CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF ELECTRICAL ENGINEERING

DEPARTMENT OF ELECTRICAL POWER ENGINEERING

Master Thesis

Photometry and Application of Tunable White Luminaires

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MASTER'S THESIS ASSIGNMENT

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1) Technical standards and requirements on tunable white luminaires usage
2) Photometric analysis of spectrum and CCT of tunable white luminaire
3) Project and operating schedule of lighting system with tunable white luminaire

Bibliography / sources:

[1] EN 12464 Light and lighting. Lighting of work places.
[2] BS EN 13032. Light and lighting. Measurement and presentation of photometric data of lamps and luminaires.
[3] David L. Dilaura, Kevin W. Houser, Richard G. Mistrick, Gary R. Steffy. The Lighting Handbook, 10th Edition. ISBN 978-0-87995-241-9

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III. Assignment receipt

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Declaration

I, Burak Gündogdu declare that this thesis and the work presented in it titled 'Photometry and Application of Tunable White Luminaires' are my own and has been generated by me as the result of my own original research. I confirm that this work was done wholly or mainly while in candidature for Master's degree in Power Engineering and management at Czech Technical University. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated. Where I have consulted the published work of others, this is always clearly attributed. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work. I have acknowledged all main sources of help. None of this work has been published before submission.

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Abstract

The purpose of this master thesis is explanation of technical standards for interior lighting and definition of required parameters for the tunable white luminaires. In addition, I have measured photometric analysis of spectrum and CCT of white luminaires for different color temperatures. These results have compared with technical standard requirements and optimized for the possible interior lighting conditions. According to the obtained optimized data, I have created a simulation of lighting for a special interior place with tunable white luminaires.

Keywords

Tunable white luminaires, interior lighting, color temperature, color rendering, photometry analysis, technical standards

Abstrakt

Téma této diplomové práce je vysvětlení technických standardů vnitřního osvětlení a definice požadovaných parametrů pro tunable white svítidla. Kromě toho jsem změřil fotometrickou analýzu spektra a CCT bílého osvětlení pro různé barevné teploty. Tyto výsledky jsem porovnal s technickými standardy, požadavky a optimalizacemi pro možné vnitřní světelné podmínky. Na základě získaných a zpracovaných dat jsem vytvořil simulaci osvětlení pro zadaný interiér s laditelnými bílými světly.

Klíčová slova

Laditelná bílá svítidla, vnitřní osvětlení, barevná teplota, barevné vykreslování, fotometrická analýza, technické standardy

Nomenclature

CEN – European Committee for Standardization

E_m – Maintained Illuminance

UGR_L – Glare Rating Limit

Ra – Color Rendering Index

CