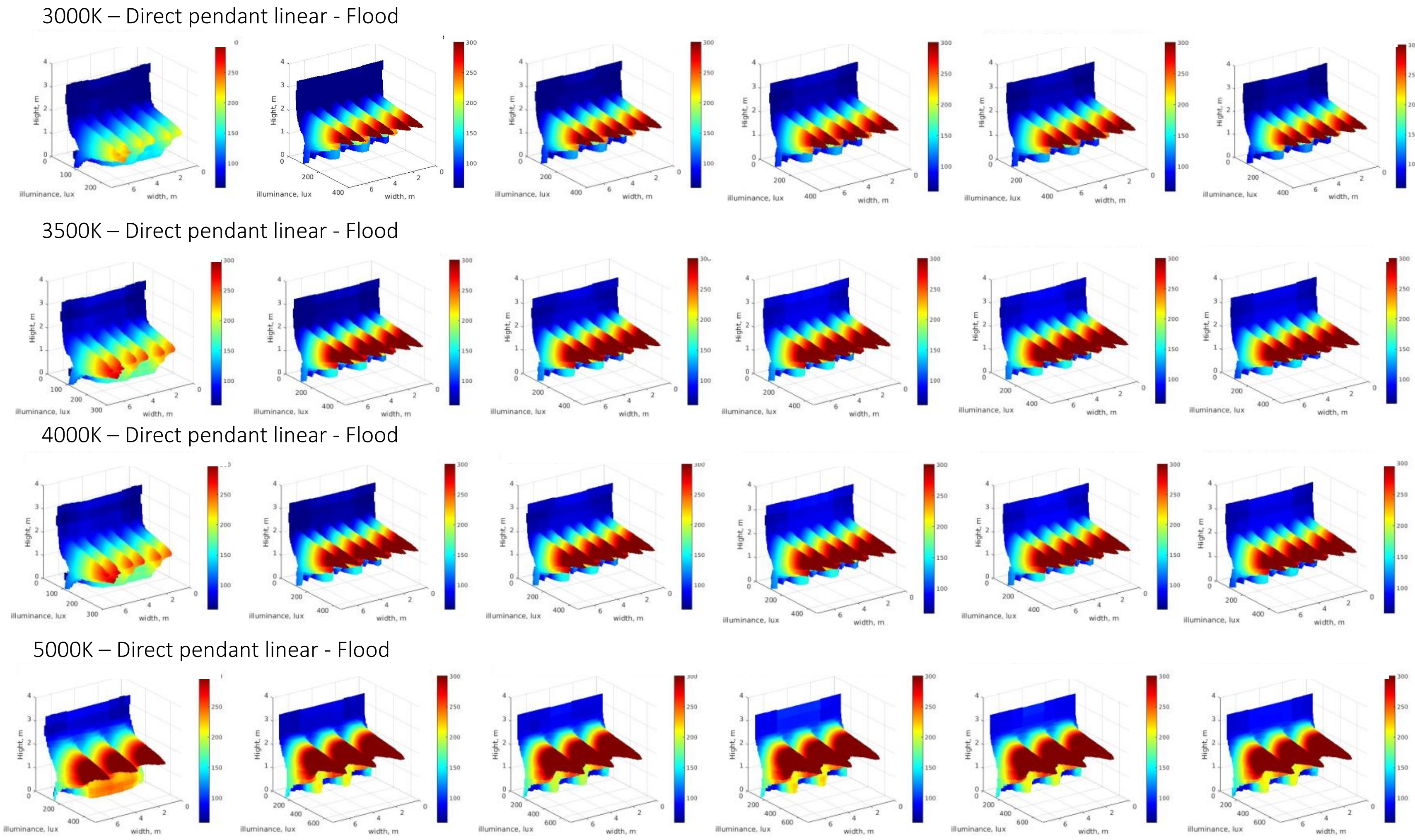


Figure 42: 3D vertical illuminance for 3000 K, 3500 K, 4000 K in the case of flood direct pendant light , from left to right (a) Teacher vertical plane (b) Row 1 vertical plane (c) Row 2 vertical plane (d) Row 3 vertical plane (e) Row 4 vertical plane (f) Row 5 vertical plane. (Author 2020)

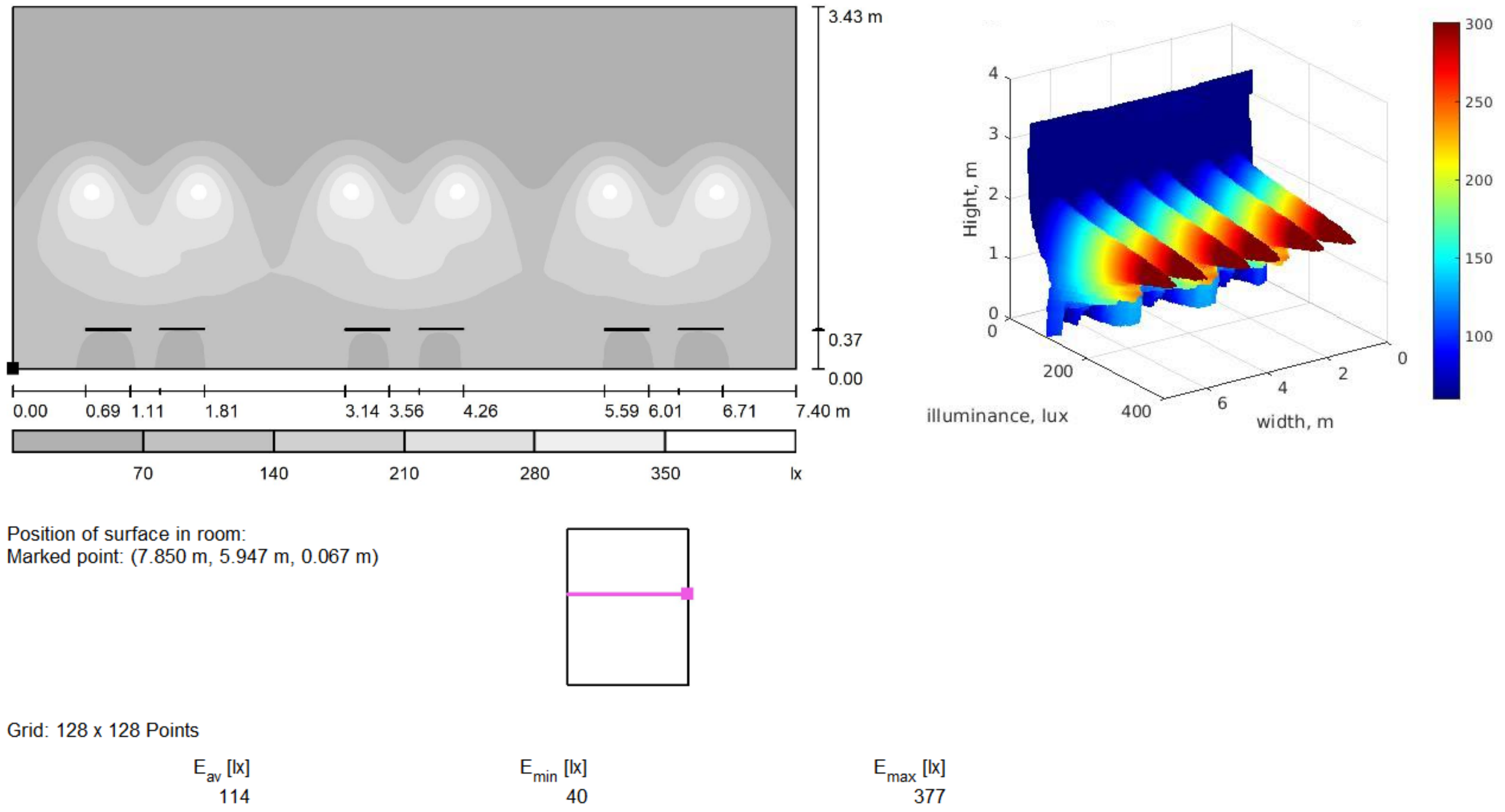


Figure 43: 2D and 3D vertical illuminance for one row in the case of direct pendant linear light, flood, 3000 K showing the average, minimum and maximum illuminance. (Author 2020)

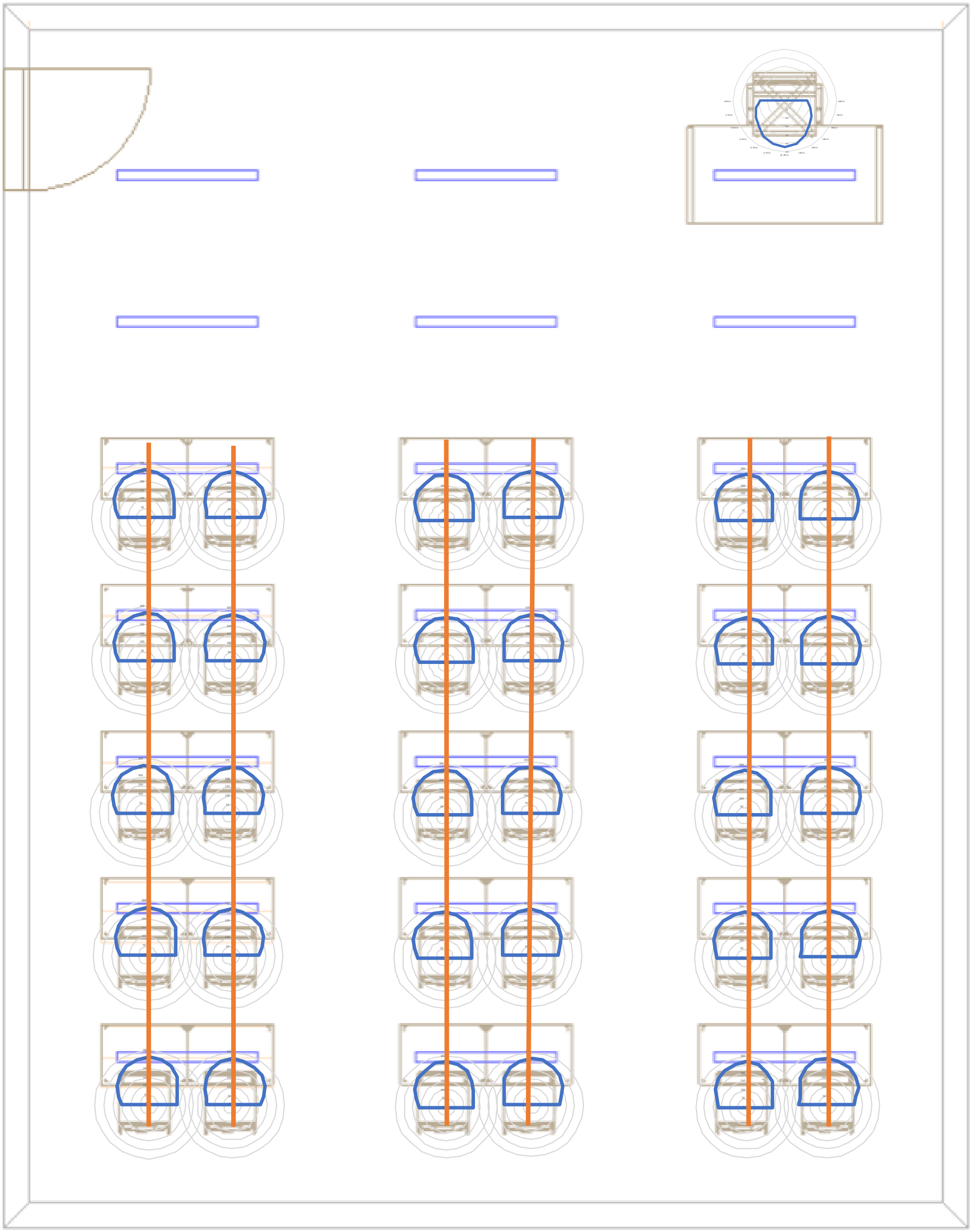


Figure 44: The calculation points polar diagram plan of direct pendant linear light, flood., 3000K (Author 2020)

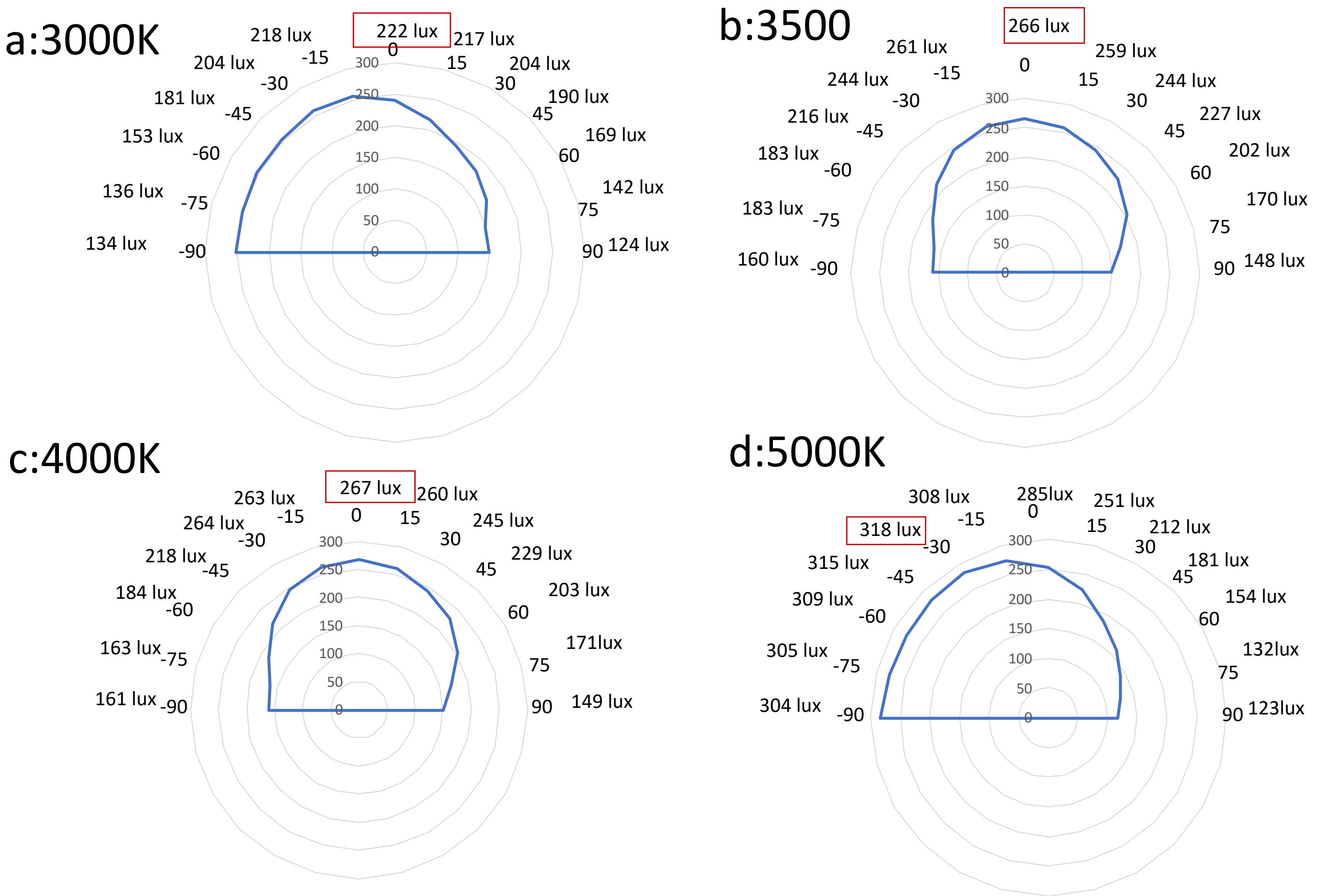


Figure 45: The calculation points polar diagram-direct pendent linear light-flood, at position B from left to right (a) 3000K (b) 3500K (c) 4000K (d) 5000 (Author 2020)

- **Direct pendant linear light, wide flood beam distribution**

The 3D perspectives from the lighting simulation for the direct pendant linear light with wide flood distribution is shown in Figure 46. For this type this type as well, four CCTs were simulated (3000K,3500K,4000K and 5000K). the horizontal illuminance on the working plane for the different CCTs are shown in Figure 47, where the average illuminance values are 530 lux, 460 lux, 463lux and 543 lux for 3000K, 3500K, 4000K and 5000K, respectively.

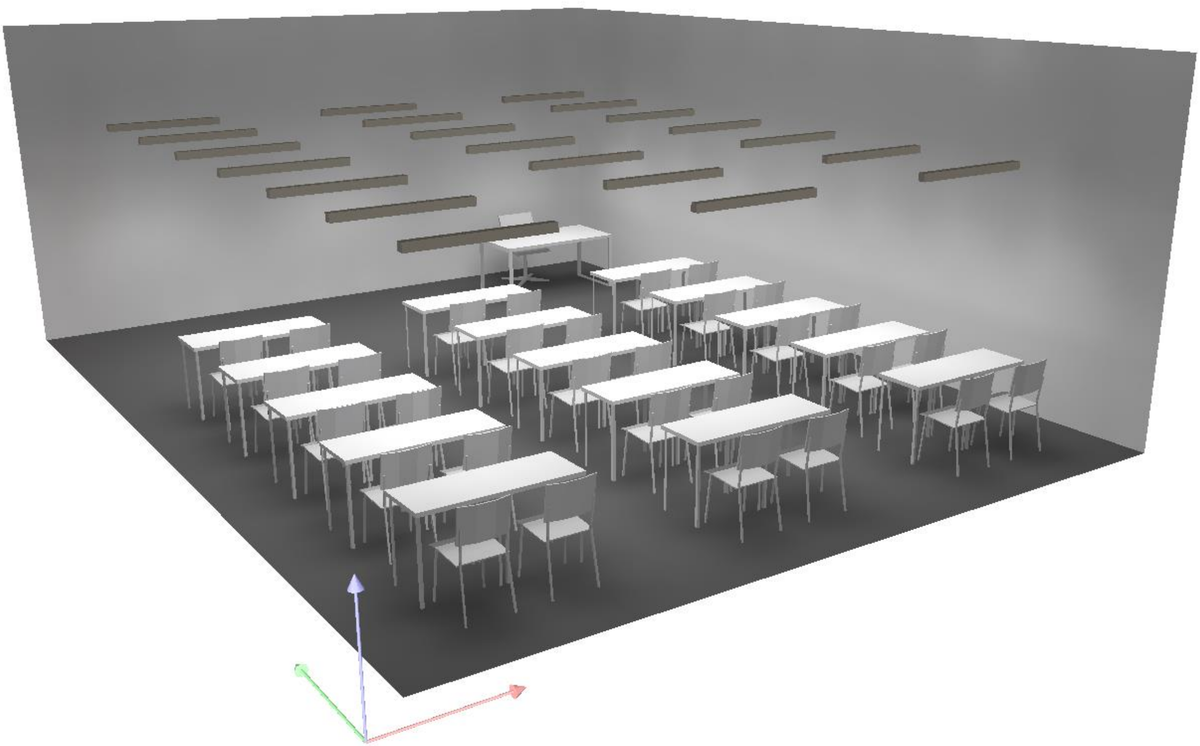


Figure 46: 3D perspective for direct pendant linear light - wide flood beam distribution. (Author 2020)

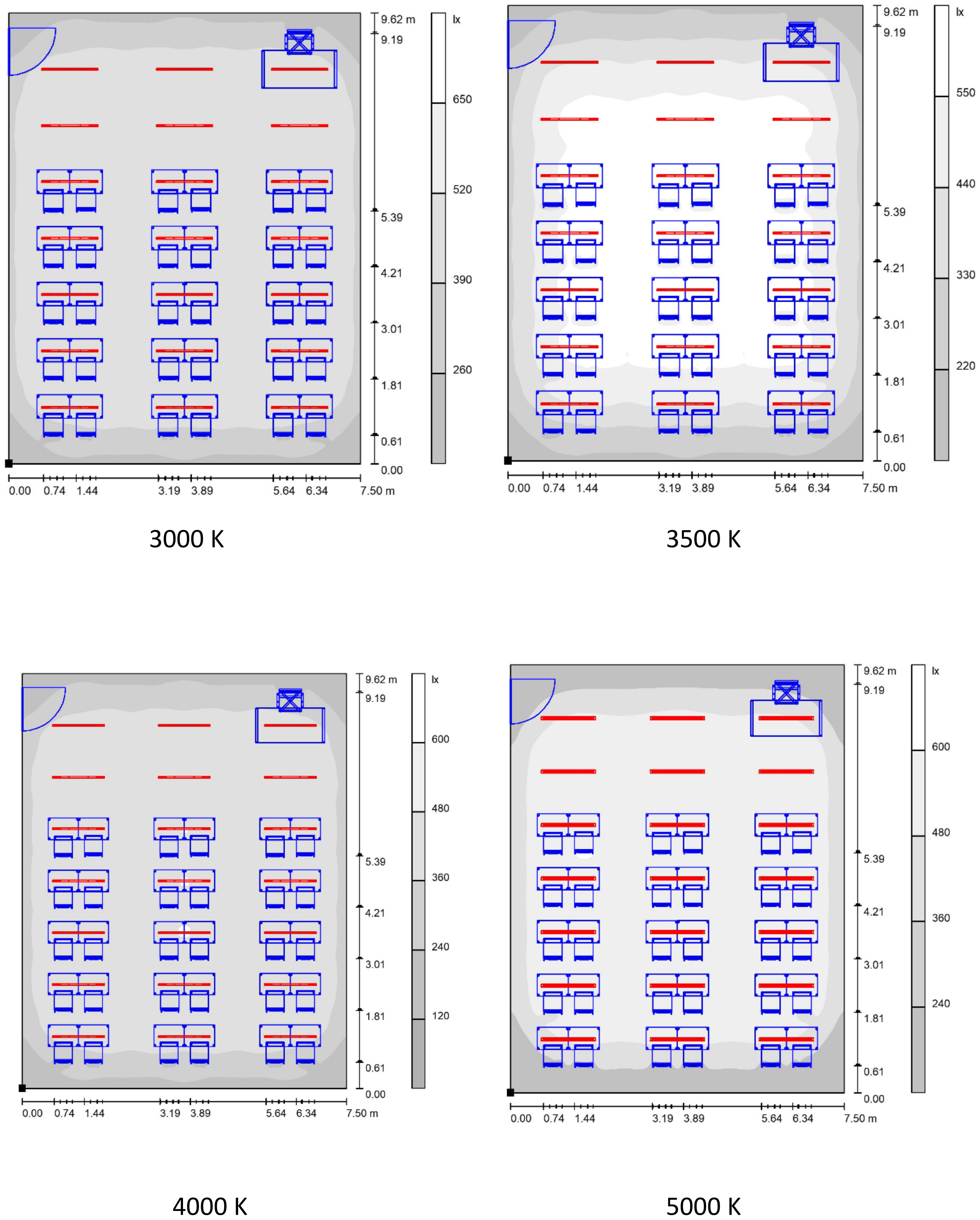


Figure 47: The horizontal calculation surface at 0.76 m for direct pendant light –wide flood, from left to right (a) 3000 K (b) 3500 K (c) 4000 k (c) 5000 k. (Author 2020)

Wide flood beam distribution as illustrated in Figure 48 has reached a higher vertical illuminance value comparing to the flood beam distribution in all CCTs trails. The maximum values for all the CCTs are located at 1.7 height, for 3000K, 3500K and 4000K cases the maximum value is almost in a the range of 600 lux, unlike the 5000K which achieved 832 lux as shown in Figure 49 and Figure 50. Pointing out that in the case of 5000K, a luminaire with 28 Watts with 2298 lm been selected in order to reach the target of E_H. Thus, it might be the reason behind the higher vertical illumination in this case. Figure 51 Show an example of the calculation points in the case of 3000K, where it is clearly shown that the group of the calculation points in one position has non-symmetrical distribution for all the positions. Furthermore, Figure 52 shows a representatives calculation points (positioned in the right side of the classroom) for 3000K,3500K,4000K and 5000K. It is noticeable that all of the cases reached the maximum vertical illuminance value at -30 degrees, where 5000K has the highest maximum value (282 lux) comparing to other CCT followed by 3000K (259 lux), whereas 3500K and 4000K has almost the vertical illuminance values with a maximum of 224 lux and 226 lux respectively. The reason behind this is that 5000K and 3000K has a higher lumen value comparing to 3500K and 4000K. Moreover, it was founded that 3000K, 3500K and 4000K has a higher uniformity ratio (0.68) than 5000K (0.53), where it is clearly shown that 5000K has a shift toward the left side. Although, the wide flood has a higher maximum value comparing to the flood distribution Figure 45 and Figure 52 shows that the amount of the vertical illuminance that reaches the eye-level (1.2m) is higher in the flood beam distribution, except for 3000K where the lumen in the wide flood beam distribution is higher than the one in the flood beam distribution.

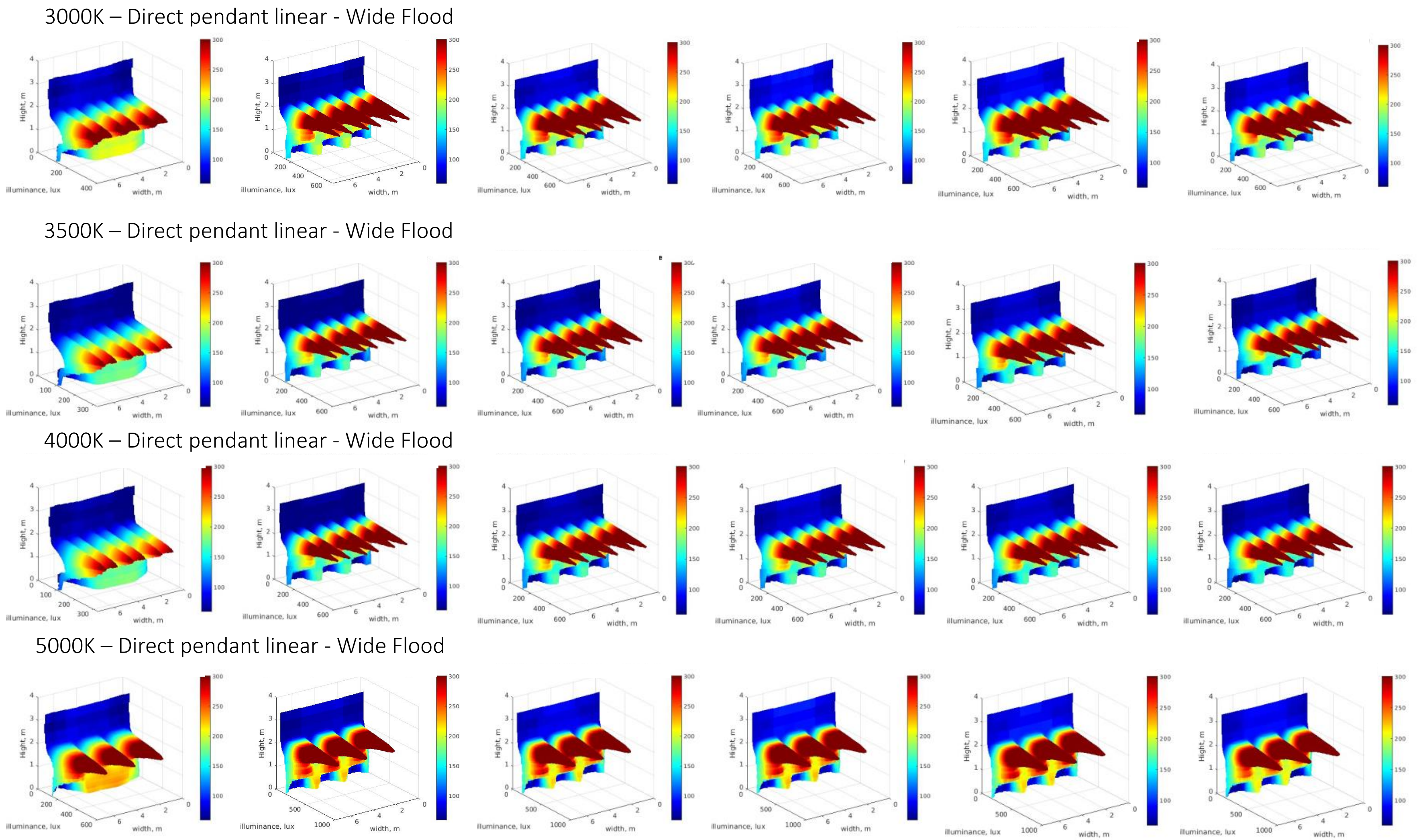


Figure 48: 3D vertical illuminance for 3000 K, 3500 K, 4000 K and 5000K in the case of wide flood direct pendant light, from left to right (a) Teacher vertical plane (b) Row 1 vertical plane (c) Row 2 vertical plane (d) Row 3 vertical plane (e) Row 4 vertical plane (f) Row 5 vertical plane. (Author 2020)

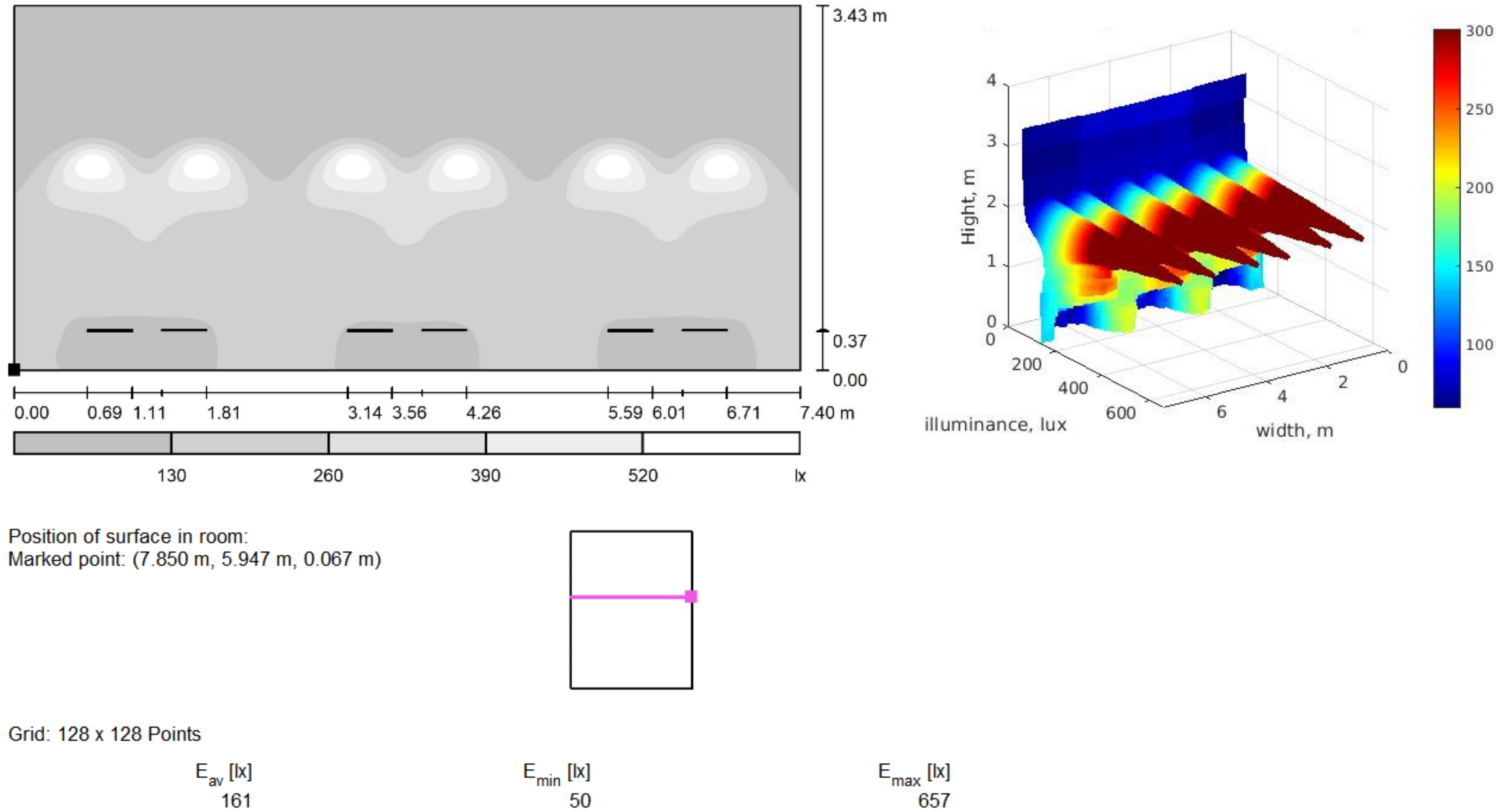
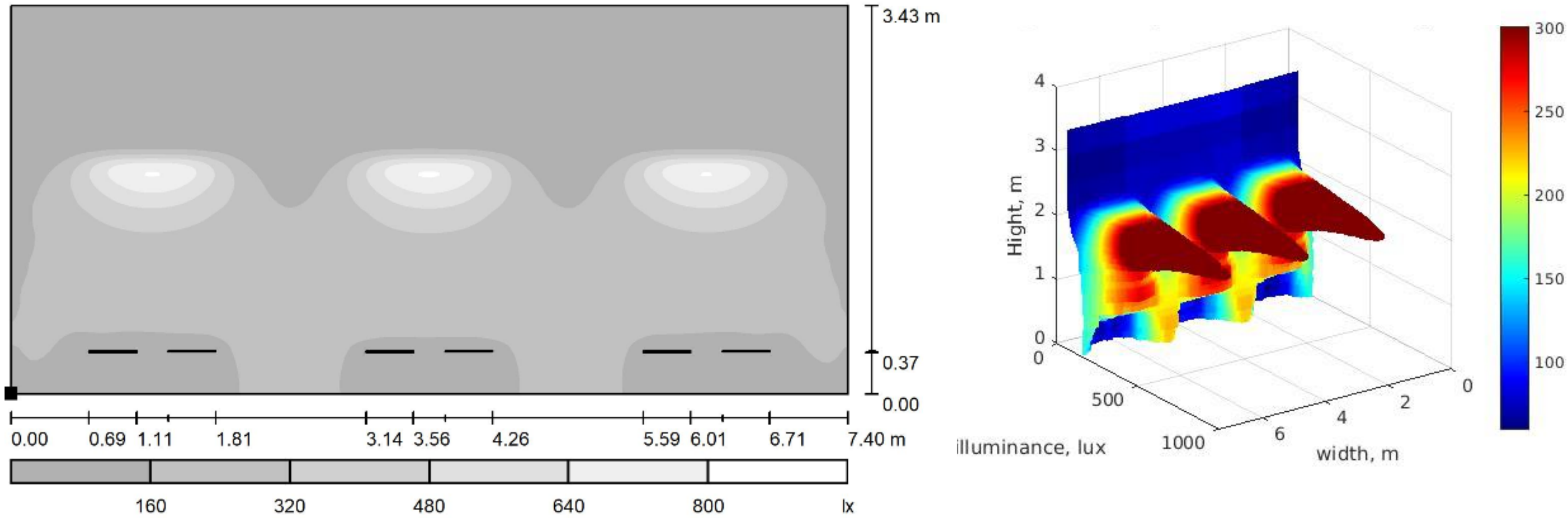
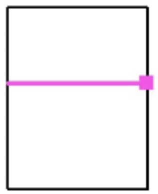


Figure 49: 2D and 3D vertical illuminance for one row in the case of direct pendant linear light, wide flood, 3000 K showing the average, minimum and maximum illuminance. (Author 2020)



Position of surface in room:
Marked point: (7.850 m, 5.947 m, 0.067 m)



Grid: 128 x 128 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]
176	60	832

Figure 50: 2D and 3D vertical illuminance for one row in the case of direct pendant linear light, flood, 5000 K showing the average, minimum and maximum illuminance. (Author 2020)

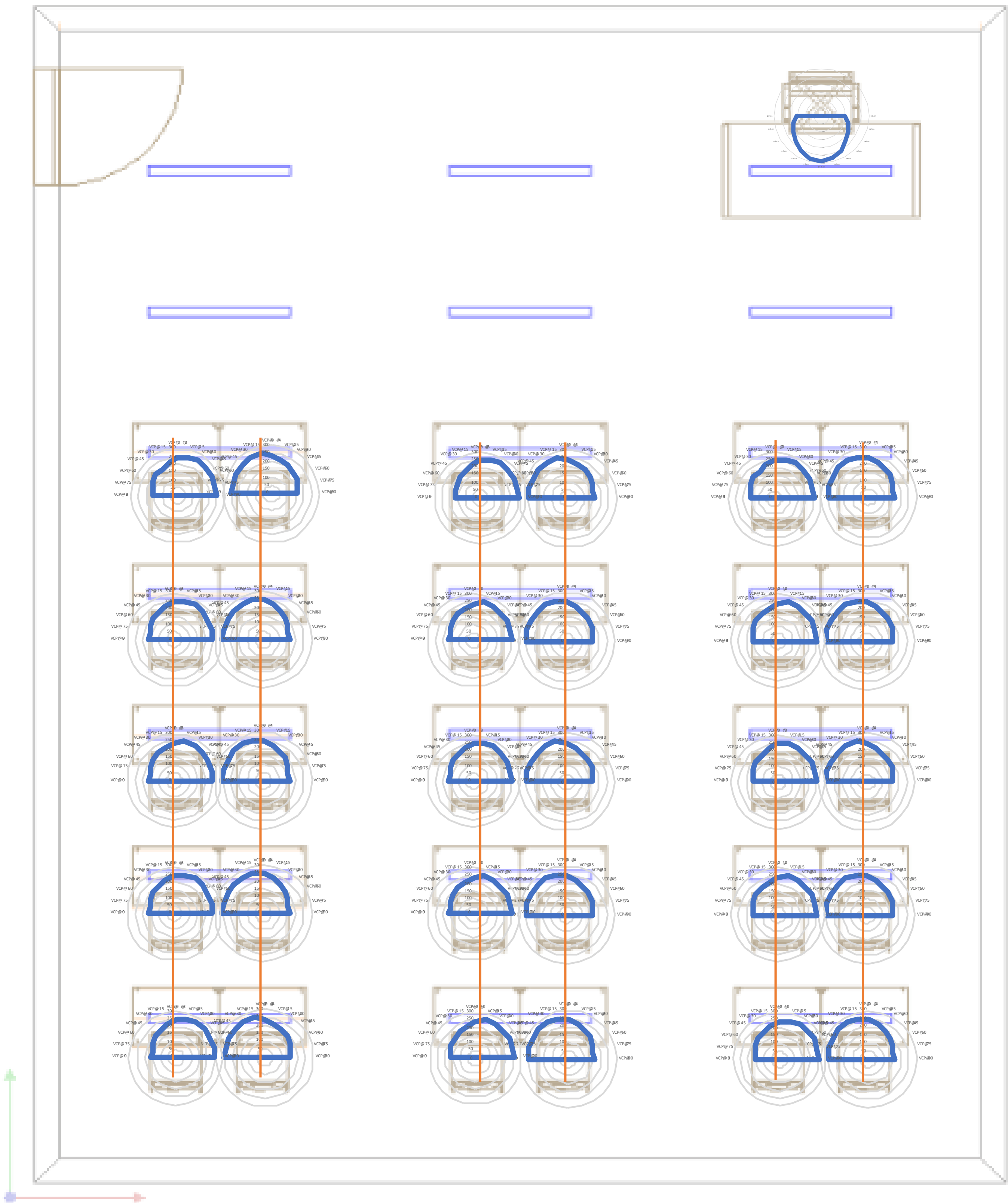


Figure 51: The calculation points polar diagrams of direct pendant linear light - wide flood- 3000K. (Author 2020)

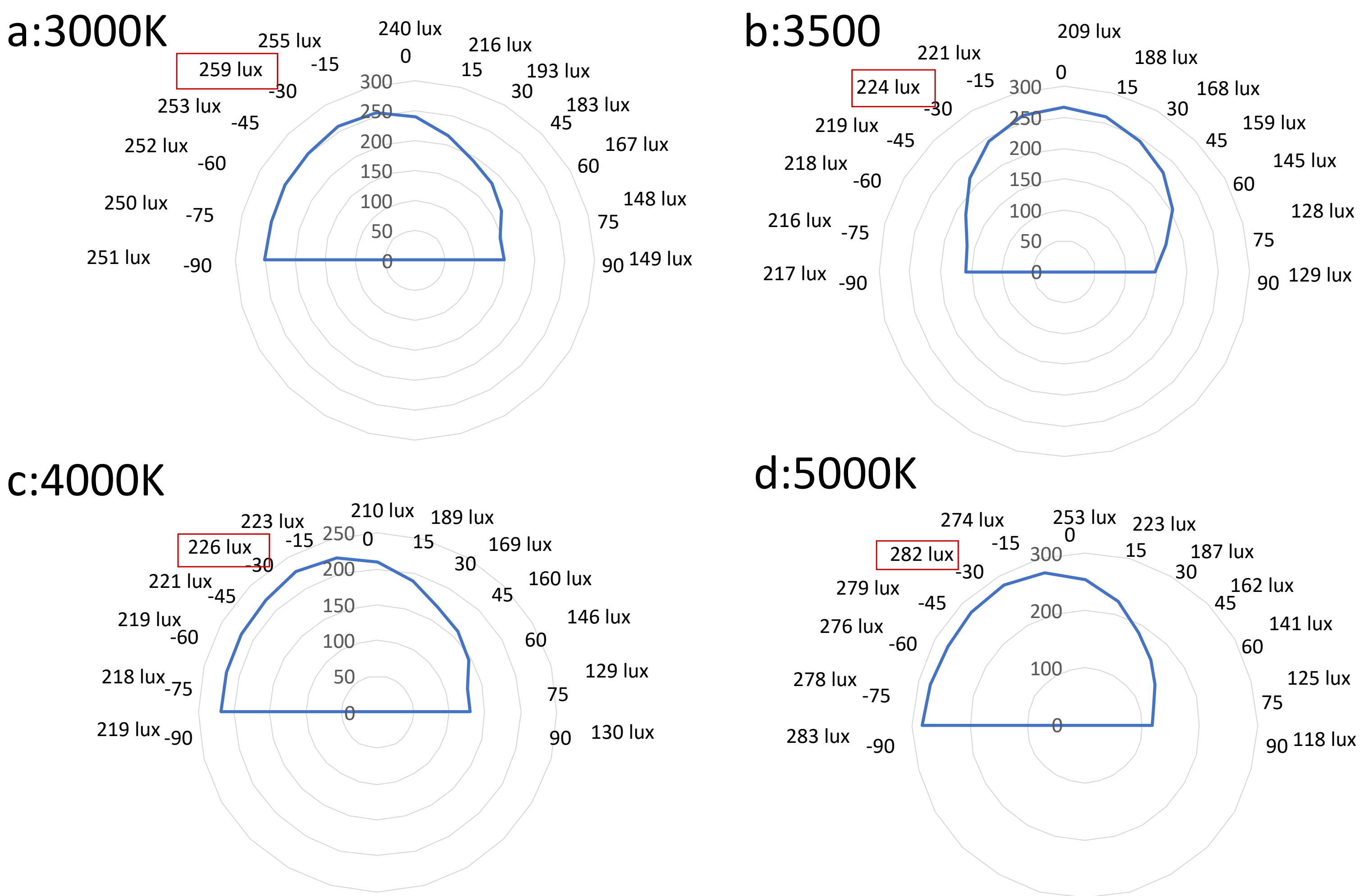


Figure 52: The calculation points polar diagram- direct pendent linear light-wide flood, from left to right (a) 3000K (b) 3500K (c) 4000K (d) 5000 (Author 2020)

4.2.3 Indirect pendant linear light

- **Indirect pendant linear light, butterfly beam distribution**

The luminaries that were selected for the indirect cases to achieve the E_H recommended value for 3000k, 3500k, 4000k, and 5000k has high lumen values comparing to others in a range of 4600 lm to 5000 lm. Figure 53 shows the distribution of light in the space ,which is reflected from the ceiling and diffused to the classroom in a uniform distribution. It is noticeable in Figure 54, which shows the horizontal illuminance gets higher as the CCT increase, because of the increment in the lumen value.

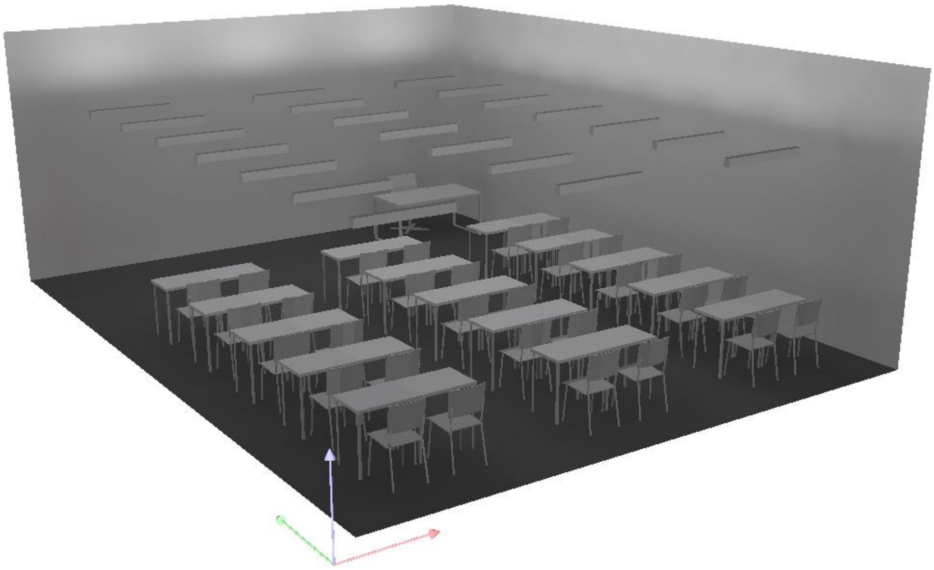


Figure 53: 3D perspective for indirect pendant linear light – butterfly beam distribution. (Author 2020)

An extreme vertical illuminance is shown in the results of the vertical calculation surfaces in Figure 55, which present the cases of 3000K, 3500K, 4000K, and 5000K. Highlighting that the maximum E_v reached up to 4000 lux, which count as a high value comparing to all other cases. Although it reached around 4000 lux, but this can't present the actual E_v at the eye level as its highlighted in Figure 56 that the maximum number was achieved at 2.7 m height.

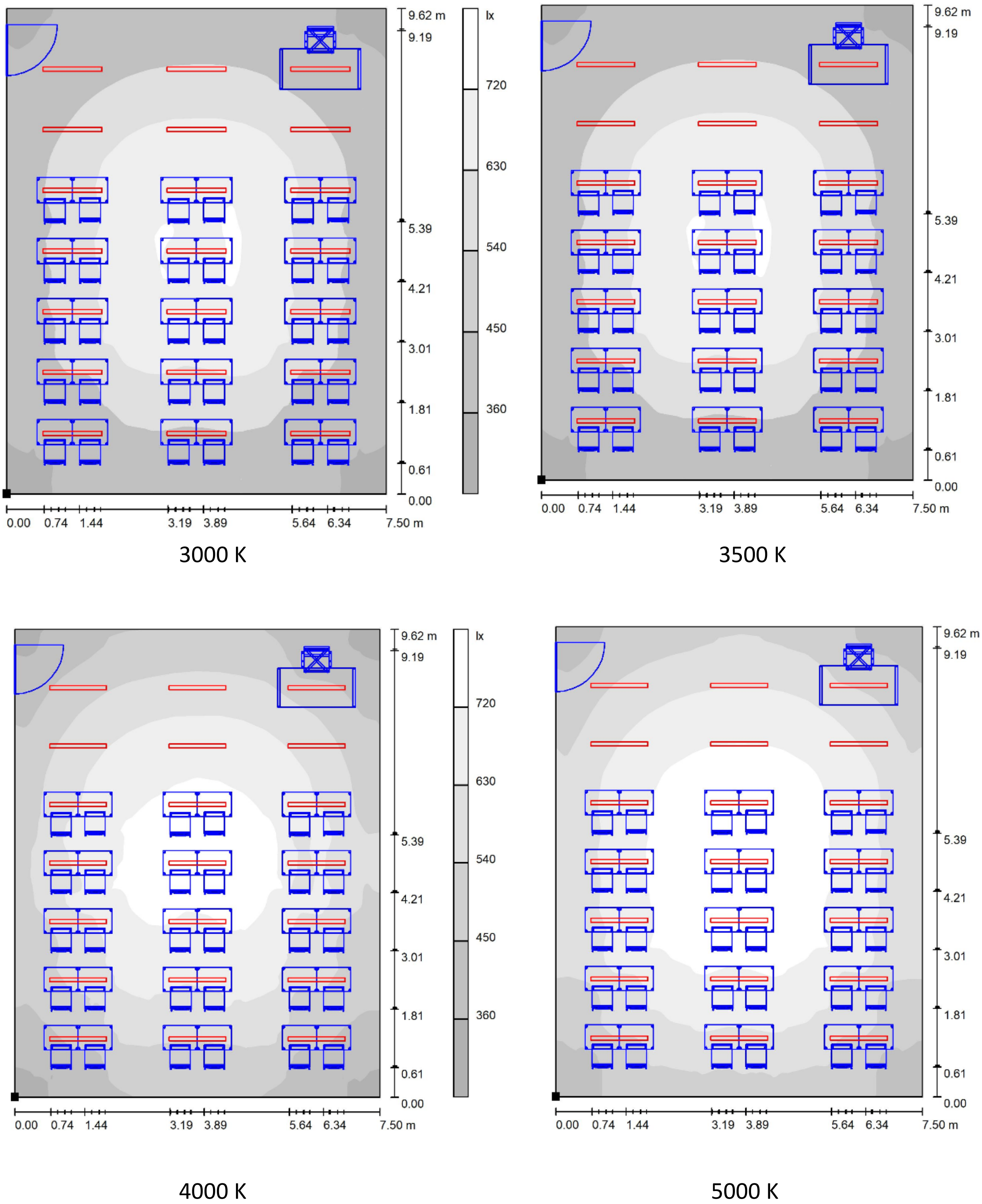


Figure 54: The horizontal calculation surface at 0.76 m for indirect pendant linear light – butterfly distribution, from left to right (a) 3000 K (b) 3500 K (c) 4000 k (c) 5000 k. (Author 2020)

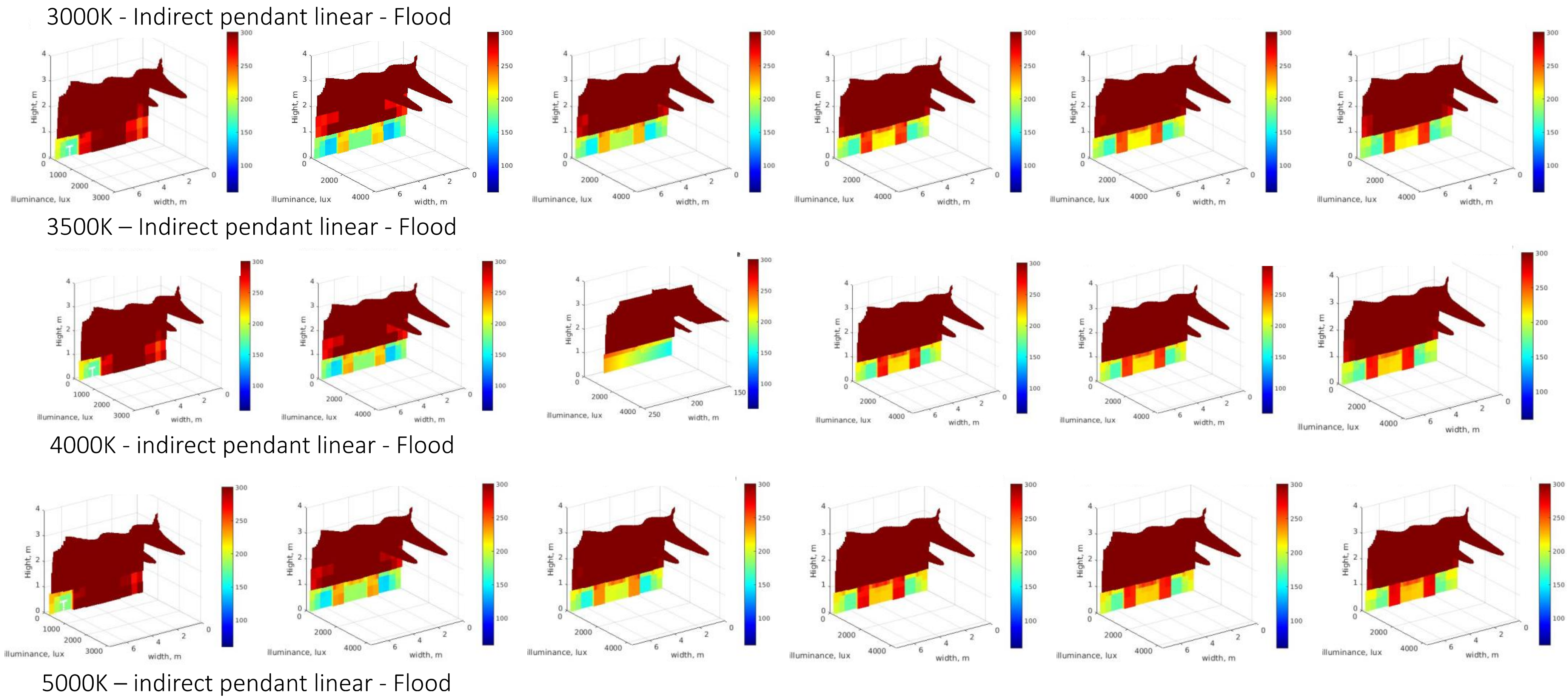


Figure 55: 3D vertical illuminance for 3000 K, 3500 K, 4000 K in the case of indirect pendant light - butterfly beam distribution, from left to right (a) Teacher vertical plane (b) Row 1 vertical plane (c) Row 2 vertical plane (d) Row 3 vertical plane (e) Row 4 vertical plane (f) Row 5 vertical plane. (Author 2020)

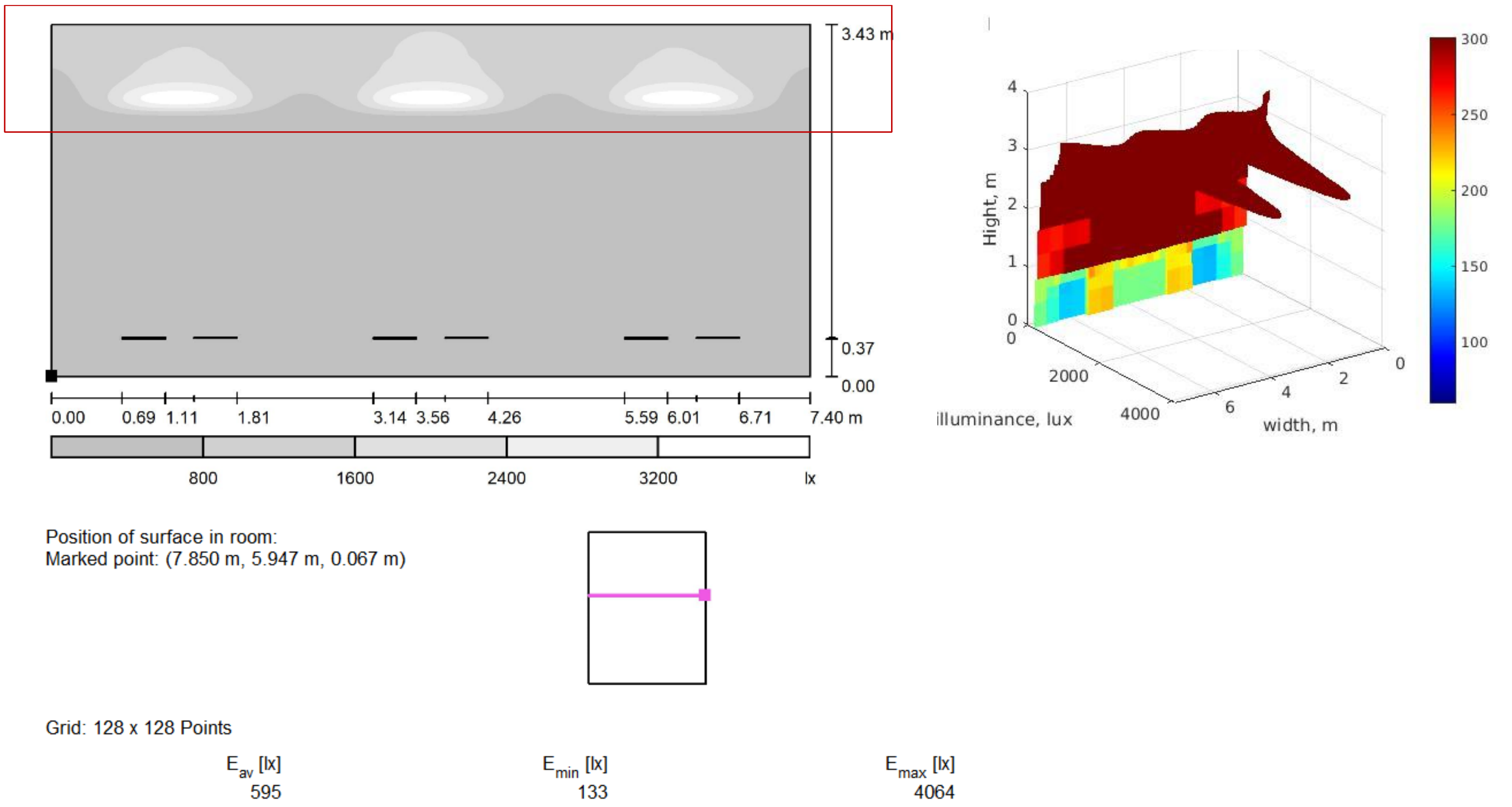


Figure 56: 2D and 3D vertical illuminance for one row in the case of indirect pendant linear light, butterfly 3000 K showing the average, minimum and maximum illuminance. (Author 2020)

In terms of vertical calculation points, the middle rows received a symmetrical vertical light distribution while the left and right rows received a non-symmetrical distribution of light shown in Figure 57. The reason behind this shift can be explained in Figure 54 which clearly shows that the right and the left sides of the classroom receive a lower illuminance compared to the middle, where the light beams intersect and result in higher illuminance. For example, in the case of 3000K, Figure 58 shows that the vertical illuminance values at position A has a uniform ratio of 0.95, while at position B it has a uniform ratio of 0.7. It is important to mention that the indirect pendant linear light has the highest vertical illuminance values at 1.2m comparing to all other cases. Moreover, the vertical calculation points at 3500K,4000K and 5000K perform the same, where all the position in the center of the classroom has a uniformity ratio of 0.95 and the one in the side has a value of 0.7.

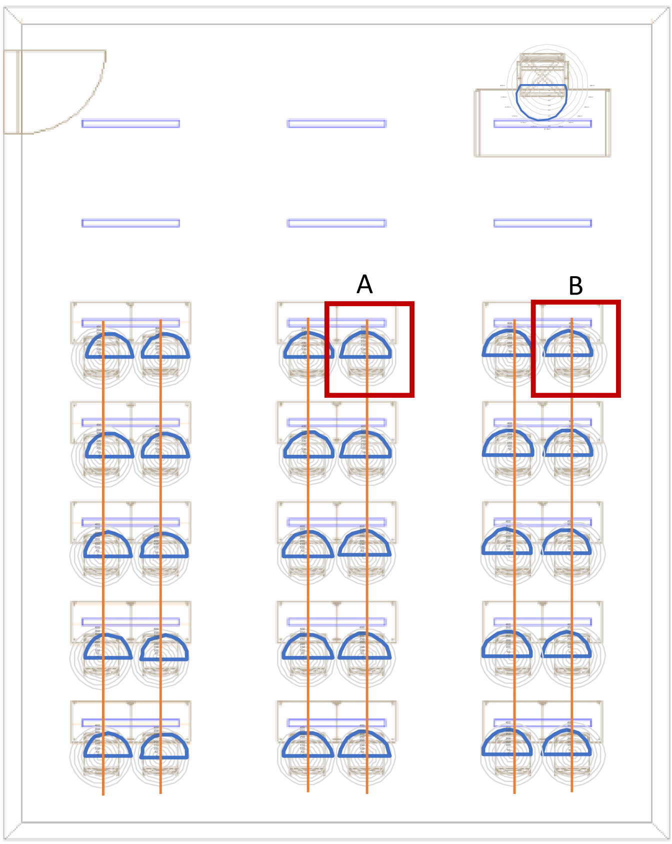


Figure 57: The calculation points polar diagrams plan of indirect pendant linear light - butterfly distribution. (Author 2020)

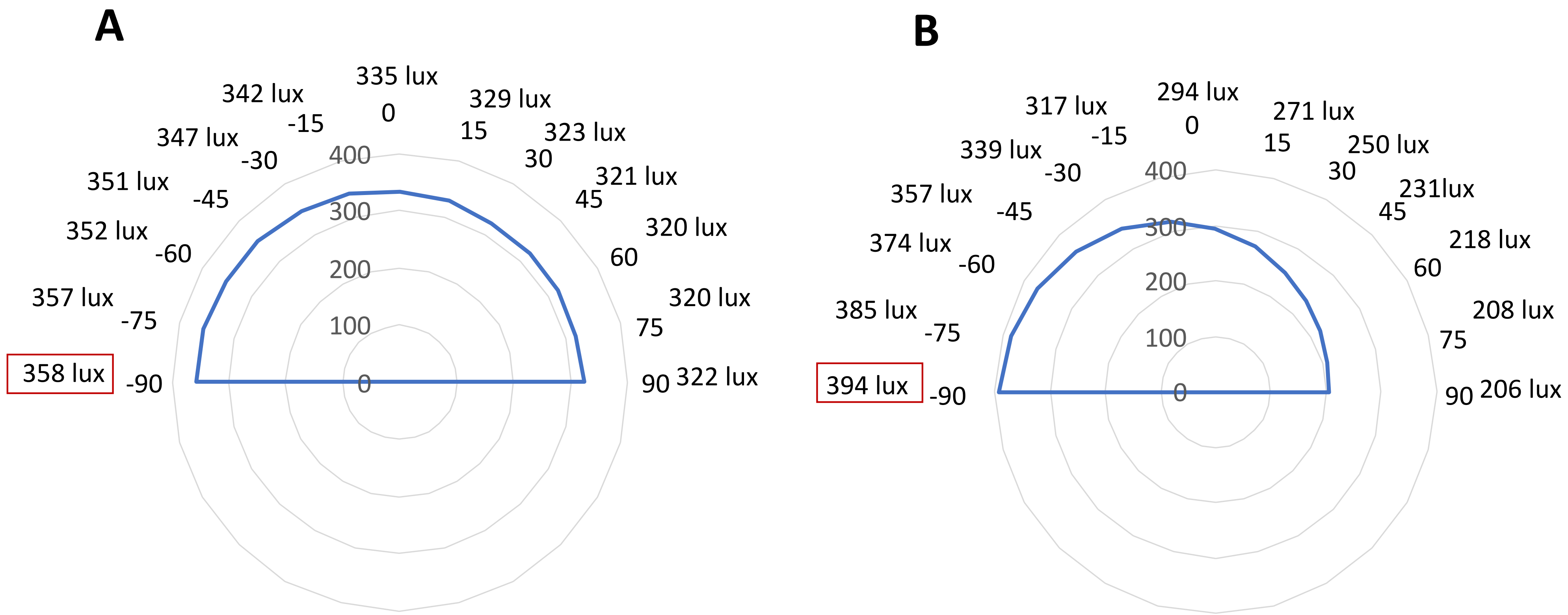


Figure 58: Calculation point polar diagram for indirect pendant linear light-3000K, from left to right (a) calculation point at position A (b) calculation point at position B, (Author 2020)

4.2.4 Direct / indirect linear pendant light

- **Direct / indirect linear pendant light, Flood beam distribution**

The simulations of direct/indirect linear pendant light with flood distribution shown in Figure 60 which result in similar result for 3000K,3500K and 4000K , noted that they have the same lumen, while there is a slight change in 5000K which has a different lumen. Moreover, Figure 61 confirm this similarity in the illustrations for the vertical illuminance planes. For the sake of clarity, Figure 62 is a representative for 3000K,3500K and 4000K and Figure 63is for 5000K case, where its shown clearly that the maximum values are in the same level (1.9 m) with a value of 580 lux for 3000K, 3500K and 4000 and a value of 610 for 5000K. although 5000K has a higher maximum value, it is clearly shown while comparing between Figure 62 and Figure 63 that the vertical illuminance is higher in the lower level at 3000K, where at 1.2m 3000K has an average vertical illuminance value of 261, while at 5000K the average at the same level is 241 lux .

The calculation points polar diagrams plan for direct/indirect linear pendent at 3000K is shown in Figure 64 as a representative of all other cases for direct/indirect linear light since they all perform in the same manner with lower vertical illuminance values only in the case of 5000K. As the other luminaire types, the calculation points which positioned near to the wall has lower vertical illuminance values and lower uniformity ratio (248 lux, 0.6 uniformity ratio) compared to the one positioned in the center (266 lux, 0.7 uniformity ratio) as shown in Figure 65.

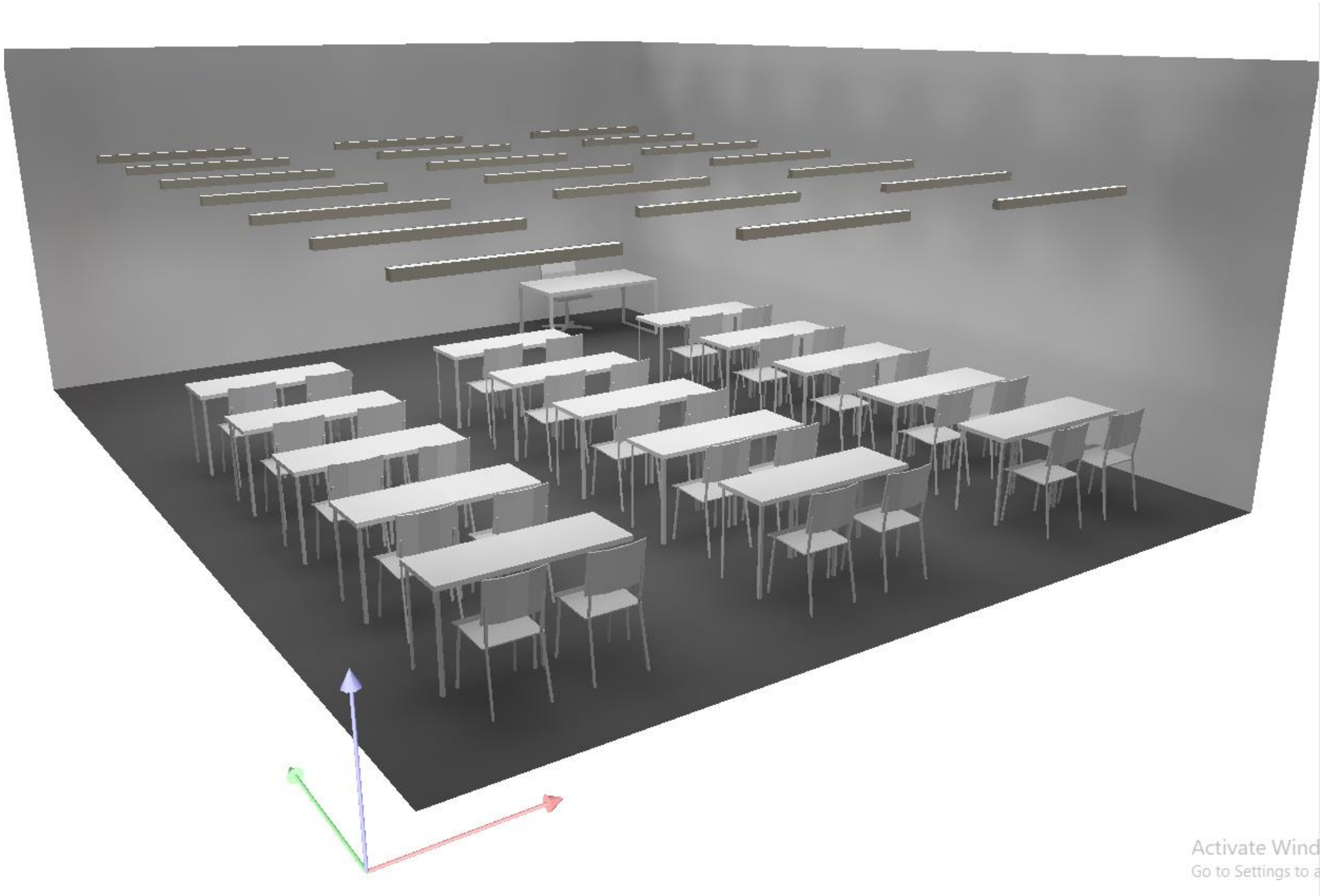


Figure 59: 3D perspective for direct / indirect pendant linear light – flood beam distribution. (Author 2020

)

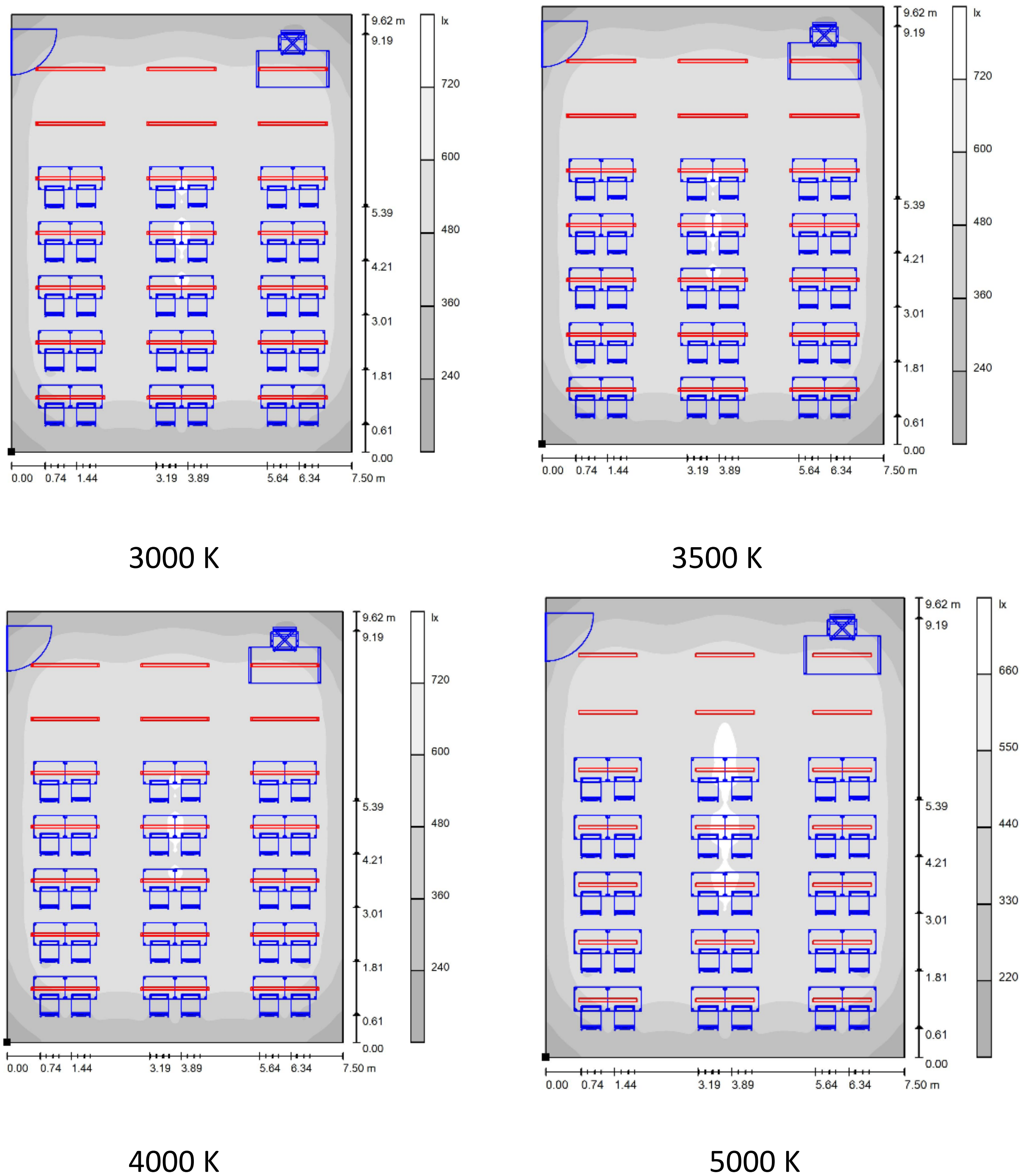
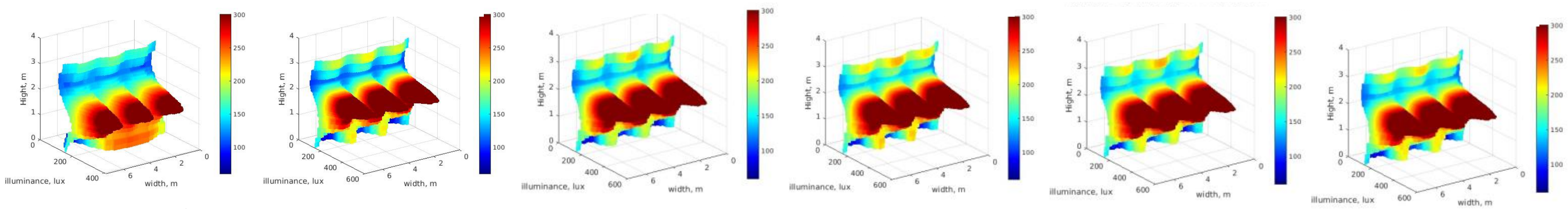
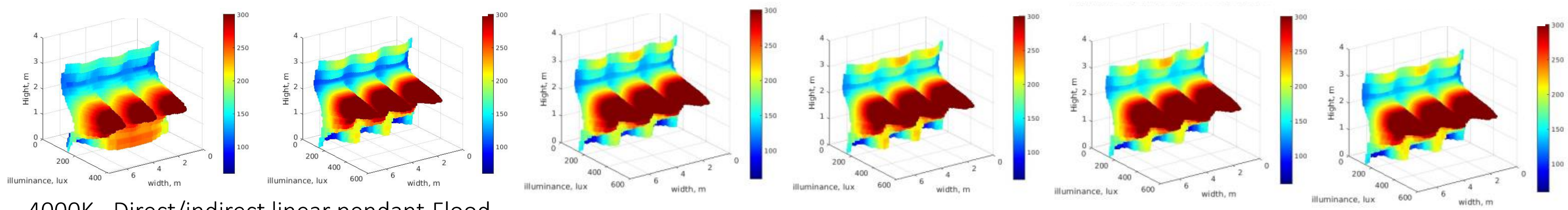


Figure 60: The horizontal calculation surface at 0.76 m for direct / indirect pendant linear light – flood, from left to right (a) 3000 K (b) 3500 K (c) 4000 k (c) 5000 k. (Author 2020)

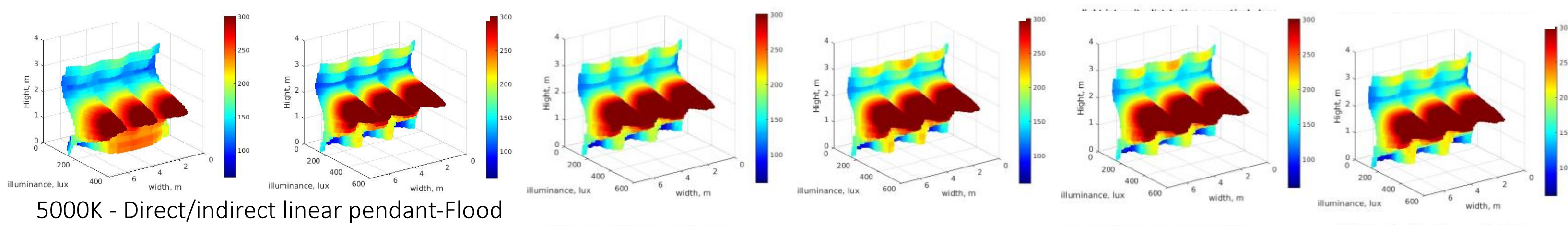
3000K – Direct/indirect linear pendant-Flood



3500K - Direct/indirect linear pendant-Flood



4000K –Direct/indirect linear pendant-Flood



5000K - Direct/indirect linear pendant-Flood

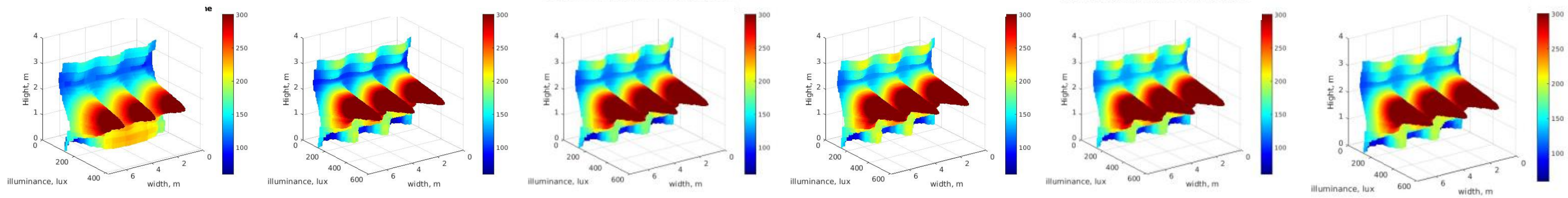


Figure 61: 3D vertical illuminance for 3000 K, 3500 K, 4000 K in the case of flood- direct / indirect pendant light. from left to right (a) Teacher vertical plane (b) Row 1 vertical plane (c) Row 2 vertical plane (d) Row 3 vertical plane (e) Row 4 vertical plane (f) Row 5 vertical plane. (Author 2020)

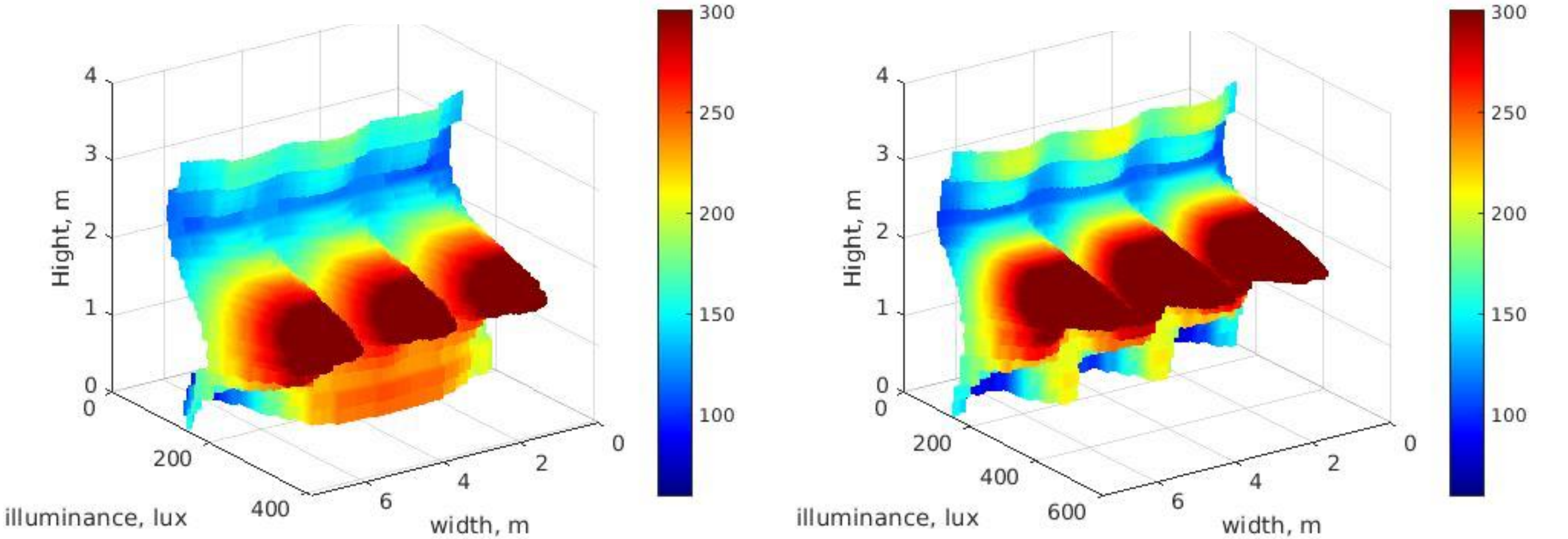


Figure 62: A representative 3D vertical illuminance for 3000 K,3500K and 4000K in the case of direct/indirect pendant linear, flood, from left to right (a) Teacher Vertical plane (b) representative vertical plane for row 1, 2, 3, 4, and 5 . (Author 2020)

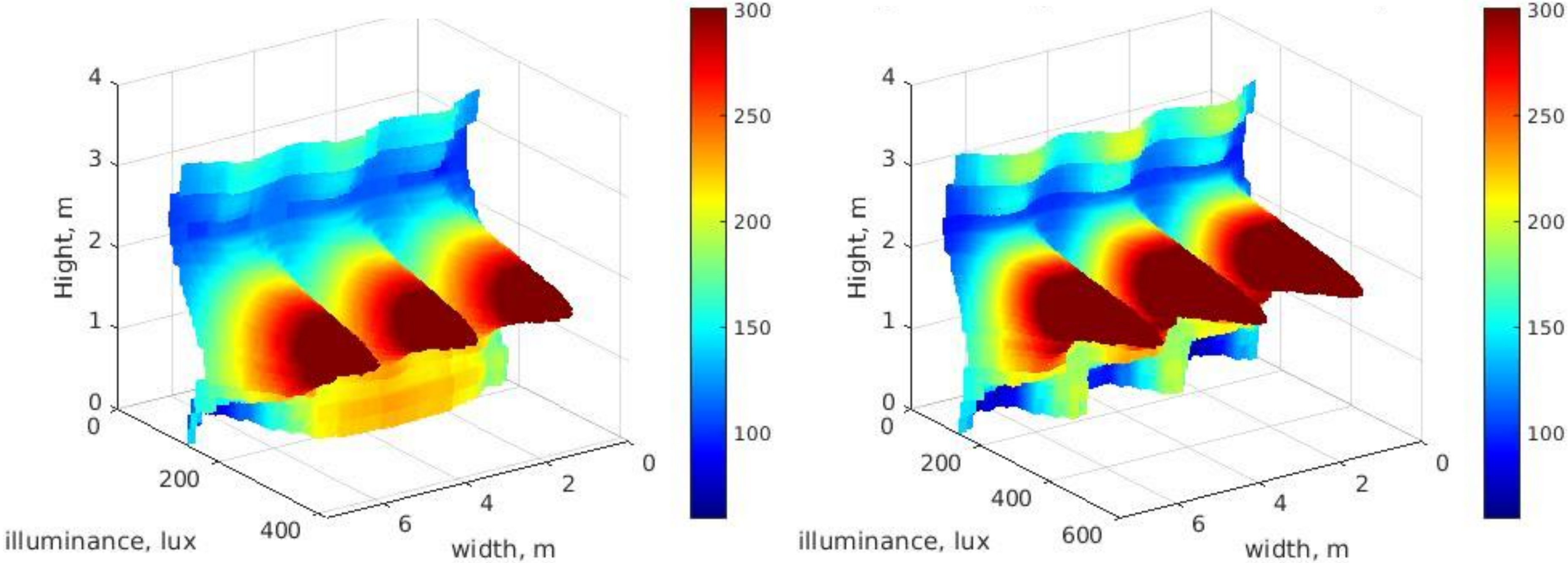


Figure 63: A representative 3D vertical illuminance 5000K in the case of direct/indirect pendant linear- flood, from left to right (a) Teacher Vertical plane (b) representative vertical plane for ro

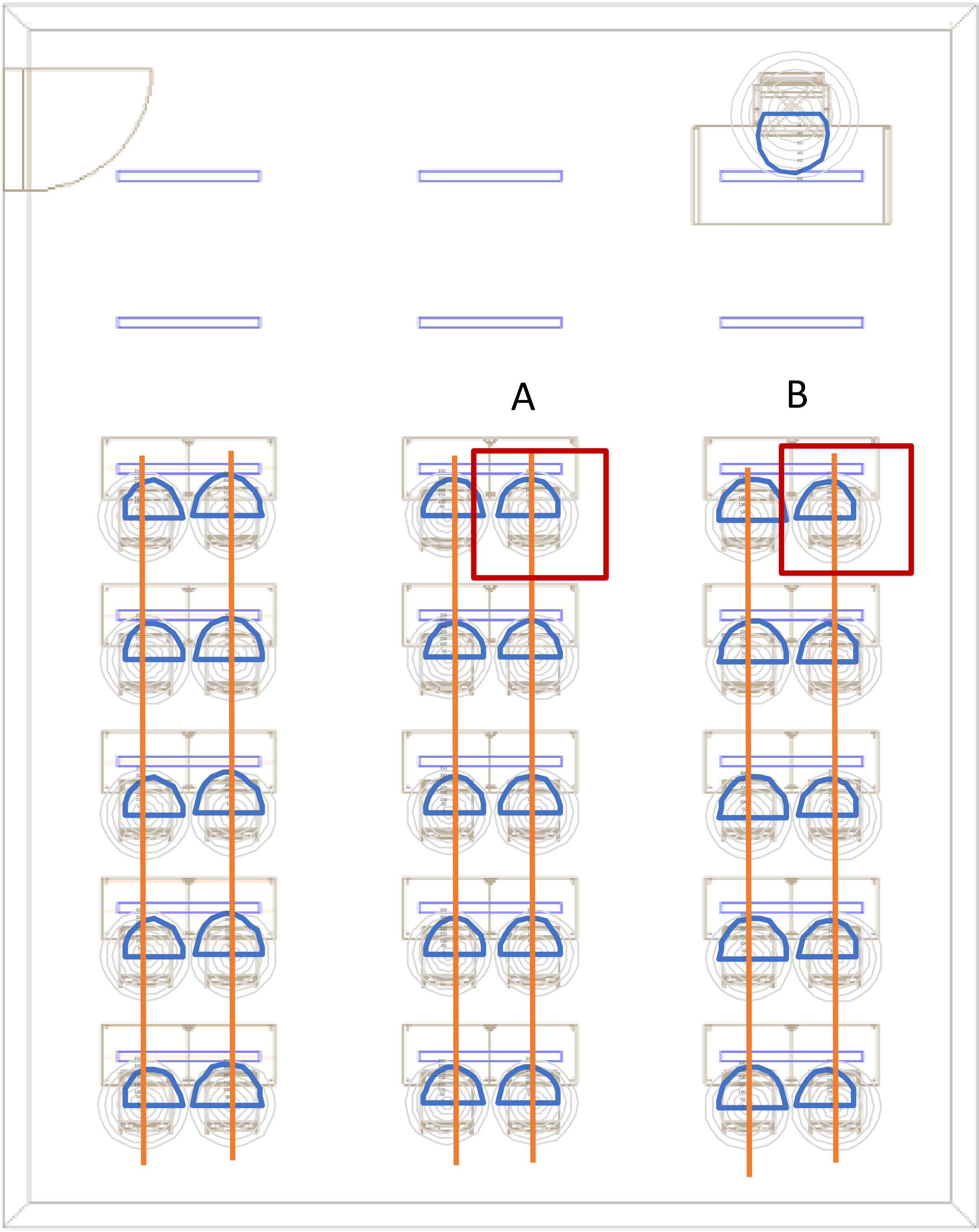


Figure 64: The calculation points polar diagrams plan of direct / indirect pendant linear light – flood distribution. (Author 2020)

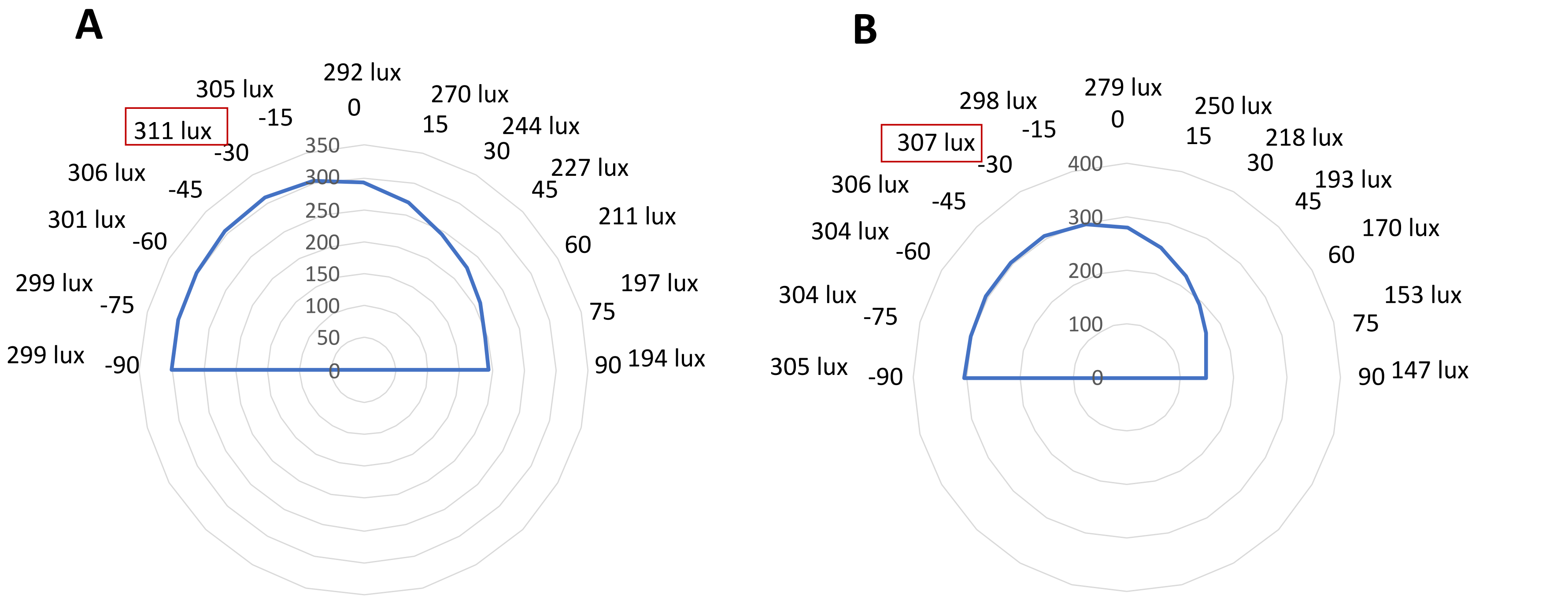


Figure 65: Calculation point polar diagram for direct/indirect pendant linear light-flood-3000K, from left to right (a) calculation point at position A (b) calculation point at position B, (Author 2020)

- **Direct / indirect linear pendant light, wide flood beam distribution**

In the wide flood cases 3000 K, 3500K and 4000K has the same horizontal and vertical illuminance values as shown in Figure 66, Figure 67. While 5000 K has lower average illuminance values and this because of the lower lumen value for the luminaire used comparing to the other CCTs. Figure 68 shows the vertical illuminance at the teacher plane and the students as a representative of the other cases. Similar to the flood distribution, the wide flood distribution cases reaches the maximum vertical illuminance at 1.9 m, where 3000k,3500k and 4000k reaches 608 lux and 5000K reaches 677 lux as shown in Figure 69 and Figure 70. It is important to mention the maximum vertical illuminance in the wide flood distribution is higher than the maximum in the flood distribution. From Figure 71, it can be noticed that the performance of wide flood is similar to the flood distribution, where the sides receive less vertical illuminance. For clarification Figure 72, showing the vertical calculation points for position A and B, where A has a more uniform values of vertical illuminance with uniformity ratio of 0.87 and an average of 253 lux, while B has a uniformity ratio of 0.6 and an average of 219 lux. Both position A and B have a slight shift to the left side, and this is happening due to the effect of combining two luminaires in the center. Comparing flood to wide flood distribution, it can be founded that the average vertical illuminance received for position A and B at 1.2 m in the flood distribution is higher than the wide flood, although the maximum vertical illuminance was higher in the wide flood distribution.

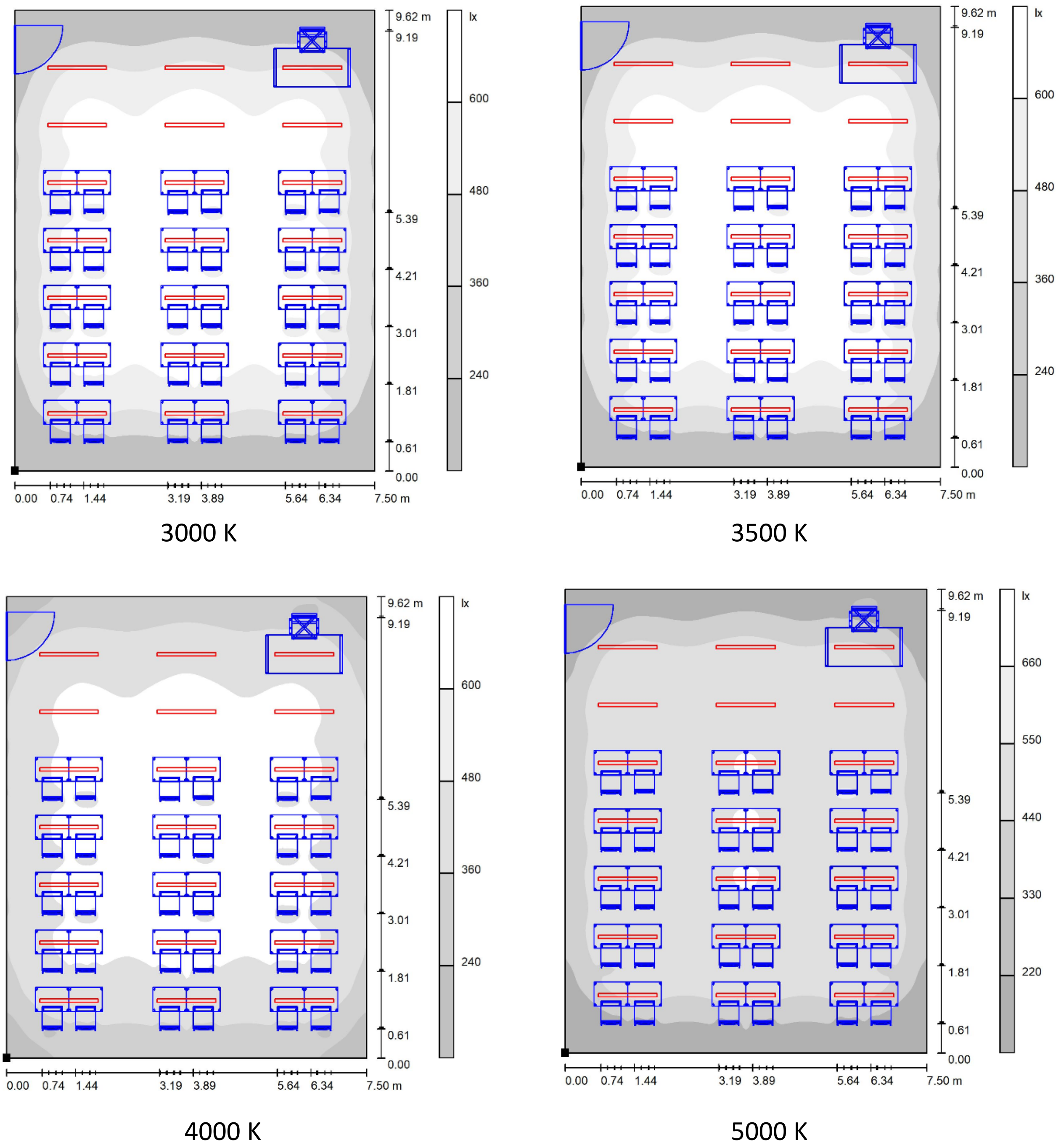
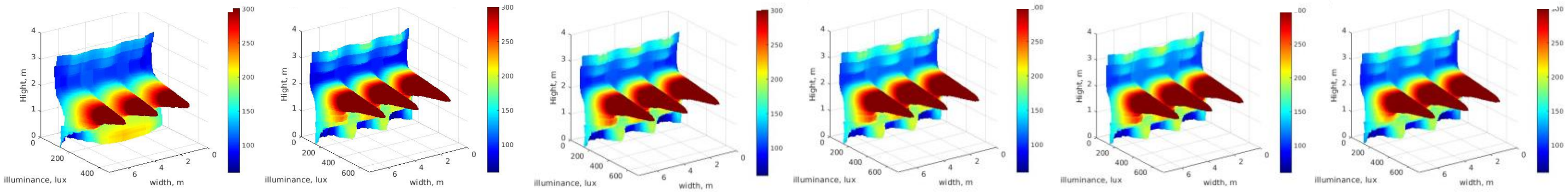
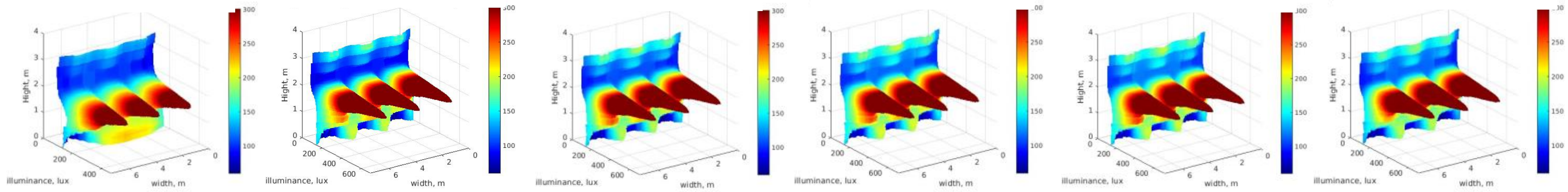


Figure 66: The horizontal calculation surface at 0.76 m for direct / indirect pendant linear light –wide flood, from left to right (a) 3000 K (b) 3500 K (c) 4000 k (c) 5000 k. (Author 2020)

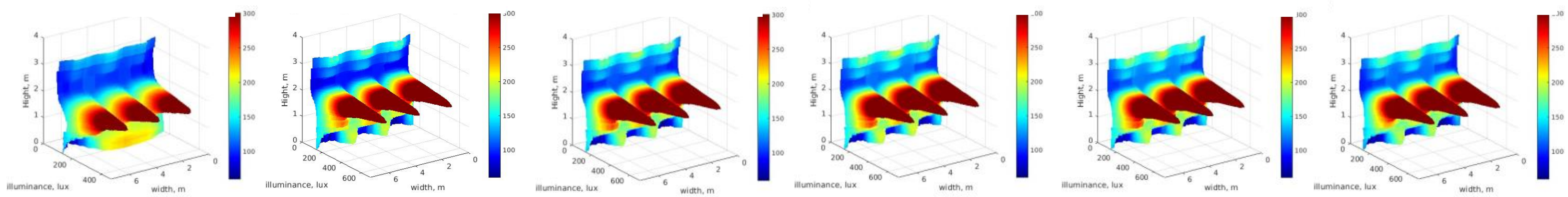
3000K – Direct/indirect linear pendant-Wide Flood



3500K – Direct/indirect linear pendant-Wide Flood



4000K – Direct/indirect linear pendant-Wide Flood



5000K – Direct/indirect linear pendant-Wide Flood

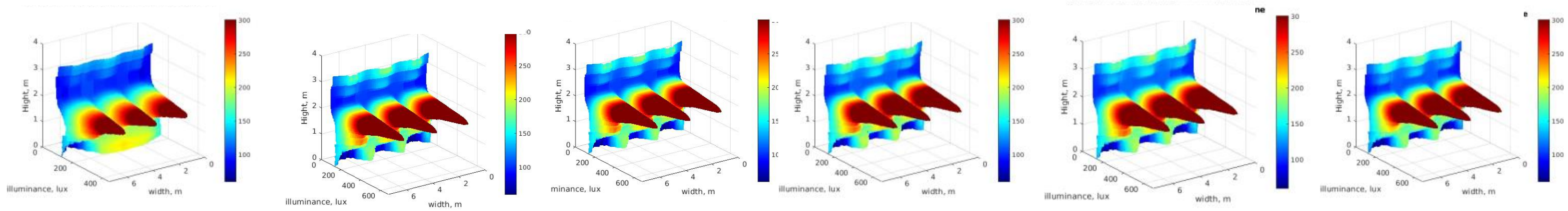


Figure 67: 3D vertical illuminance for 3000 K, 3500 K, 4000 K in the case of wide flood- direct / indirect pendant light, from left to right (a) Teacher vertical plane (b) Row 1 vertical plane (c) Row 2 vertical plane (d) Row 3 vertical plane (e) Row 4 vertical plane (f) Row 5 vertical plane. (Author 2020)

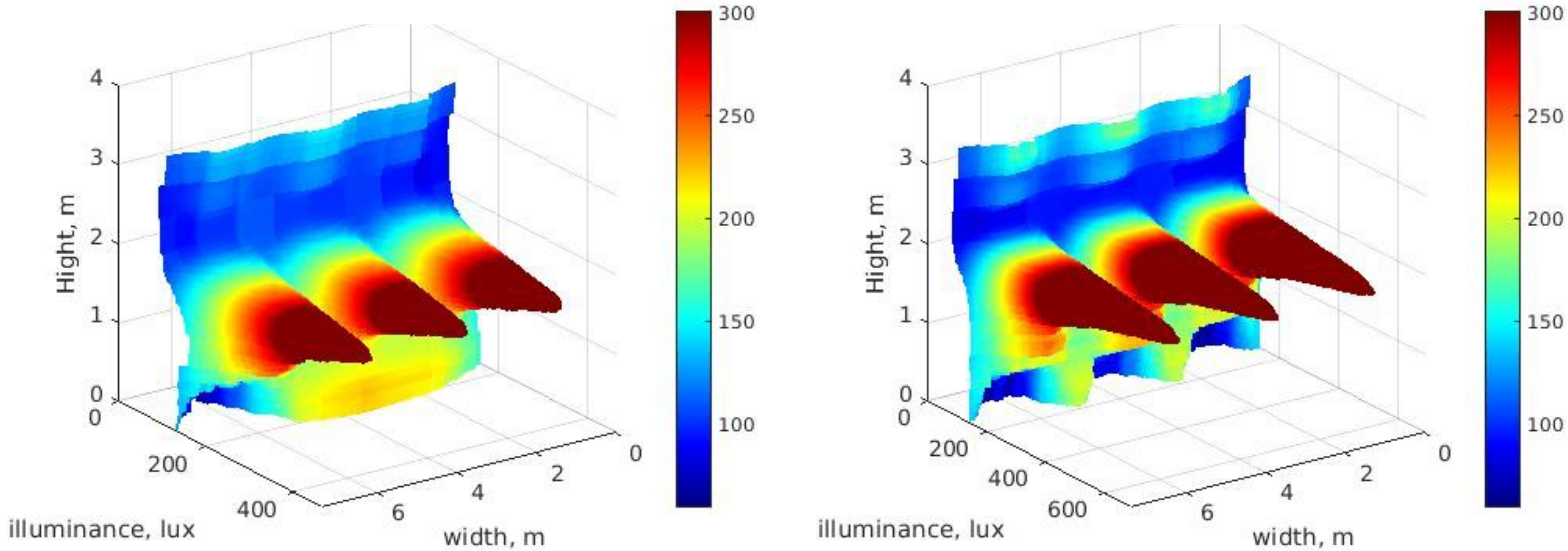


Figure 68: A representative 3D vertical illuminance for 3000 K,3500K and 4000K in the case of direct/indirect pendant linear- wide flood, from left to right (a) Teacher Vertical plane (b) representative vertical plane for row 1, 2, 3, 4, and 5 . (Author 2020)

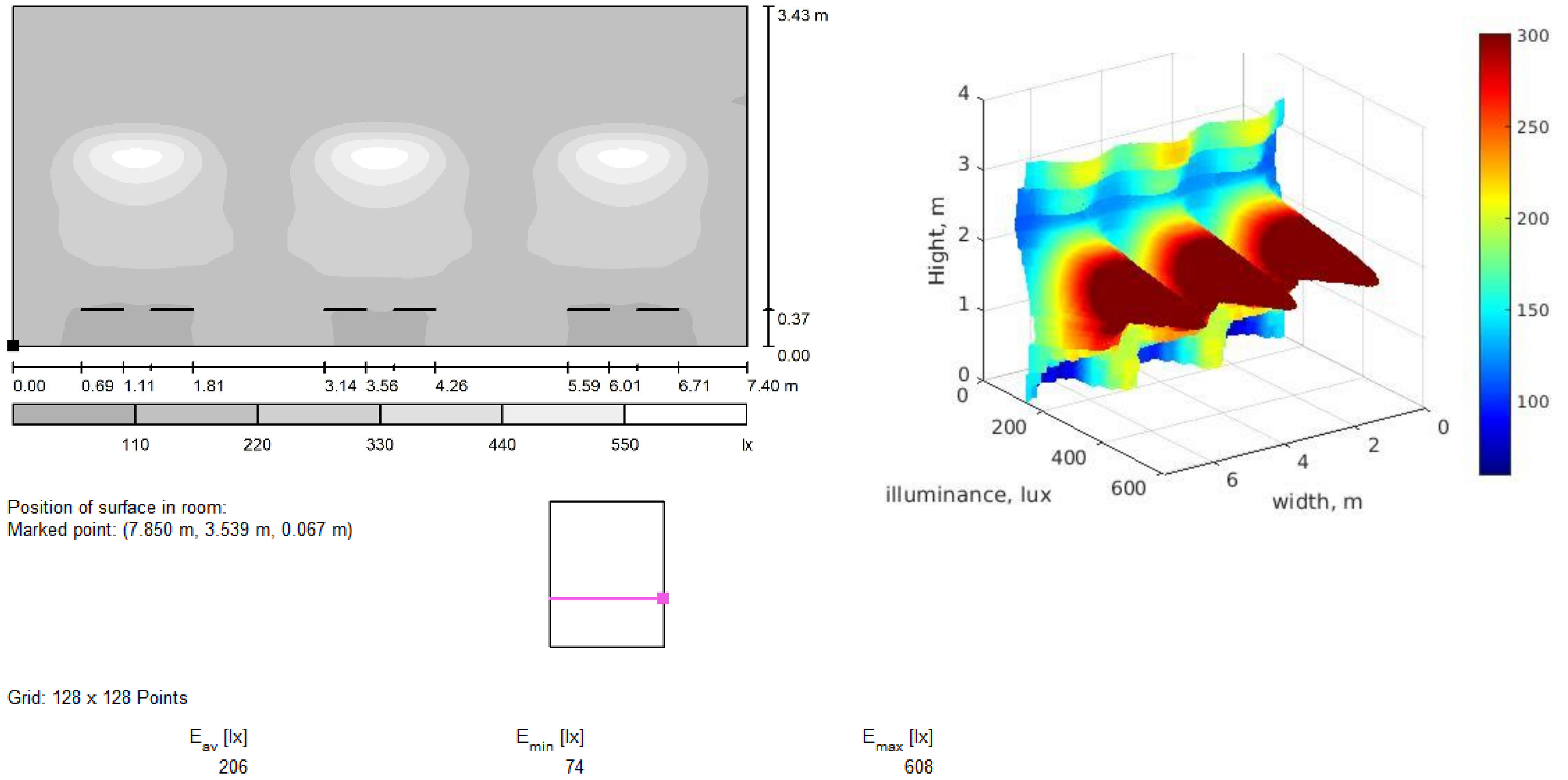
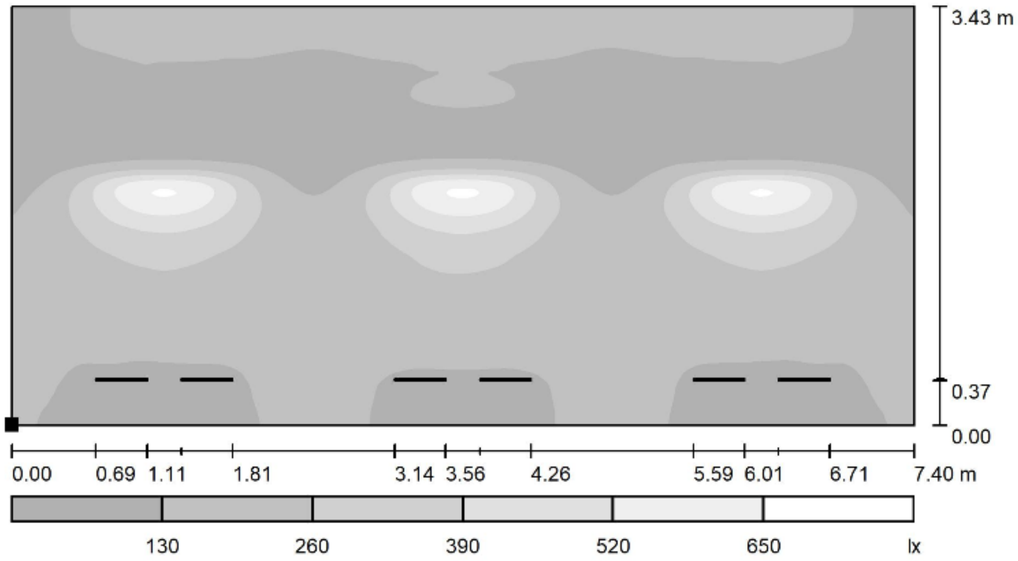
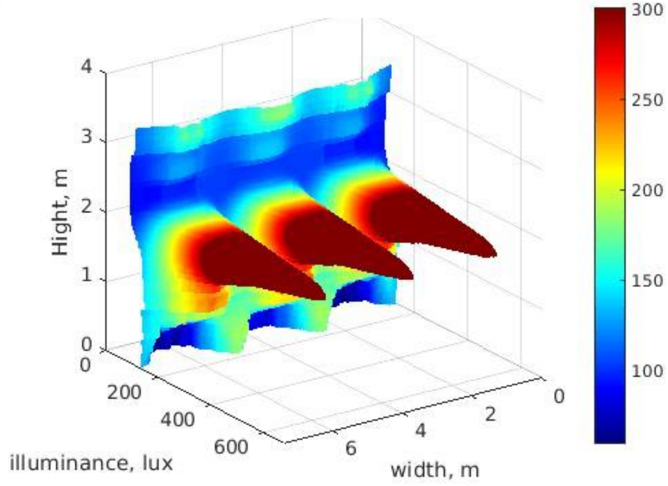
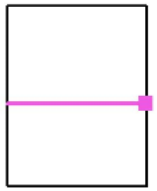


Figure 69: 2D and 3D vertical illuminance for one row in the case of direct/direct pendant linear light, wide flood, 3000 K showing the average, minimum and maximum illuminance. (Author 2020)





Position of surface in room:
Marked point: (7.850 m, 4.741 m, 0.067 m)



Grid: 128 x 128 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]
179	61	677

Figure 70: 2D and 3D vertical illuminance for one row in the case of direct/direct pendant linear light, wide flood, 5000 K showing the average, minimum and maximum illuminance. (Author 2020)

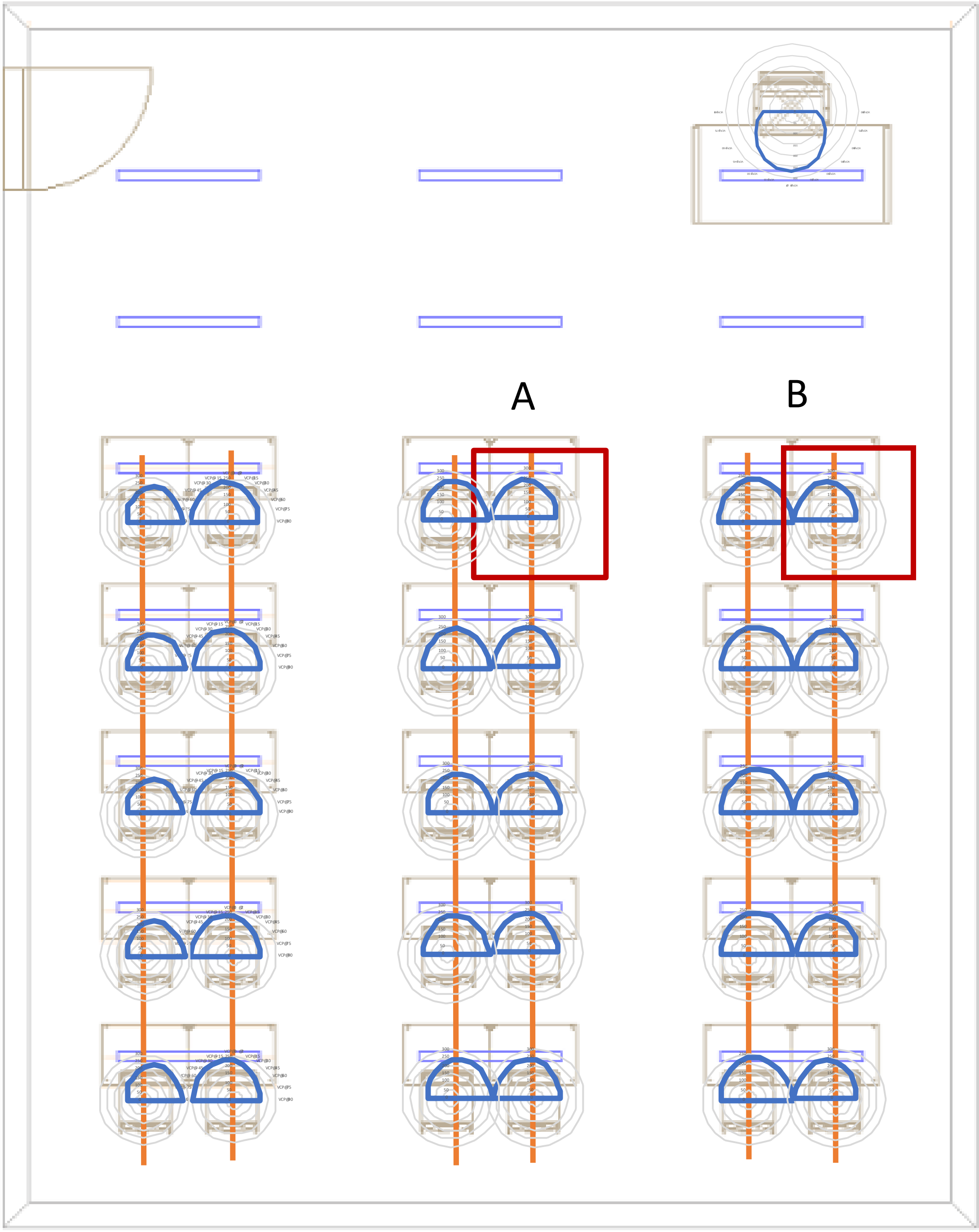


Figure 71: The calculation points polar diagrams plan of direct / indirect pendant linear light –wide flood distribution. (Author 2020)

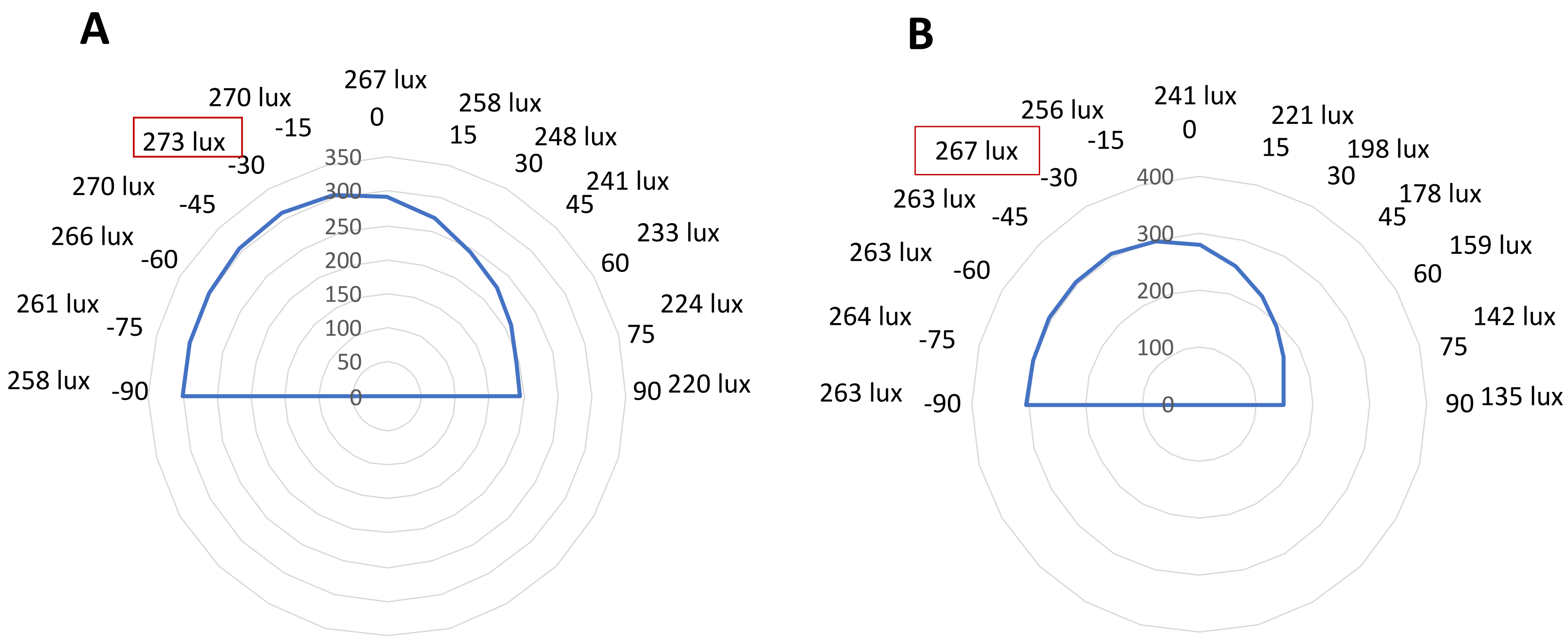


Figure 72:Calculation point polar diagram for direct/indirect pendant linear light-wide flood-3000K, from left to right (a) calculation point at position A (b) calculation point at position B, (Author 2020)

4.2.5 Direct recessed linear light

- **Direct recessed linear light, flood beam distribution**

The simulations for direct recessed linear light using flood beam distribution as shown in Figure 73. The simulated luminaries at 3000K, 3500K and 4000K have the same wattage and lumen, therefore all horizontal and vertical illuminance values were the same for these cases as shown in Figure 74 and Figure 75. For the case of 5000K, the lumen was lower which result in a lower horizontal and vertical illuminance. Figure 76 and Figure 77 shows 2D and 3D vertical illuminance for 3000K and 5000K, where the maximum vertical illuminance value of 3000K is higher than 5000K. In this luminaire type the maximum vertical illuminance is at a height of 3 m with a value of 723 lux and 694 lux for 3000K and 5000K, respectively. The vertical calculation points is shown in Figure 78 and Figure 79 where it shows the vertical illuminance values in position A and B. At position A the average vertical illuminance is 241 lux and the uniformity ratio is 0.9, while position B has a shift to the left side results in lower uniformity ration (0.6) and an average vertical illuminance of 204 lux

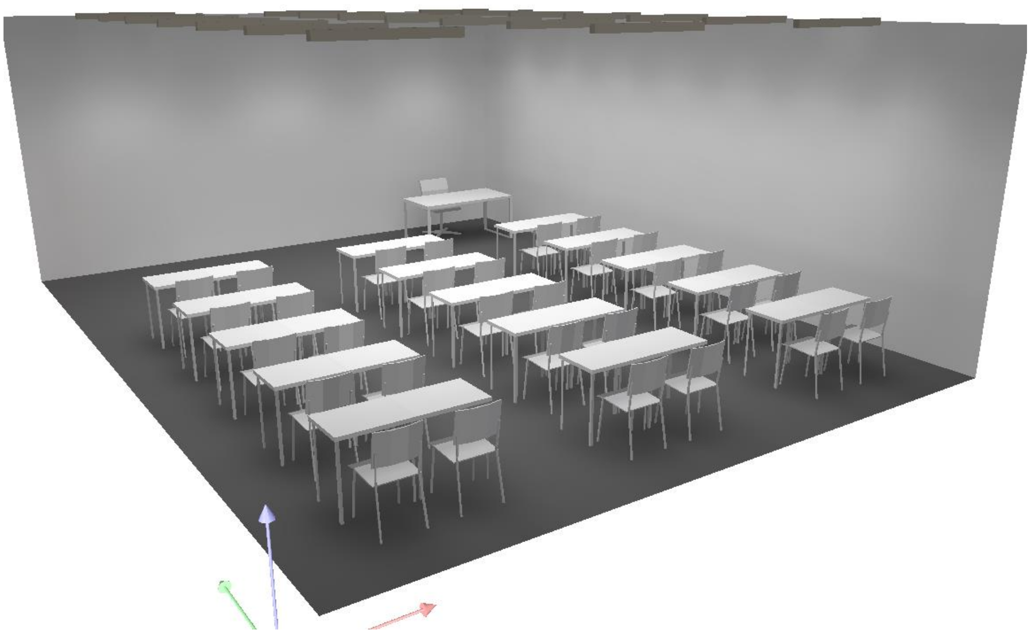


Figure 73: 3D perspective for direct recessed linear light – flood beam distribution. (Author 2020)

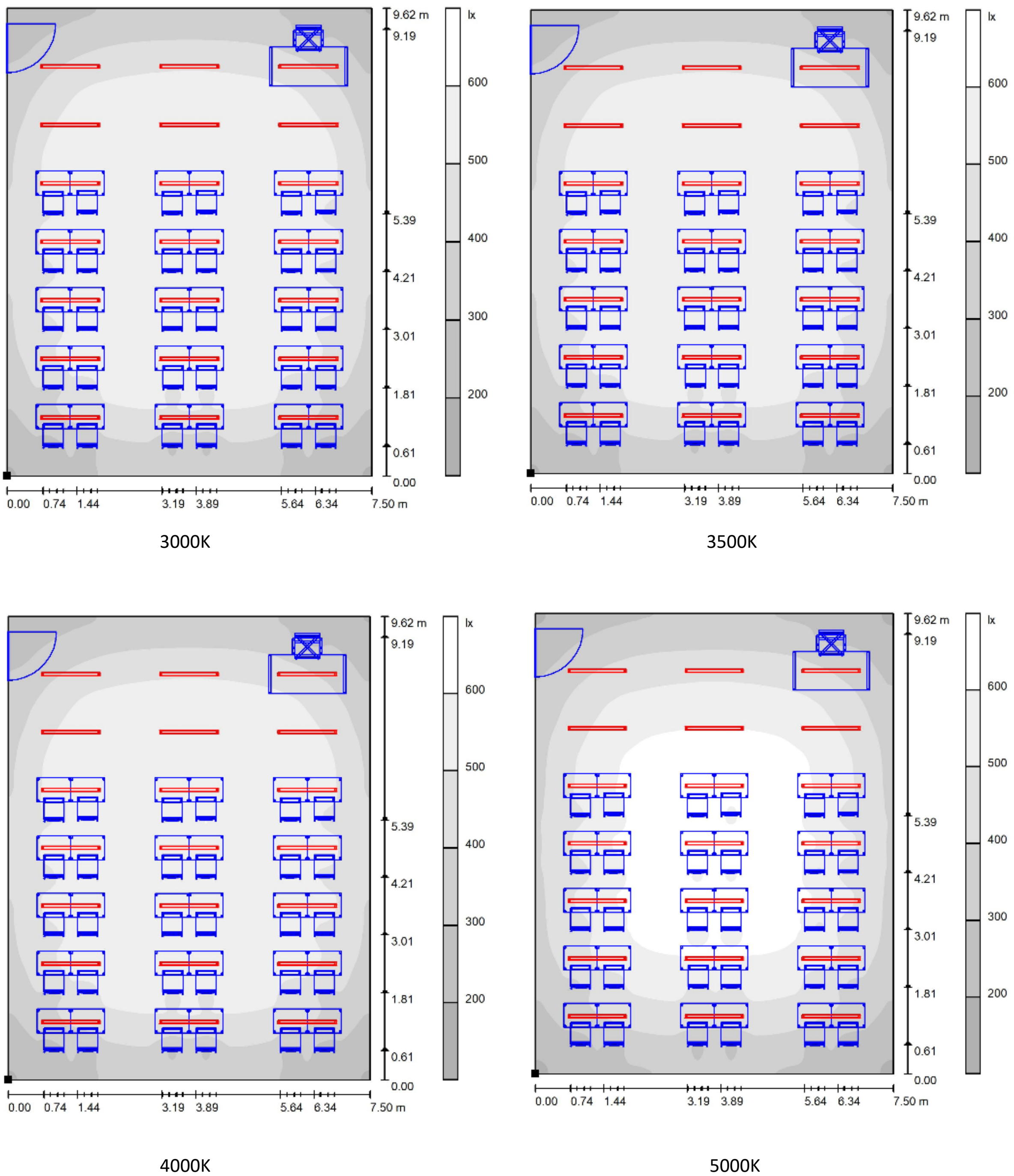
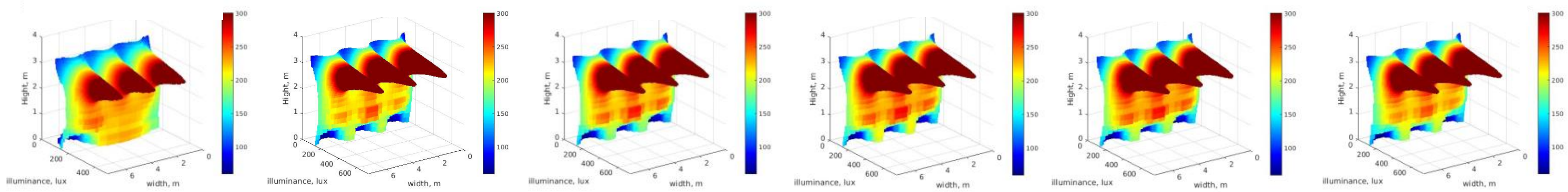
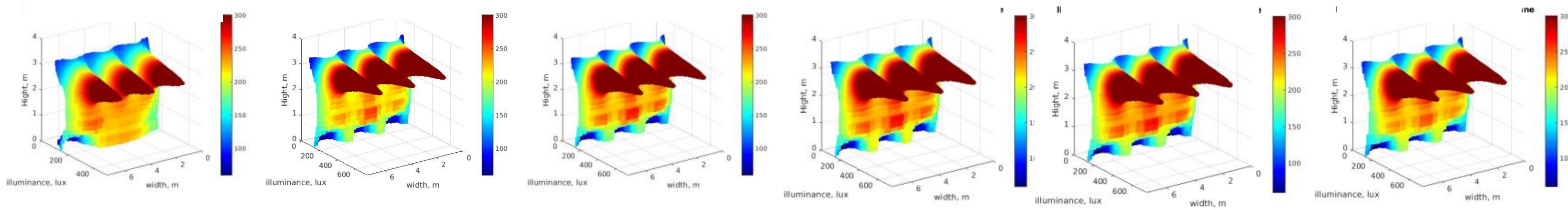


Figure 74: The horizontal calculation surface at 0.76 m for direct recessed linear light – flood, from left to right (a) 3000 K (b) 3500 K (c) 4000 k (c) 5000 k. (Author 2020)

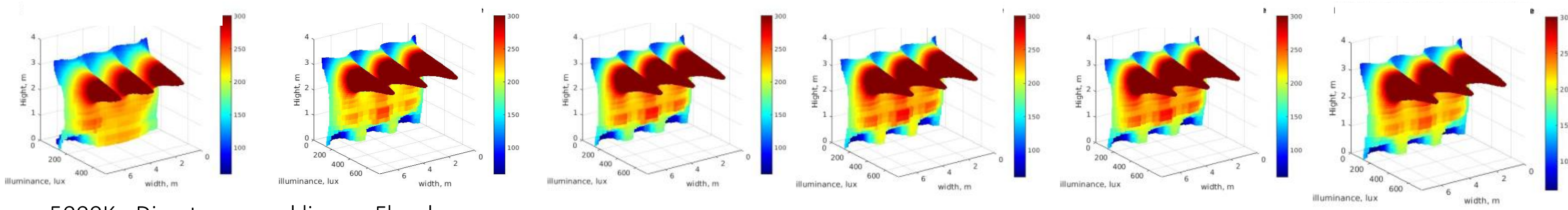
3000K – Direct recessed linear -Flood



3500K - Direct recessed linear -Flood



4000K - Direct recessed linear -Flood



5000K - Direct recessed linear -Flood

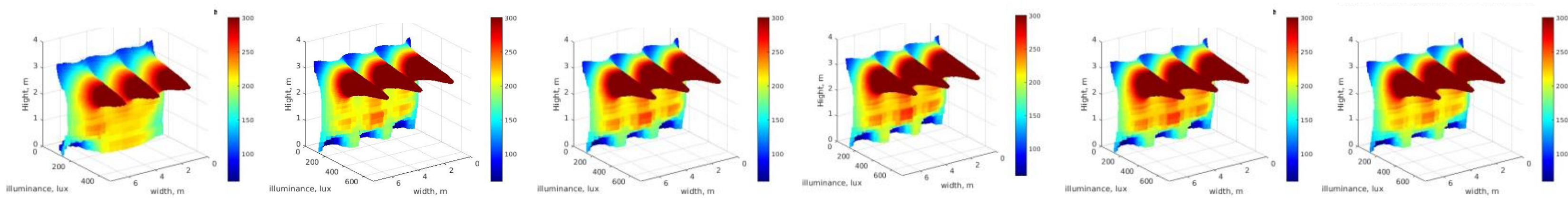
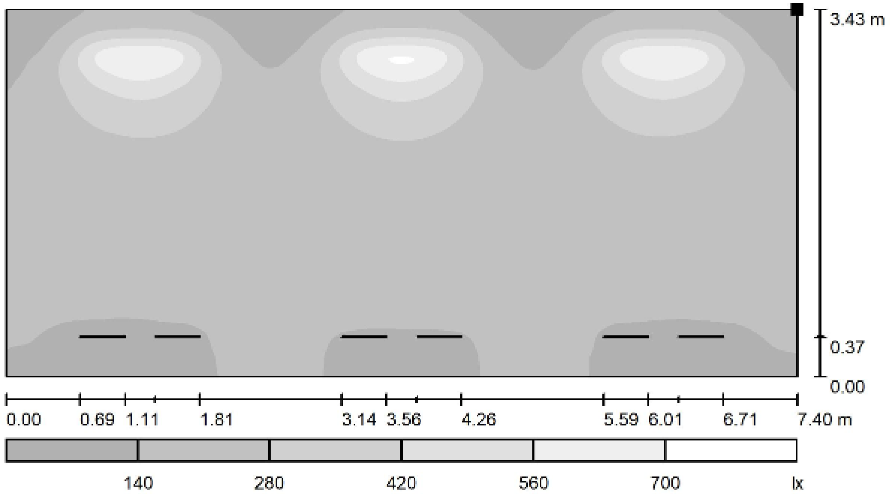
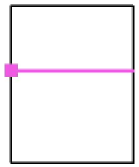
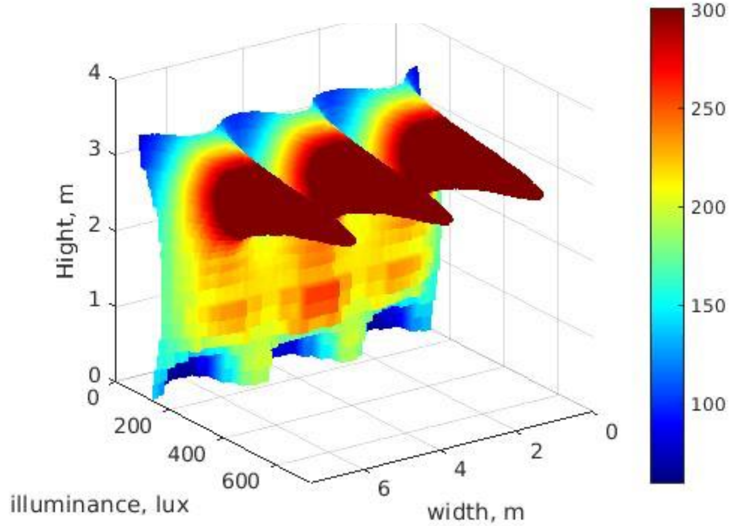


Figure 75: 3D vertical illuminance for 3000 K, 3500 K, 4000 K and 5000K in the case of direct recessed light, flood. (Author 2020)



Position of surface in room:
Marked point: (0.450 m, 5.947 m, 3.500 m)





Grid: 128 x 128 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]
226	66	723

Figure 76: 2D and 3D vertical illuminance for one row in the case of direct recessed linear light, flood, 3000 K showing the average, minimum and maximum illuminance. (Author 2020)

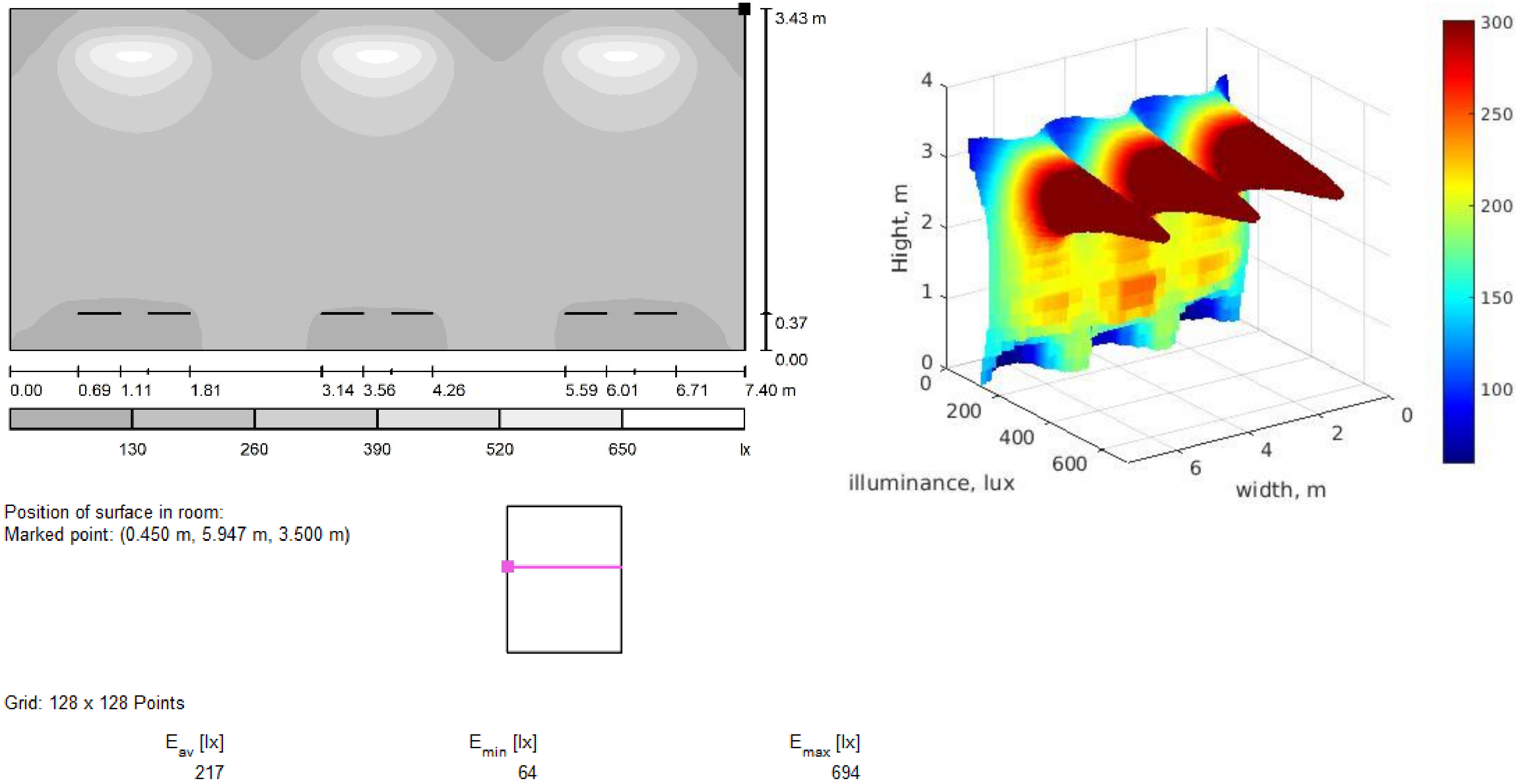


Figure 77: 2D and 3D vertical illuminance for one row in the case of direct recessed linear light, flood, 5000 K showing the average, minimum and maximum illuminance. (Author 2020)

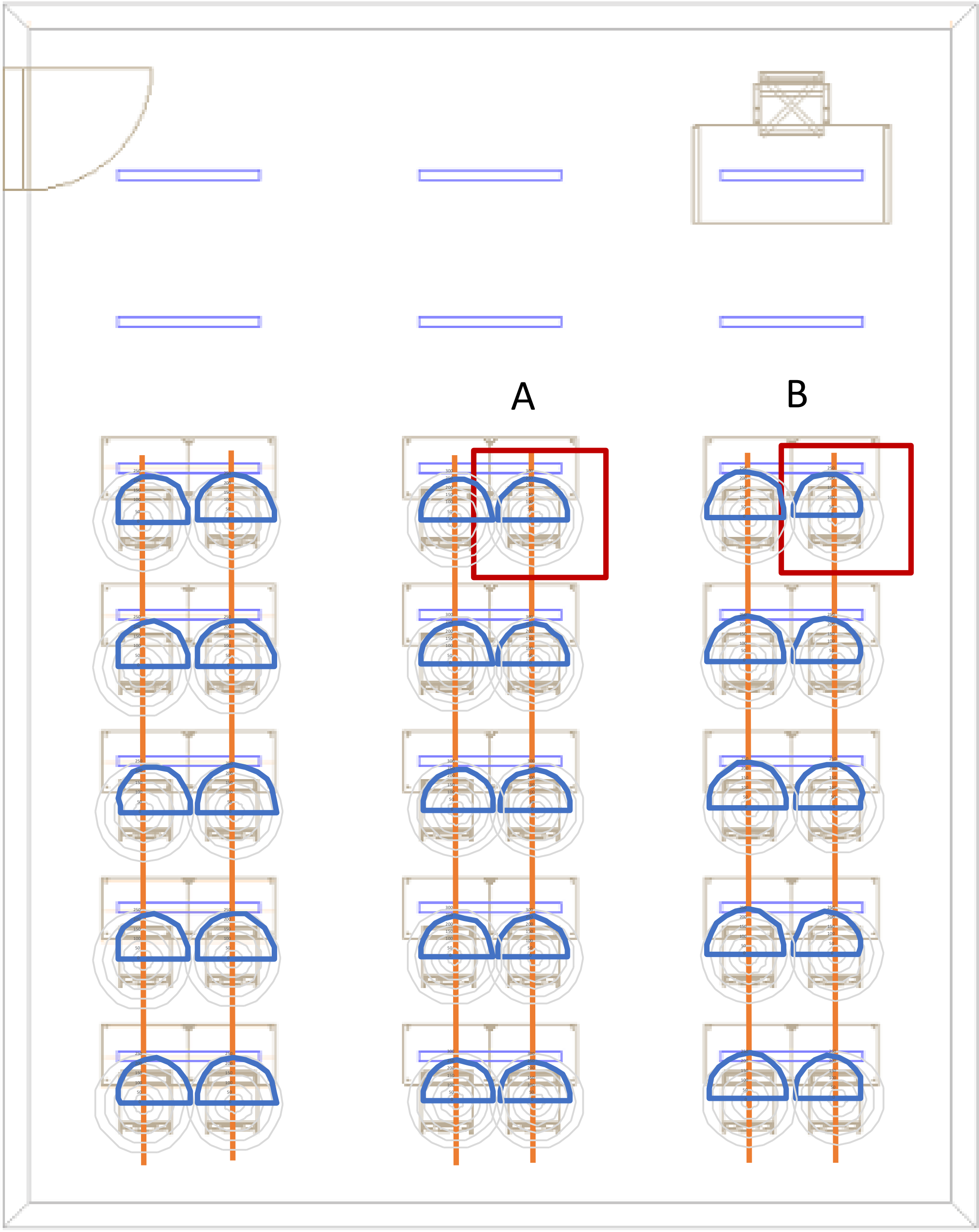


Figure 78: The calculation points polar diagrams plan of direct recessed linear light –flood distribution. (Author 2020)

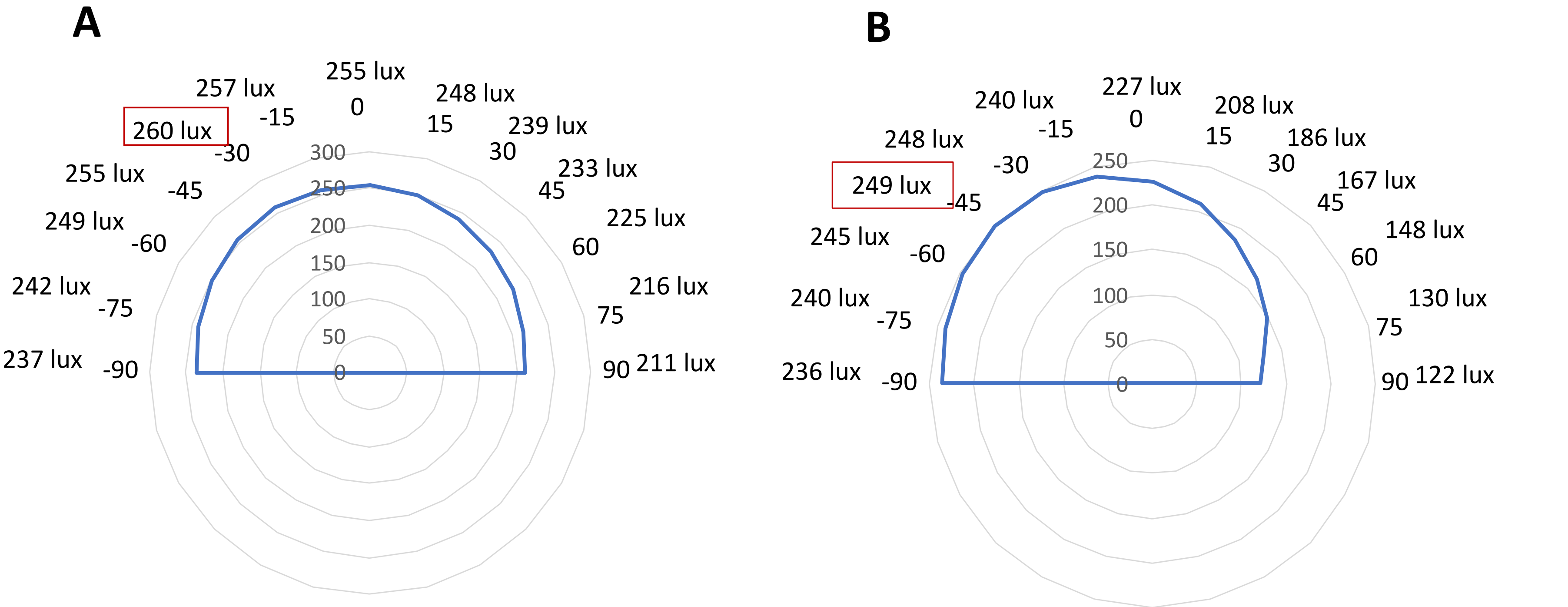


Figure 79: Calculation point polar diagram for direct recessed linear light, flood, 3000K, from left to right (a) calculation point at position A (b) calculation point at position B, (Author 2020)

- **Direct recessed linear light, wide flood beam distribution**

The simulation for direct recessed linear light with wide flood distribution shows that the cases 3000K, 3500K and 4000K have the same results, where they have common lumen value for the luminaire. While 5000K case is a bit different as shown in Figure 80. Moreover, the vertical illuminance results as shown in figure Figure 81, a high similarity between the flood and wide flood is noticed, where the maximum illuminance value for all the cases at 3 m height. By comparing, Figure 82 and Figure 83, it is noticeable that the vertical illuminance in 3000K case is a bit higher than 5000K case, where the maximum value at 3000K is 861 lux, while it is 829 lux in the case of 5000K. Moreover, the vertical calculation points plan as shown in Figure 84 confirms the similarity between the flood and the wide flood distribution. The vertical calculation points at 1.2 m height for position A and B are shown in Figure 85, where it is shown that at position A the average of vertical illuminance values is 249 lux with a high uniformity ratio (0.92), while at position B the average is 201 with a lower uniformity ratio (0.6), due to the shift in the vertical illuminance toward the left side.

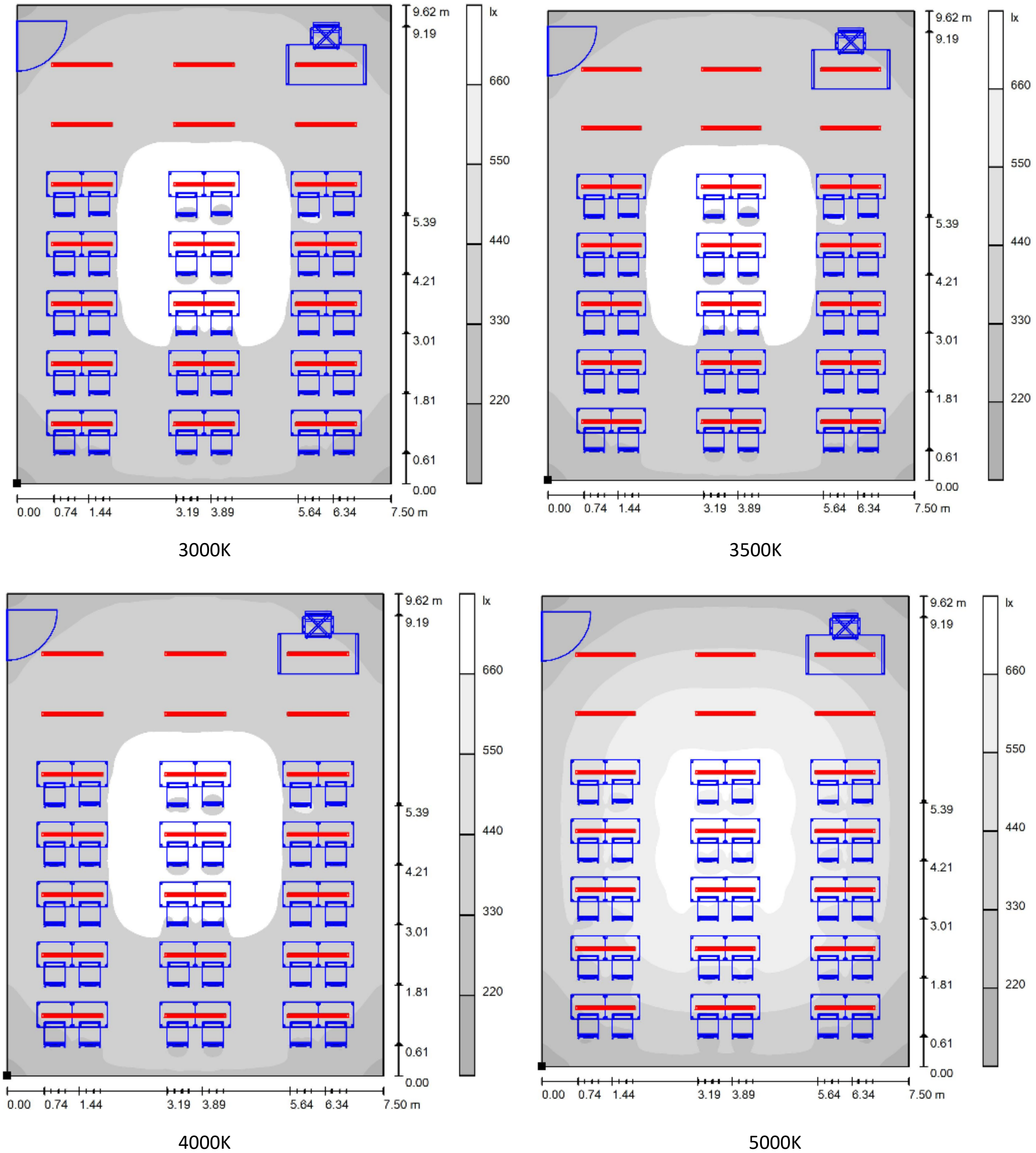
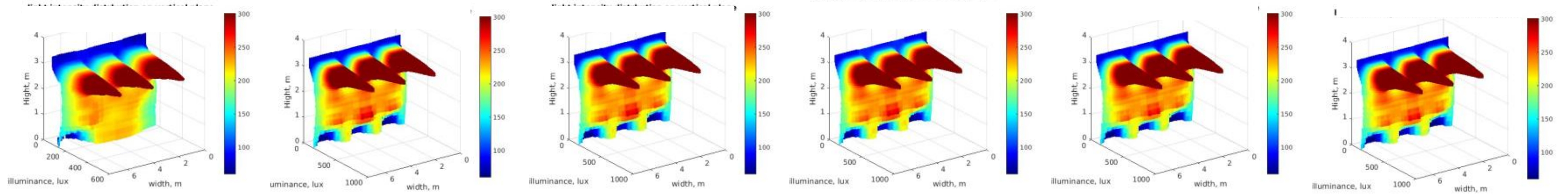
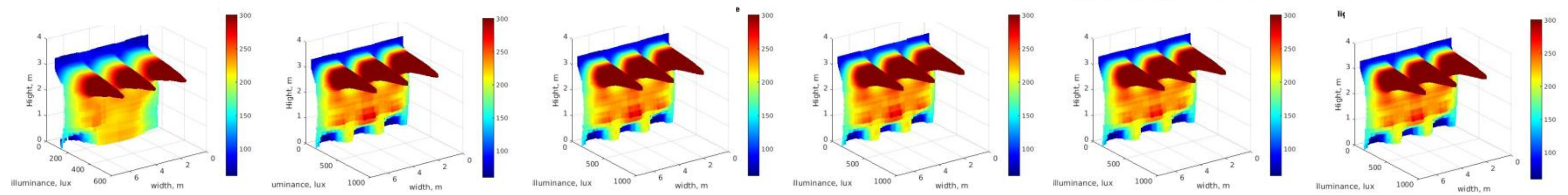


Figure 80: The horizontal calculation surface at 0.76 m for direct recessed linear light –wide flood, from left to right (a) 3000 K (b) 3500 K (c) 4000 k (c) 5000 k. (Author 2020)

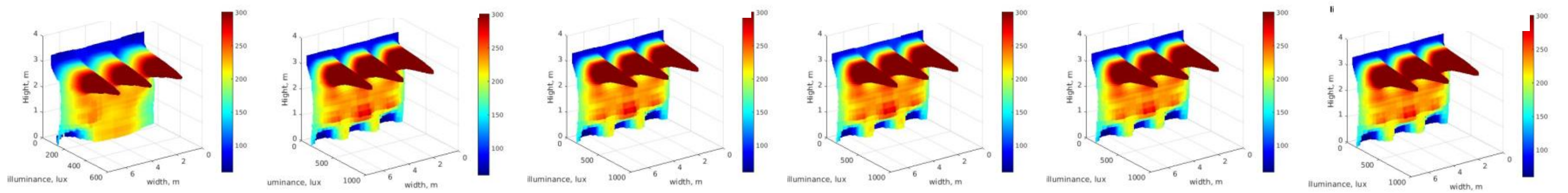
3000K – Direct recessed linear –Wide Flood



3500K - Direct recessed linear –Wide Flood



4000K - Direct recessed linear – Wide Flood



5000K - Direct recessed linear –Wide Flood

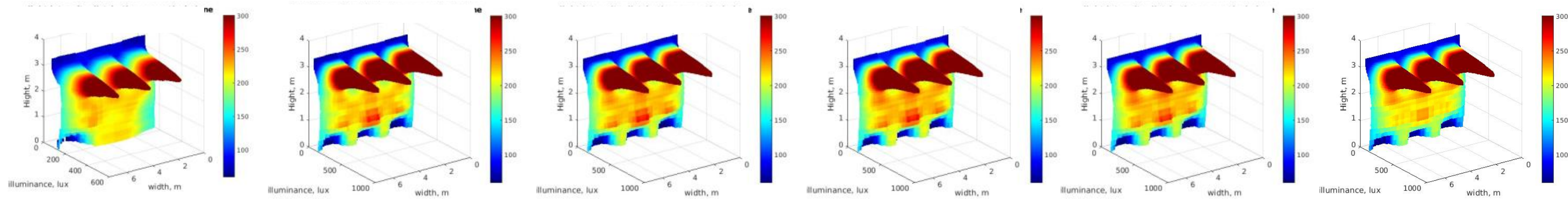
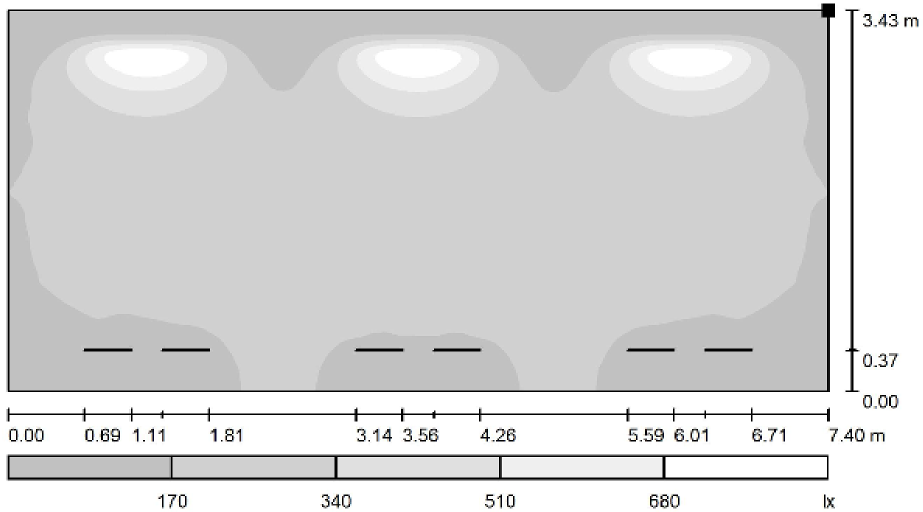
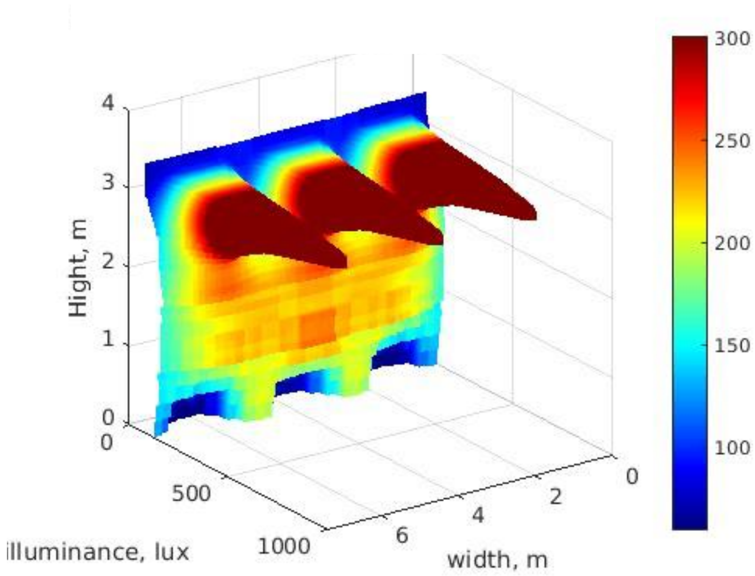
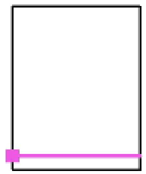


Figure 81: 3D vertical illuminance for 3000 K, 3500 K, 4000 K in the case of wide flood direct recessed light. (Author 2020)





Position of surface in room:
Marked point: (0.450 m, 1.125 m, 3.500 m)



Grid: 128 x 128 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]
222	55	862

Figure 82: 2D and 3D vertical illuminance for one row in the case of direct recessed linear light, wide flood, 3000 K showing the average, minimum and maximum illuminance. (Author 2020)

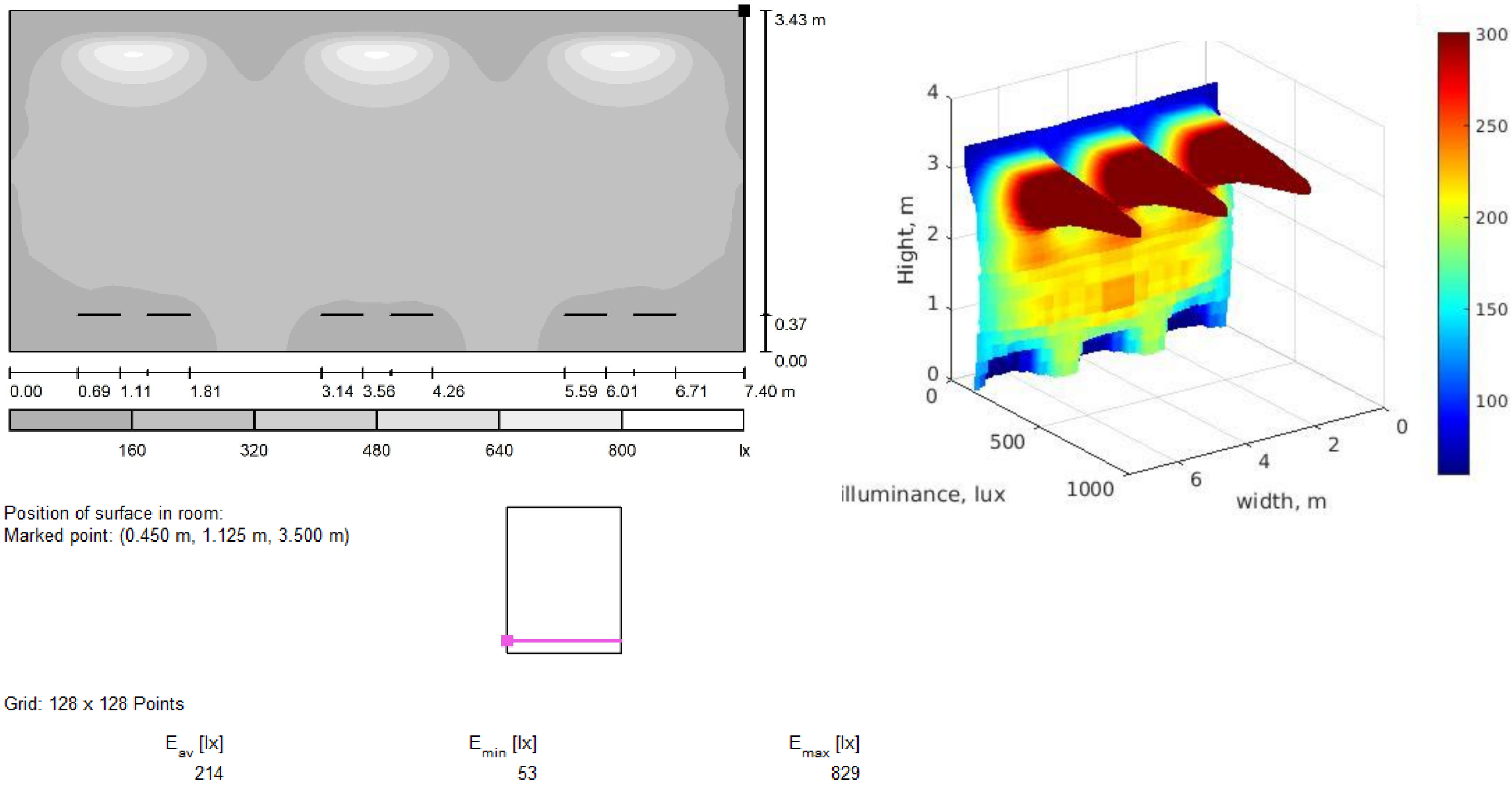


Figure 83: 2D and 3D vertical illuminance for one row in the case of direct recessed linear light, wide flood, 5000 K showing the average, minimum and maximum illuminance. (Author 2020)

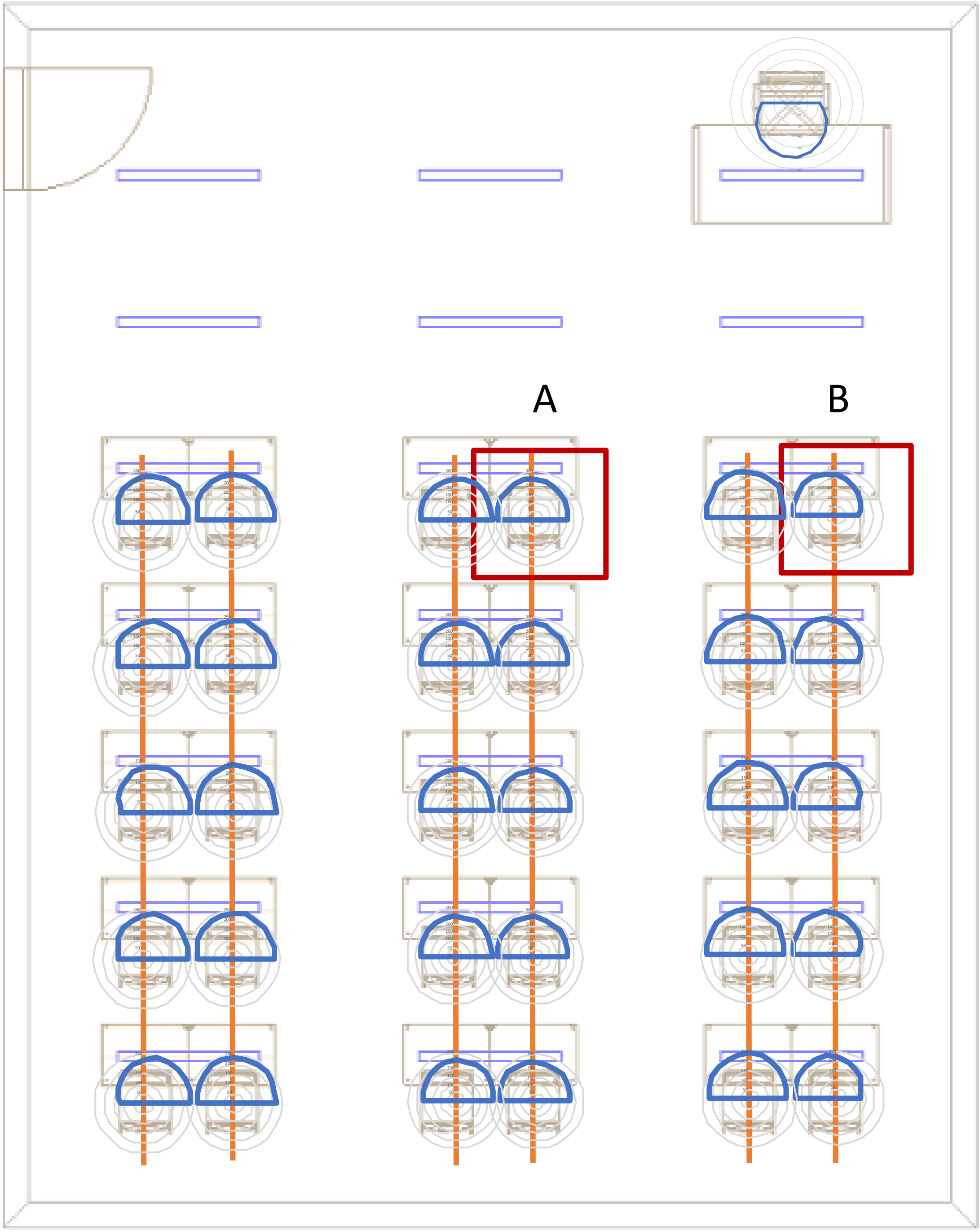


Figure 84: The calculation points polar diagrams plan of direct recessed linear light, wide flood distribution. (Author 2020)

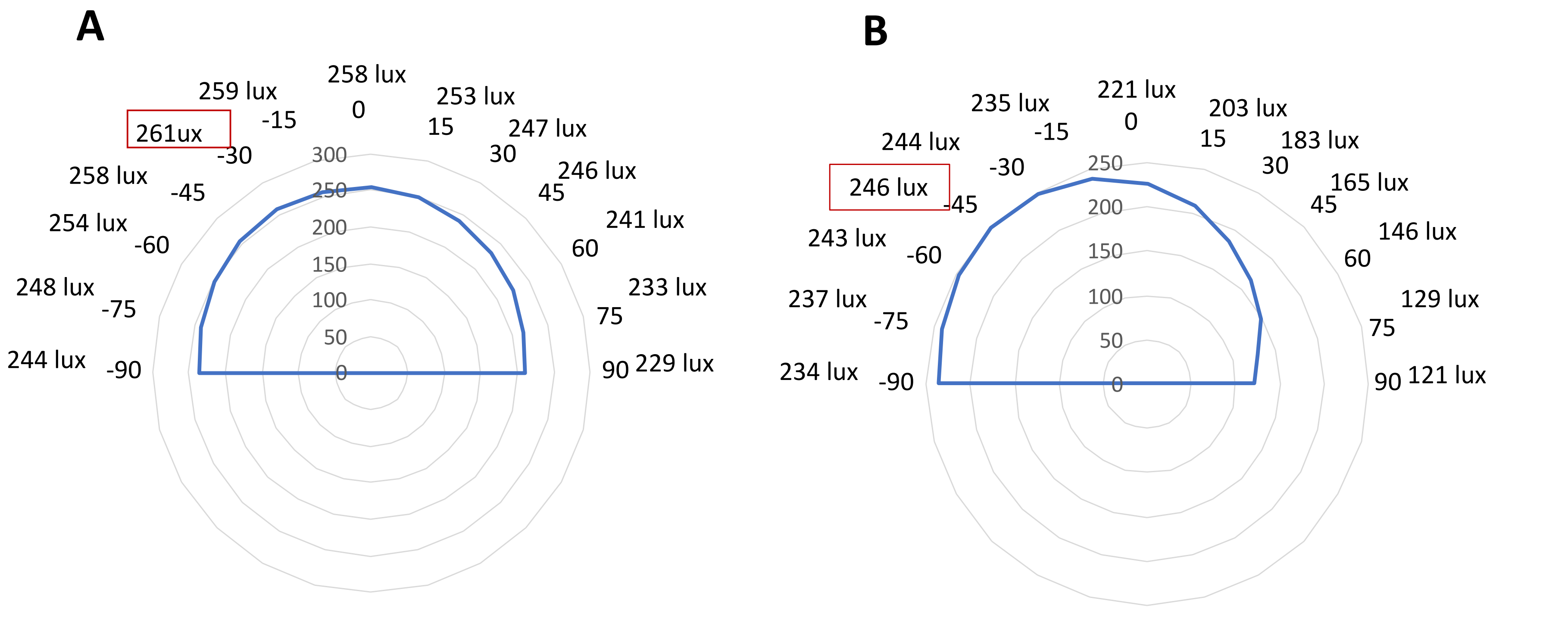


Figure 85: Calculation point polar diagram for direct recessed linear light, wide flood,3000K, from left to right (a) calculation point at position A (b) calculation point at position B, (Author 2020)

4.2.6 Summary of the vertical illuminance results for all the cases

Table 9 summarizes the results of vertical illuminance for all cases, where it can be found that the maximum E_v at the eye level reached 363 lux by the indirect pendent linear at 5000K, knowing that the luminaire used for this case has the highest lumen value among all other case (5021 lm). It is noticeable when comparing between luminaries under the same type and beam distribution that the value of the vertical illuminance at the eye level increase when the lumen is increase. Moreover, the indirect pendant linear light can deliver the most uniform vertical illuminance along the different viewing angle at eye level (uniformity ratio 0.95), followed by the direct recessed linear light with wide flood distribution. On the other hand, among all the types the recessed downlight with narrow distribution has the lowest vertical illuminance and the lowest uniformity ratio at the eye level. A further comparison between the different luminaire types at 3000K is shown in Figure 86 and Figure 87, where it can be found that the indirect pendant light result in the highest vertical illuminance along the plane with maximum value (4064 lux) at 2.7 m height and decreases until it reaches 335 lux at 1.2 m (eye level). On the other hand, the recessed downlight with narrow beam distribution has the lowest maximum vertical illuminance value (262 lux) at 2.2 m and only 203 lux reaches the eye. For downlight with flood distribution, a higher maximum value can be noticed at 2.6 m with a value of 488 lux. Moreover, it is noticeable that recessed downlight with wide flood distribution and direct recessed linear light with flood and wide flood distribution reaches the maximum vertical illuminance at the same height (3m) with a values of 704 lux, 723 lux and 851 lux, respectively, among this three types the recessed linear with wide flood has the highest value at the eye level (258 lux). In the direct pendent linear luminaire (flood and wide flood) the vertical illuminance start to increase at a lower height and reaches the maximum at 1.7 m in the case of flood beam distribution with a value of 377 lux and decreases by 133 lux to reach 224 lux at the eye level, while in the case of wide flood the maximum value at 2 m height is 657 lux which decreases sharply until it reaches 244 lux at 1.2 m. Making the flood beam distribution a better choice in delivering vertical illuminance to the eye-level. The direct/indirect pendant linear light in the case of flood and wide flood distribution reaches the maximum vertical illuminance at 1.9 m with a value of 292 lux and 267 lux, in addition it is clearly shown that the effect of the indirect light in the flood distribution has more impact in the vertical illuminance at higher levels where it can reach up to 250 lux, whereas in the wide flood it barely reaches 150 lux.

Table 9: Summary of the vertical illuminance results for all the cases. (Author 2020)

Type	Beam distrbution	CCT	Maximum E_v	Height of Maximum E_v height	Ev At 1.2 (A)	Uniformity ratio at A	Luminare lumen
Recessed downlight	Narrow	3000K	262 lux	2.2 m	203	0.5	1007
Recessed downlight	Narrow	3500K	268 lux	2.2 m	210	0.5	1043
Recessed downlight	Narrow	4000K	258 lux	2.2 m	194	0.5	969
Recessed downlight	Flood	3000K	351 lux	2.6 m	161	0.6	1001
Recessed downlight	Flood	3500K	488 lux	3 m	209	0.7	1072
Recessed downlight	Flood	4000K	492 lux	3 m	210	0.7	1080
Recessed downlight	Wide flood	3000K	704 lux	3 m	244	0.9	1079
Recessed downlight	Wide flood	3500K	645 lux	3 m	235	0.84	1117
Recessed downlight	Wide flood	4000K	650 lux	3 m	237	0.84	1125
Direct pendant linear	Flood	3000K	377 lux	1.7 m	224	0.74	924
Direct pendant linear	Flood	3500K	450 lux	1.7 m	267	0.74	1103

Direct pendant linear	Flood	4000K	453 lux	1.7 m	269	0.74	1111
Direct pendant linear	Flood	5000K	692 lux	1.9 m	294	0.6	2351
Direct pendant linear	Wide flood	3000K	657 lux	2 m	244	0.72	1107
Direct pendant linear	Wide flood	3500K	567 lux	2 m	212	0.72	960
Direct pendant linear	Wide flood	4000K	571 lux	2 m	213	0.72	967
Direct pendant linear	Wide flood	5000K	832 lux	2 m	258	0.6	2298
Indirect pendant linear	Butterfly	3000K	4064 lux	2.7 m	335	0.95	4636
Indirect pendant linear	Butterfly	3500K	4170 lux	2.7 m	344	0.95	4753
Indirect pendant linear	Butterfly	4000K	4269 lux	2.7 m	352	0.95	4870
Indirect pendant linear	Butterfly	5000K	4401 lux	2.7 m	363	0.95	5021
Direct/indirect pendant	Flood	3000K	556 lux	1.9 m	292	0.73	2581
Direct/indirect pendant	Flood	3500K	556 lux	1.9 m	292	0.73	2581
Direct/indirect pendant	Flood	4000K	556 lux	1.9 m	292	0.73	2581
Direct/indirect pendant	Flood	5000K	585 lux	1.9 m	272	0.66	2351

Direct/indirect pendant	Wide flood	3000K	689 lux	1.9 m	267	0.87	2310
Direct/indirect pendant	Wide flood	3500K	689 lux	1.9 m	267	0.87	2310
Direct/indirect pendant	Wide flood	4000K	689 lux	1.9 m	267	0.87	2310
Direct/indirect pendant	Wide flood	5000K	663 lux	1.9 m	233	0.69	2222
Direct recessed linear	Flood	3000K	723 lux	3 m	255	0.88	2448
Direct recessed linear	Flood	3500K	723 lux	3 m	255	0.88	2448
Direct recessed linear	Flood	4000K	723 lux	3 m	255	0.88	2448
Direct recessed linear	Flood	5000K	694 lux	3 m	245	0.88	2351
Direct recessed linear	Wide flood	3000K	851 lux	3 m	258	0.92	2389
Direct recessed linear	Wide flood	3500K	851 lux	3 m	258	0.92	2389
Direct recessed linear	Wide flood	4000K	851 lux	3 m	258	0.92	2389
Direct recessed linear	Wide flood	5000K	818 lux	3 m	248	0.92	2298

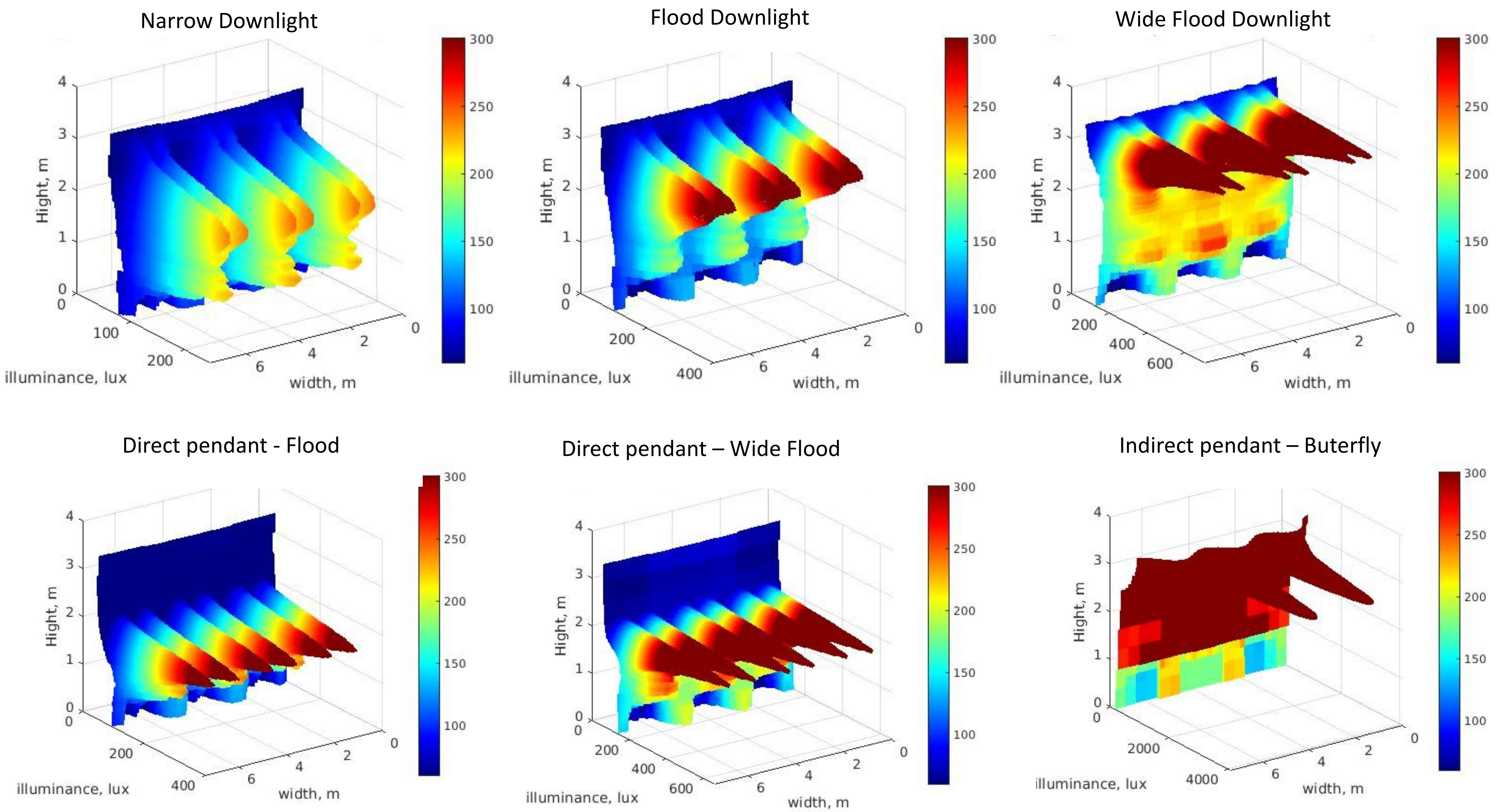


Figure 86: 3D vertical illuminance for one row plane, from left to right(a)downlight narrow (b) downlight flood (c) downlight wide flood (d) direct pendant flood (e) direct pendant wide flood (f) indirect pendant. (Author 2020)

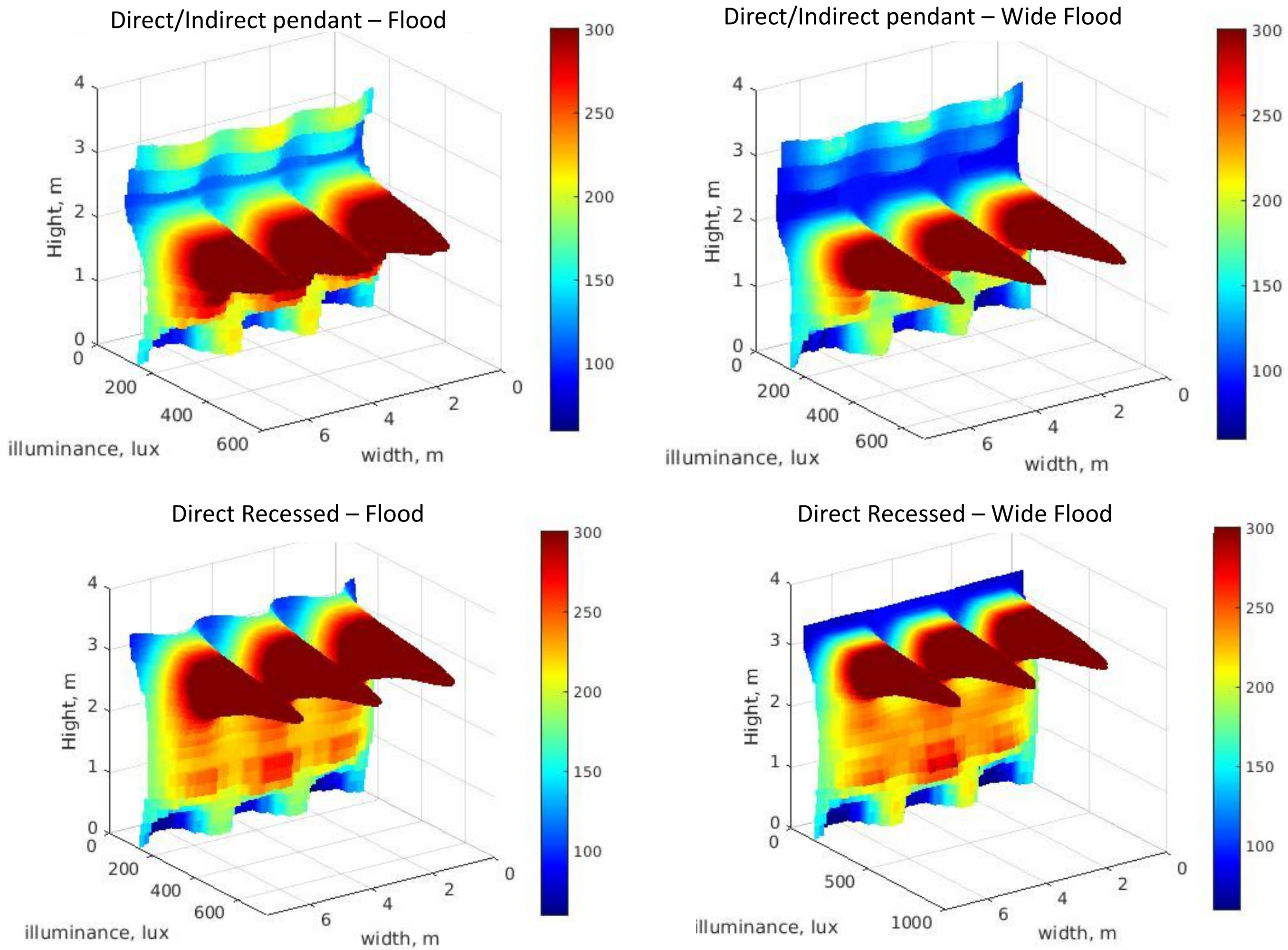


Figure 87: 3D vertical illuminance for one row plane, from left to right ,(a) direct/indirect flood (b)direct/indirect wide flood (c) direct recessed linear flood (e) direct recessed linear wide flood.(Author 2020)

4.3 CS Calculations

The CS is a metric developed by LRC and was validated in many previous researches. In this research, CS is used to evaluate the selected luminaries in terms of circadian lighting. The values of CS were obtained using CS calculator which shown in Figure 88. The calculator enables different light source selection based on the CCT. The selected source in this research is LED Phosphor Blue, which changes according to the different examined CCTs. In addition, it is required to add the vertical illuminance value at the eye level in order to obtain the CS value.

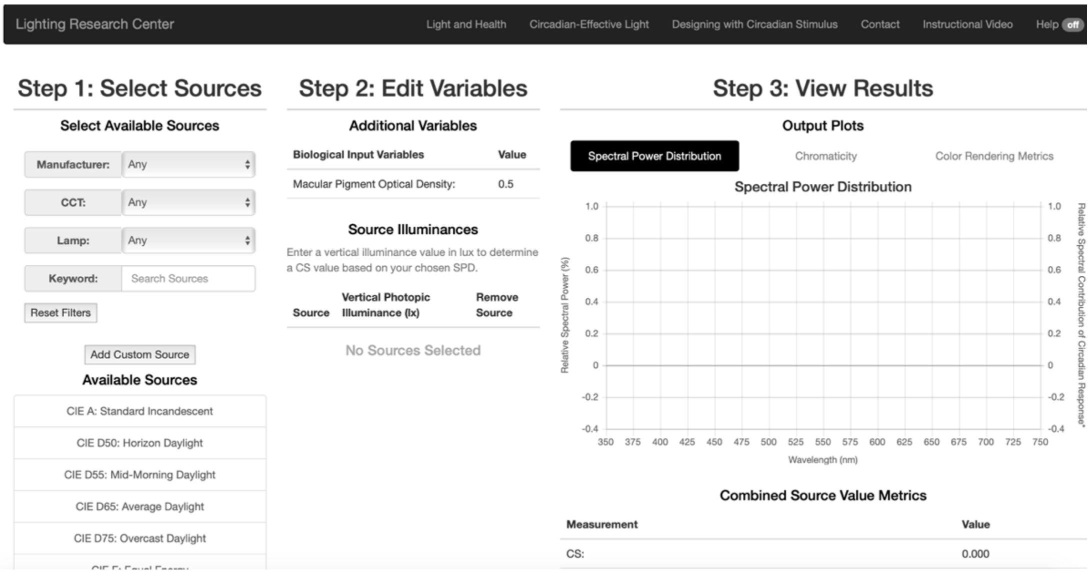


Figure 88: CS calculator (Author 2020)

Two positions (A and B) were selected to represent the other positions in order to calculate the CS value as shown in Figure 89 , expecting that the two points will have different results based on their location. The vertical illuminance value which used to calculate the CS is measured at 1.2 m (eye level) toward the whiteboard.

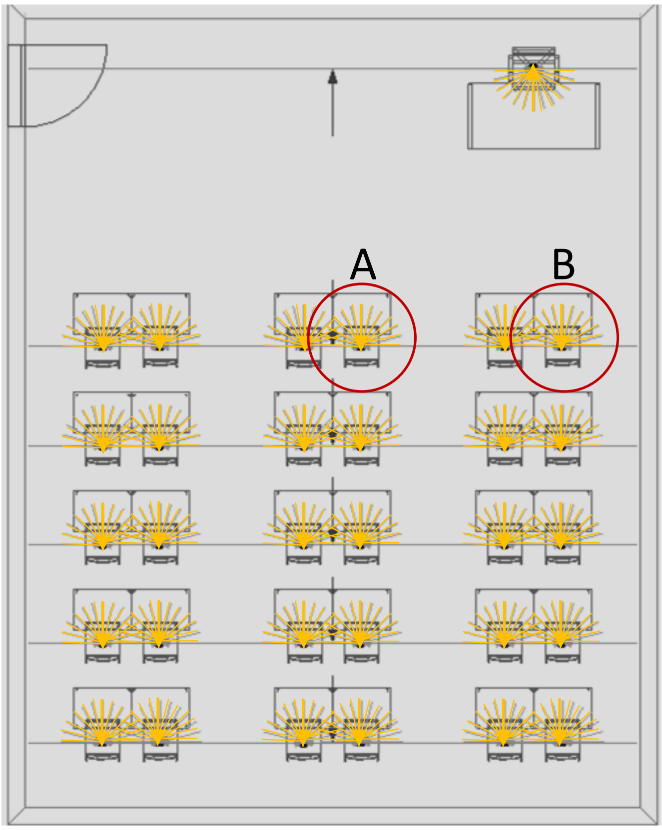


Figure 89: The selected position to calculate the CS value (Author 2020)

In educational spaces, the recommended CS values were settled based on schools operating hours as following; from wake to 12 pm CS should meet 0.4 while from 12 pm – 1 pm CS can be from 0.4 – 0.3. In all trials, 0.3 was the selected CS to be met across the classroom. It is important to mention that the CS value has to decrease as time passes to not disturb the student circadian rhythm. During the data collection stage, it was notable that luminaires' lumen value varies depending on the different manufactures. This was reflected on the simulation results where it was founded that the higher lumens result in a higher vertical illuminance. In order eliminate the effect of the change in lumen values among the different luminaires across all cases, a data normalization step was applied to the vertical illuminance, which tends calculate the ratio of lux/lumen. This will help to select the best luminaire type regardless of its lumen. In terms of lux/lumen, the higher ratio means the higher amount of vertical illuminance in lux that the students' eye receives. Moreover, the results show that the CS value is increasing when changing the CCT from 3000K to 3500K, then it drops at 4000K and increases at 5000K. For instance, in all cases, 4000 K achieved lower CS than 3000 K and 3500 K, which confirms previous studies' conclusion.

4.3.1 Recessed downlight CS calculations

Table 10 shows that none of the recessed downlights meet the target of 0.3 CS. It is also notable that at 3000 K and 3500 K with narrow light beam distribution, the difference in vertical illuminance between A and B positions is the lowest compared to other cases. Moreover, as the light beam distribution gets wider, the difference in vertical illuminance between positions A and B gets higher. Therefore, the difference in the CS between them is getting higher.

Table 10: Recessed downlight CS calculations (Author 2020)

Recessed Downlight					
	Measuring position @1.2 m	**3000K**			
		Vertical E (lux)	CS	lumen(lm)	Lux/lumen
Narrow	**A**	203	0.213	1007	0.202
	B	199	0.210	1007	0.198
Flood	**A**	180	0.194	1001	0.180
	B	174	0.189	1001	0.174
Wide flood	**A**	244	0.244	1079	0.226
	B	212	0.220	1079	0.196
	Measuring position @1.2 m	**3500K**			
		Vertical E (lux)	CS	lumen(lm)	Lux/lumen
Narrow	**A**	210	0.268	1043	0.201
	B	206	0.264	1043	0.198
Flood	**A**	209	0.267	1072	0.195
	B	195	0.255	1072	0.182
Wide flood	**A**	235	0.289	1117	0.210
	B	212	0.270	1117	0.190
		4000K			

	Measuring position @1.2 m	Vertical E (lux)	CS	lumen(lm)	Lux/lumen
Narrow	**A**	194	0.110	969	0.200
	B	189	0.107	969	0.195
Flood	**A**	210	0.119	1080	0.194
	B	196	0.111	1080	0.181
Wide flood	**A**	237	0.133	1125	0.211
	B	214	0.121	1125	0.190

4.3.2 Direct pendant linear light CS calculations

In the case of direct pendant linear light as shown in Table 11, only one case meets the value of 0.3 CS, which is flood beam distribution at 3500 K.it is In addition, it is noticeable that the cases of 3000K, 3500K, and 4000K has the same value of (Lux/Lumen), which means that their capability to deliver vertical illuminance is the same. Only at 5000K the lux/lumen is different, where it founded that the luminaire watt is different only in this case.

Table 11: Direct pendant linear light CS calculations (Author 2020)

Direct Pendant Linear Light					
	Measuring position @1.2 m	**3000K**			
		Vertical E (lux)	CS	lumen(lm)	Lux/lumen
Flood	**A**	224	0.229	924	0.242
	B	222	0.228	924	0.240
Wide-Flood	**A**	244	0.244	1107	0.220
	B	240	0.241	1107	0.217
	Measuring position @1.2 m	**3500K**			
		Vertical E (lux)	CS	lumen(lm)	Lux/lumen
Flood	**A**	267	**0.313**	1103	0.242
	B	266	**0.312**	1103	0.241
Wide-Flood	**A**	212	0.27	960	0.221
	B	209	0.267	960	0.218
	Measuring position @1.2 m	**4000K**			
		Vertical E (lux)	CS	lumen(lm)	Lux/lumen
Flood	**A**	269	0.149	1111	0.242

	B	267	0.148	1111	0.240
Wide-Flood	**A**	213	0.12	967	0.220
	B	210	0.119	967	0.217
	Measuring position @1.2 m	**5000K**			
		Vertical E (lux)	CS	lumen(lm)	Lux/lumen
Flood	**A**	294	0.281	2351	0.125
	B	285	0.275	2351	0.121
Wide-Flood	**A**	258	0.257	2298	0.112
	B	253	0.253	2298	0.110

4.3.3 Indirect pendant linear light CS calculations

As shown in Table 12 for the indirect pendant linear light, 3000K, and 5000K delivered 0.3 CS in position B only, while 3500K achieved 0.3 CS in both A and B positions. On the other hand, 4000 K did not meet the target. It is important to mention that although most of the cases in this luminaire type meet the target, the lux/lumen is the lowest among all cases.

Table 12:Indirect pendant linear light CS calculations (Author 2020)

Indirect Pendant Linear Light					
	Measuring position @1.2 m	**3000K**			
		Vertical E (lux)	CS	lumen(lm)	Lux/lumen
Butterfly	**A**	335	**0.302**	4636	0.072
	B	294	0.278	4636	0.063
	Measuring position @1.2 m	**3500K**			
		Vertical E (lux)	CS	lumen(lm)	Lux/lumen
Butterfly	**A**	344	**0.362**	4753	0.072
	B	301	**0.336**	4753	0.063
	Measuring position @1.2 m	**4000K**			
		Vertical E (lux)	CS	lumen(lm)	Lux/lumen
Butterfly	**A**	352	0.187	4870	0.072
	B	309	0.168	4870	0.063
	Measuring position @1.2 m	**5000K**			
		Vertical E (lux)	CS	lumen(lm)	Lux/lumen

Butterfly	**A**	363	**0.322**	5021	0.072
	B	318	0.296	5021	0.063

4.3.4 Direct/indirect pendant linear light CS calculations

In Direct/indirect pendant linear cases only 3500K with flood distribution delivered 0.3 CS in both positions, while at 3500K with wide flood only position A meet the target as shown in Table 13.

Table 13: Direct/indirect pendant linear light CS calculations (Author 2020)

Direct/Indirect Pendant Linear					
	Measuring position @1.2 m	**3000K**			
		Vertical E (lux)	CS	lumen(lm)	Lux/lumen
Flood	**A**	292	0.276	2581	0.113
	B	279	0.268	2581	0.108
Wide-Flood	**A**	267	0.260	2310	0.116
	B	241	0.242	2310	0.104
	Measuring position @1.2 m	**3500K**			
		Vertical E (lux)	CS	lumen(lm)	Lux/lumen
Flood	**A**	292	**0.330**	2581	0.113
	B	279	**0.321**	2581	0.108
Wide-Flood	**A**	267	**0.313**	2310	0.116
	B	241	0.293	2310	0.104
	Measuring position @1.2 m	**4000K**			
		Vertical E (lux)	CS	lumen(lm)	Lux/lumen
Flood	**A**	292	0.160	2581	0.113
	B	279	0.154	2581	0.108
Wide-Flood	**A**	267	0.148	2336	0.114
	B	241	0.135	2336	0.103
	Measuring position @1.2 m	**5000K**			
		Vertical E (lux)	CS	lumen(lm)	Lux/lumen
Flood	**A**	272	0.267	2351	0.116
	B	261	0.259	2351	0.111
Wide-Flood	**A**	233	0.239	2222	0.105
	B	224	0.232	2222	0.101

4.3.5 Direct recessed linear light CS calculations

Table 14 shows that both flood and wide flood distribution at 3500K, position A achieved 0.3CS with a vertical illuminance difference of 28 lux and 37 lux between A and B for flood and wide flood respectively. Figure 90 shows the difference clearly, where point A receive more vertical illuminance comparing to position B. in addition, it is noticeable that difference between flood and wide flood CS values is minimal, as both flood and wide flood distribution in the case have a high similarity in overall vertical illuminance as shown in Figure 91.

Table 14: Direct recessed linear light CS calculations (Author 2020)

Direct Recessed linear Light					
	Measuring position @1.2 m	**3000K**			
		Vertical E (lux)	CS	lumen(lm)	Lux/lumen
Flood	**A**	255	0.252	2448	0.104
	B	227	0.232	2448	0.093
Wide-Flood	**A**	258	0.254	2389	0.108
	B	221	0.227	2389	0.093
	Measuring position @1.2 m	**3500K**			
		Vertical E (lux)	CS	lumen(lm)	Lux/lumen
Flood	**A**	255	**0.304**	2448	0.104
	B	227	0.282	2448	0.093
Wide-Flood	**A**	258	**0.306**	2389	0.108
	B	221	0.277	2389	0.093
	Measuring position @1.2 m	**4000K**			
		Vertical E (lux)	CS	lumen(lm)	Lux/lumen
Flood	**A**	255	0.142	2448	0.104
	B	227	0.127	2448	0.093
Wide-Flood	**A**	258	0.143	2389	0.108
	B	221	0.124	2389	0.093
	Measuring position @1.2 m	**5000K**			
		Vertical E (lux)	CS	lumen(lm)	Lux/lumen
Flood	**A**	245	0.248	2351	0.104
	B	218	0.227	2351	0.093
Wide-Flood	**A**	248	0.25	2298	0.108
	B	213	0.223	2298	0.093

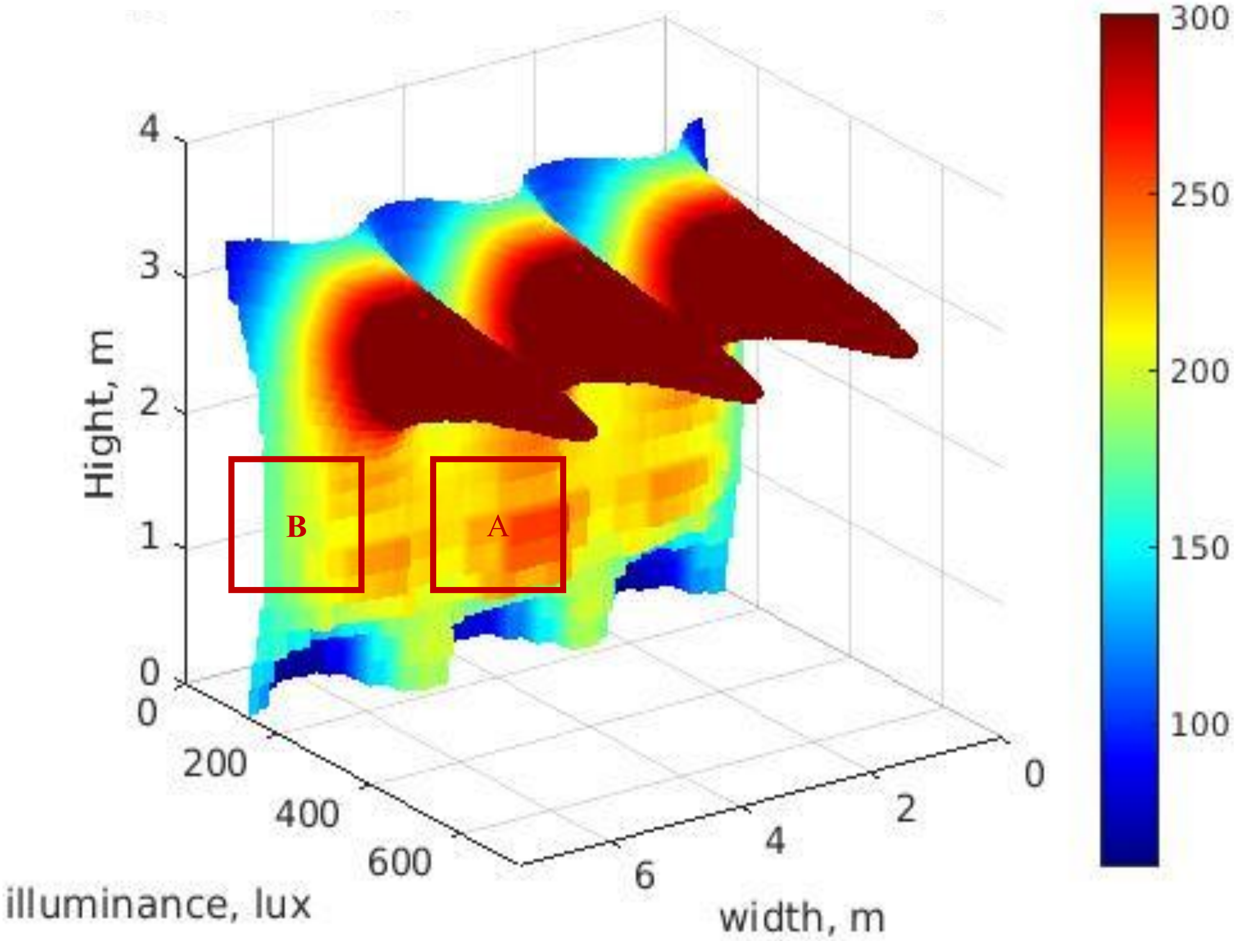


Figure 90: 3D representation of the vertical illuminance value for Direct Recessed linear Light with wide flood distribution. (Author 2020

Direct Recessed – Flood

Direct Recessed – Wide Flood

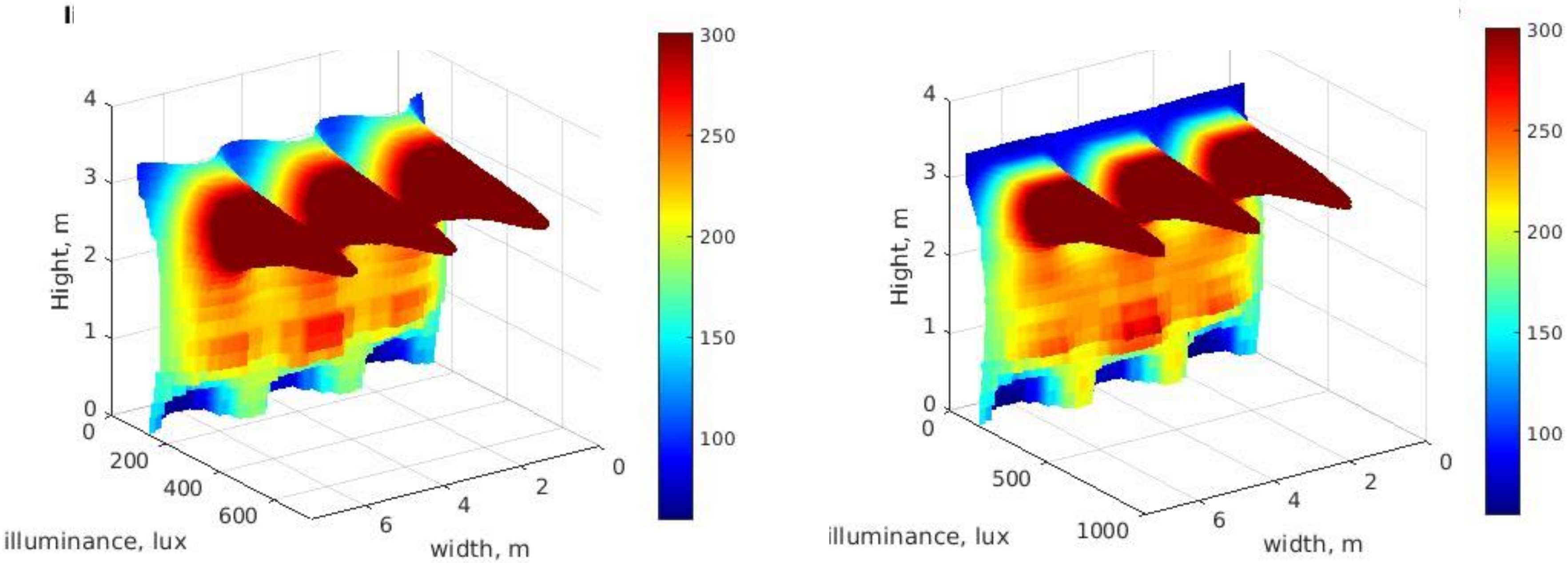


Figure 91: 3D vertical illuminance for direct recessed linear light, from left to right (a) Flood (b) Wide flood. (Author 2020)

CHAPTER FIVE
CONCLUSION

Chapter 5 Conclusion

5.1 Research summary and conclusions

Human-centric lighting (HCL) is a concept of lighting design that represents the sum of visual, biological, and emotional effects of light on humans. It is a new popular term in which many researchers investigate in, since it deals directly with human health and well-being. Nowadays, people spend most of their time indoor under a constant rate of light all day around; this can affect the circadian rhythm, which results in non-visual effects such as sleep disruption, higher stress levels, low productivity, and long-term Diseases. Lighting design plays a key role in educational buildings, where it is essential to deliver a healthy and productive environment. Studying the circadian light will help to addresses the biological aspect of HCL. In order to measure the non-visual effects of light, vertical illuminance should be measured rather than horizontal illuminance on the working plane. Obtaining the vertical illuminance values will help to calculate circadian stimulus (CS), which is a metric developed by the lighting research center (LRC) to design for proper circadian light.

In this research, computer simulation method was used to investigate the effect on circadian light for different luminaries with different CCTs and light beam distribution.

The classroom simulation model was modeled using DIALux 4.13 with a dimension of (10x8x3.6 m), six vertical calculation planes were distributed to measure the vertical illuminance toward the student view angle (whiteboard) and the teacher toward the students. Moreover, a horizontal calculation plane placed at 0.76 m to ensure 500 lux on the working plane. To measure the vertical illuminance values, 13 calculation points were positioned in every chair in the classroom at the eye level to demonstrate how the light will affect the students according to their position in different viewing angles. The selected types of luminaires included reassessed downlight, direct pendant linear light, indirect pendant linear light, direct/indirect pendant linear light, and direct recessed linear light. All of these luminaires examined with different beam distributions and various CCTs.

The resultant vertical illuminance of the calculation points from DIALux 4.13 used to calculate the CS value using the CS calculator. Based on LRC recommendations, the required CS value for the educational environment is between 0.3-0.4, depending on the school operating hours.

The simulation output provided a full view of the vertical illuminance along the length and the width of the space and highlighted the difference between the luminaire types in delivering the vertical illuminance to the eye level by analyzing the maximum vertical illuminance, its height and effect along the different planes. Moreover, the output of the vertical calculation points which was illustrated in polar diagrams were distributed in the students positions with different viewing angles toward the whiteboard, it examines the ability of delivering a uniform vertical illuminance. It was founded that the center of the class delivers a more uniform vertical illuminance comparing to the sides. The highest uniformity ratio (average/minimum) was delivered by the indirect pendant linear light with a value of 0.95. In addition, it can be noted that, as the beam of light distribution increases, the uniformity ratio is increases. The vertical illuminance seems to change significantly relative to the height. So, a small change in the height of the observer will cause a significant change in the vertical illuminance. This change is not as significant in the case of indirect light. Similarly, as the position of the observer changes from one side of the room to the other, the direct downlight result in significant change in the vertical illuminance. Moreover, the results of the simulation highlighted the importance of selecting the luminaires based on its lumen value, where it was founded that the highest vertical illuminance at the eye level was achieved by the luminaire with the highest lumen value which is the indirect pendant linear light. The indirect pendant light achieved 0.3 CS at 3000K, 3500K and 5000K, whereas at 4000K the CS values were lower than 0.2 as in all cases the CS value is drops at 4000k. Among all the CCTs examined, 3500K was achieving the highest CS values in all luminaire types. In order to eliminate the effect of the lumen a ratio of (lux/lumen) was calculated to find the luminaire type that could deliver the higher vertical illuminance to the eye level regardless its lumen. It was founded that the direct pendent linear light has the highest (lumen/lux) ratio, which mean this type needs a lower lumen value than the other type to deliver high vertical illuminance, therefore CS.

5.2 Recommendations

Lighting designers and architects should always select artificial lighting in learning environments in which it delivers a visually comfortable space for students without affecting their circadian system. Since the amount of vertical illuminance received by the eye has a critical impact on human circadian rhythm, therefore, it is important that lighting designers should design lighting to maximize the delivered vertical illuminance to the eye level. Placing the luminaires should always be distributed over the students' tables, where it was founded that the vertical illuminance reaches the highest value. Moreover, it was founded that the lumen plays an important role in delivering vertical illuminance; as the lumen increases, the vertical illuminance at the eye level increases, therefore choosing luminaire with higher lumen value is recommended. According to the findings in this study, it is recommended that the manufacturers show different lumen values for different

CCTs since it affects the vertical illuminance, therefore the calculation of circadian lighting.

Regarding the CCT selection, It is not recommended to select a luminaire with a CCT of 4000K, since all of the luminaire types did not achieve the recommended CS value at 4000K, whereas 3500K with the same conditions result in higher CS values. In terms of light beam distribution, using a narrow beam distribution is not recommended in the classrooms, since the student will not receive a uniform light among different viewing angles. On the other hand, flood beam distribution will help to deliver almost the same amount of vertical illuminance for all the students, while the wide flood distribution will result in an unequal distribution of vertical illuminance between the students, which will cause variation in the CS vale based in the student position.

The results shows that the direct pendent linear light with flood beam distribution has the highest ability to deliver vertical illuminance at the eye level regardless its lumen value.

These recommendations will help lighting designers, architects, and lighting manufacturers to design and create luminaires, which will help to provide healthier learning environments for the students in which it will promote circadian entrainment and raise the alertness levels for the students besides ensuring visual comfort.

5.3 Research limitation

There are some potential limitations that may affect this study. In this study, one of the limitations was is not to take the glare into consideration while simulating the cases which may affect the selection of the appropriate luminaire. Moreover, selecting the appropriate luminaire to conduct the simulation was challenging while maintaining the recommended E_H on the working plane and fixing the luminaire's number and positions. Another limitation that was founded after the end of the simulation is not taking the surface reflectance value of the furniture into considerations, where it can play an important role in the results.

One of the limitations concerns the lockdown due to Covid-19, which limited the study to computer simulation only. Moreover, DIAlux software slows down when adding the furniture; therefore the time spent in the simulation part was the most. There are limited selections for the indirect pendant luminaires with LED, which limited this type to only one beam distribution.

In the field of human centric lighting, there are many gaps and questions that need further studies and investigation and gaps in defining the parameters that could affect the human body. Moreover, linking the body anatomy to measurable metrics need a link between the researchers in the medical field, lighting designers, engineers, and manufacturers.

It is important to be aware that the results of the CS measuring only the level of melatonin segregation, although more considerations have to be taking into accounts such as the time and the duration in which the human exposed to the light, the photic history and the fact that CS metric is based on one hour of light exposure.

5.4 Future work

While this study is concerning about how different types of luminaries affect the vertical illuminance for a typical classroom. Further studies are needed to evaluate the different luminaire types for additional spaces such as offices, homes, and airports. Moreover, studies can be done to examine the effects of changing the mounting height for the pendant luminaries and how it will influence the vertical illuminance. Power consumption is one of the important aspects that should be taking into consideration while choosing the luminaire type, therefore more studies should be conducted to evaluate and optimize the best luminaire type in term of its ability to deliver a good circadian light besides maintaining low energy consumption. In addition, glare is one of the parameters that should be included in the future study of luminaires and how to balance between the high lumen value and the glare to find the optimum selection in term of circadian light.

LIST OF REFERENCES

Acosta, I., Campano, M., Leslie, R. & Radetsky, L. (2019). Daylighting design for healthy environments: Analysis of educational spaces for optimal circadian stimulus. *Solar Energy*, vol. 193, pp. 584-596.

Acosta, I., Leslie, R. & Figueiro, M. (2016). Analysis of circadian stimulus allowed by daylighting in hospital rooms. *Lighting Research & Technology*, vol. 49 (1), pp. 49-61.

Acosta, I., Molina, J. & Campano, M. (2017). Analysis of Circadian Stimulus and Visual Comfort Provided by Window Design in Architecture. *International Journal of Engineering and Technology*, vol. 9 (3), pp. 198-204.

Adamsson, M., Laike, T. and Morita, T., (2016). Annual variation in daily light exposure and circadian change of melatonin and cortisol concentrations at a northern latitude with large seasonal differences in photoperiod length. *Journal of Physiological Anthropology*, 36(1).

Arguelles-Prieto, R., Bonmati-Carrion, M., Rol, M. and Madrid, J., (2019). Determining Light Intensity, Timing and Type of Visible and Circadian Light From an Ambulatory Circadian Monitoring Device. *Frontiers in Physiology*, 10.

Baeza Moyano, D., San Juan Fernández, M. and González Lezcano, R., (2020). Towards a Sustainable Indoor Lighting Design: Effects of Artificial Light on the Emotional State of Adolescents in the Classroom. *Sustainability*, 12(10), p.4263.

Blume, C., Garbazza, C. and Spitschan, M., (2019). Effects of light on human circadian rhythms, sleep and mood. *Somnologie*, 23(3), pp.147-156.

Brennan, M., AIA & Collins, A. (2018). Outcome-Based Design for Circadian Lighting: An Integrated Approach to Simulation & Metrics. *2018 Building Performance Analysis Conference and SimBuild co-organized by ASHRAE and IBPSA*-USA [online]. [Accessed 1 March 2020]. Available at: https://www.ashrae.org/File%20Library/Conferences/Specialty%20Conferences/2018%20Building%20Performance%20Analysis%20Conference%20and%20SimBuild/Papers/C021.pdf

Brown, T., (2020). Melanopic illuminance defines the magnitude of human circadian light responses under a wide range of conditions. *Journal of Pineal Research*,

Burnett, D., (2012). Circadian Adaptive Lighting. *A Landmark Paradigm Shift with Unprecedented ROI Potential*,

Cajochen, C., Freyburger, M., Basishvili, T., Garbazza, C., Rudzik, F., Renz, C., Kobayashi, K., Shirakawa, Y., Stefani, O. & Weibel, J. (2019). Effect of daylight LED on visual comfort, melatonin, mood, waking performance and sleep. *Lighting Research & Technology*, vol. 51 (7), pp. 1044-1062.

Chen, X., Zhang, X. & Du, J. (2020). The potential of circadian lighting in office buildings using a fibre optics daylighting system in Beijing. *Building and Environment*, vol. 182, p. 107118.

Cupkova, D., Kajati, E., Mocnej, J., Papcun, P., Koziorek, J. & Zolotova, I. (2019). Intelligent human-centric lighting for mental wellbeing improvement. *International Journal of Distributed Sensor Networks*, vol. 15 (9), p. 155014771987587.
Energy.gov. 2020. [online] Available at: https://energy.gov/sites/prod/files/2017/10/f37/2017_gateway_tuning-classroom_0.pdf

Fabio, B., Chiara, B., Ornella, L., Laura, B. and Simonetta, F., (2015). Non Visual Effects of Light: An Overview and an Italian Experience. *Energy Procedia*, 78, pp.723-728.

Figueiro, M. (2017). Disruption of Circadian Rhythms by Light During Day and Night. *Current Sleep Medicine Reports*, vol. 3 (2), pp. 76-84.

Figueiro, M., Kalsher, M., Steverson, B., Heerwagen, J., Kampschroer, K. & Rea, M. (2018). Circadian-effective light and its impact on alertness in office workers. *Lighting Research & Technology*, vol. 51 (2), pp. 171-183.

Figueiro, M., Nagare, R. & Price, L. (2017). Non-visual effects of light: How to use light to promote circadian entrainment and elicit alertness. *Lighting Research & Technology*, vol. 50 (1), pp. 38-62.

Figueiro, M., Steverson, B., Heerwagen, J., Kampschroer, K., Hunter, C., Gonzales, K., Plitnick, B. and Rea, M., (2017). The impact of daytime light exposures on sleep and mood in office workers. *Sleep Health*, 3(3), pp.204-215.

Figueiro, M., Steverson, B., Heerwagen, J., Yucel, R., Roohan, C., Sahin, L., Kampschroer, K. and Rea, M., (2019). Light, entrainment and alertness: A case study in offices. *Lighting Research & Technology*, p.147

G. Figueiro, M., Gonzal es, K. and Pedl er, D., (2016). Designing with Circadian Stimulus. *lighting research center*,.
Ies.org. 2020. *Circadian Lighting: An Engineer'S Perspective – Illuminating Engineering Society*. [online] Available at: <https://www.ies.org/fires/circadian-lighting-an-engineers-perspective/>

Jain, S., Fernandes, L., Regnier, C. & Garg, V. (2019). Circadian lighting in a space daylit by a tubular daylight device. *IOP Conference Series: Earth and Environmental Science*, vol. 238, p. 120

Jarboe, C., (2020). *Strategies For Delivering Circadian Stimulus In An Office Space While Minimizing Energy Use*. [online] Walalight. Available at:

https://www.walalight.com/strategies-for-delivering-circadian-stimulus-in-an-office-space-while-minimizing-energy-use/

Jarboe, C., Snyder, J. & Figueiro, M. (2019). The effectiveness of light-emitting diode lighting for providing circadian stimulus in office spaces while minimizing energy use. *Lighting Research & Technology*, vol. 52 (2), pp. 167-188. [Accessed 6 April 2020].
Jung, B. and Inanici, M., 2018. Measuring circadian lighting through high dynamic range photography. *Lighting Research & Technology*, 51(5), pp.742-763.

Konis, K. (2018). Field evaluation of the circadian stimulus potential of daylit and non-daylit spaces in dementia care facilities. *Building and Environment*, vol. 135, pp. 112-123.

Konis, Kyle. (2016). A novel circadian daylight metric for building design and evaluation. Building and Environment.

licht. (2018). *HCL*. image [online]. [Accessed 13 August 2020]. Available at: https://www.licht.de/

Lighting Research center, (2020). *Visible Light Spectrum*. [image] Available at: <https://www.lrc.rpi.edu/healthyliving/img/background/fundamentals/what_is_light/1.png> [Accessed 11 April 2020].

LOWRY, G. (2018). A comparison of metrics proposed for circadian lighting and the criterion adopted in the WELL Building Standard. *CIBSE Technical Symposium, Stretching the Envelope* [online]. [Accessed 14 March 2020]. Available at: https://openresearch.lsbu.ac.uk/item/86v50

LRC. (2020). *Time givers for the circadian clock*. image [online]. [Accessed 13 August 2020]. Available at: https://www.lrc.rpi.edu/healthyliving/#section-schoolGeneralInformation
Lrc.rpi.edu. 2020. *Healthy Living*. [online] Available at: https://www.lrc.rpi.edu/healthyliving/#section-schoolGeneralInformation

Mangkuto, R. (2015). Validation ofDIALux4.12 andDIALux evo4.1 against the Analytical Test Cases of CIE 171:2006. *LEUKOS*, vol. 12 (3), pp. 139-150.

National Aeronautics and Space Administration (NASA). (2020). *Visible Light Science Mission Directorate* [online]. [Accessed 18 April 2020]. Available at: https://science.nasa.gov/ems/09_visiblelight

Pici, N. & Pieper, J. (2019). Daylight, manual sunshade use and occupant-centric circadian lighting stimulus in an open office.

Price, L., Udovičić, L., Behrens, T., van Drongelen, A., Garde, A., Hogenelst, K., Jensen, M., Khazova, M., Nowak, K., Rabstein, S., Romanus, E. & Wolska, A. (2019). Linking the non-visual effects of light exposure with occupational health. *International Journal of Epidemiology*, vol. 48 (5), pp. 1393-1397.

Rea, M. & Figueiro, M. (2016). Light as a circadian stimulus for architectural lighting. *Lighting Research & Technology*, vol. 50 (4), pp. 497-510.
Rea, M. and Figueiro, M., 2016. Light as a circadian stimulus for architectural lighting. *Lighting Research & Technology*, 50(4), pp.497-510.

Rossi & Maurizio. (2019). *Circadian Lighting Design in the LED Era.* 1st edn.

Saiedlue, S., Amirazar, A., Hu, J. & Place, W. (2019). Assessing circadian stimulus potential of lighting systems in office buildings by simulations. *ARCHITECTURE FOR HEALTH AND WELL-BEING*.

Schulz, A. (2020). *Guide to Human Centric Lighting (HCL)* [online]. Frankfurt:licht.de. [Accessed 2 June 2020]. Available at: https://www.licht.de/fileadmin/Publications/licht-wissen/1809_lw21_E_Guide_HCL_web.pdf

Science.nasa.gov. (2020). *Visible Light | Science Mission Directorate*. [online]. [Accessed 24 March 2020]. Available at: <https://science.nasa.gov/ems/09_visiblelight>.

Skeldon, A., Phillips, A. and Dijk, D., (2017). The effects of self-selected light-dark cycles and social constraints on human sleep and circadian timing: a modeling approach. *Scientific Reports*, 7(1).

Snyder, H., (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, 104, pp.333-339.

Standard.wellcertified.com. 2020. *Circadian Lighting Design | WELL Standard*. [online]. [Accessed 15 March 2020]. Available at: <https://standard.wellcertified.com/light/circadian-lighting-design>

Standard.wellcertified.com. (2020). *Circadian Lighting Design | WELL Standard - V3*. [online]. [Accessed 24 March 2020]. Available at: <https://standard.wellcertified.com/v3/light/circadian-lighting-design?>

Tähkämö, L., Partonen, T. & Pesonen, A. (2018). Systematic review of light exposure impact on human circadian rhythm. *Chronobiology International*, vol. 36 (2), pp. 151-170.

Thayer A., (2020). *Lighting Research Center, Rensselaer Polytechnic Institute*. [online]. [Accessed 28 March 2020]. Lrc.rpi.edu. Available at: <https://www.lrc.rpi.edu/healthyliving>

Tidbury, L., Czanner, G. and Newsham, D., (2016). Fiat Lux: the effect of illuminance on acuity testing. *Graefe's Archive for Clinical and Experimental Ophthalmology*, 254(6), pp.1091-1097.

van Hoof, J., Aarts, M., Rense, C. & Schoutens, A. (2009). Ambient bright light in dementia: Effects on behaviour and circadian rhythmicity. *Building and Environment*, vol. 44 (1), pp. 146-155.

Yao, Q., Cai, W., Li, M., Hu, Z., Xue, P. and Dai, Q., (2020). Efficient circadian daylighting: A proposed equation, experimental validation, and the consequent importance of room surface reflectance. *Energy and Buildings*, 210, p.109.

LIST OF ABBREVIATIONS

Amundadottir, M., Rockcastle, S., Sarey Khanie, M. & Andersen, M. (2017). A human-centric approach to assess daylight in buildings for non-visual health potential, visual interest and gaze behavior. *Building and Environment*, vol. 113, pp. 5-21.

Barroso, A., Simons, K. & de Jager, P. (2013). Metrics of circadian lighting for clinical investigations. *Lighting Research & Technology*, vol. 46 (6), pp. 637-649.

Bodrogi, P., Vinh, Q. & Khanh, T. (2017). Opinion: The usefulness of light sources in human centric lighting. *Lighting Research & Technology*, vol. 49 (3), pp. 292-292.

Boyce, P. (2016). Editorial: Exploring human-centric lighting. *Lighting Research & Technology*, vol. 48 (2), pp. 101-101.

Chaopu, Y., Wenqing, F., Jiancheng, T., Fan, Y., Yanfeng, L. & Chun, L. (2018). Change of blue light hazard and circadian effect of LED backlight displayer with color temperature and age. *Optics Express*, vol. 26 (21), p. 27021.

Dai, Q., Huang, Y., Hao, L., Lin, Y. & Chen, K. (2018). Spatial and spectral illumination design for energy-efficient circadian lighting. *Building and Environment*, vol. 146, pp. 216-225.

Jeon, G., Seung-Taek, O. & Lim, J. (2019). Natural Light Property-Based LED Lighting System to Maintain Human Circadian Rhythm. *IOP Conference Series: Materials Science and Engineering*, vol. 630, p. 012019.

Nagare, R., Plitnick, B. & Figueiro, M. (2018). Effect of exposure duration and light spectra on nighttime melatonin suppression in adolescents and adults. *Lighting Research & Technology*, vol. 51 (4), pp. 530-543.

Nowozin, C., Wahnschaffe, A., Rodenbeck, A., Zeeuw, J., Hädel, S., Kozakov, R., Schöpp, H., Münch, M. & Kunz, D. (2017). Applying Melanopic Lux to Measure Biological Light Effects on Melatonin Suppression and Subjective Sleepiness. *Current Alzheimer Research*, vol. 14 (10).

Pechacek, C., Andersen, M. & Lockley, S. (2008). Preliminary Method for Prospective Analysis of the Circadian Efficacy of (Day)Light with Applications to Healthcare Architecture. *LEUKOS*, vol. 5 (1), pp. 1-26.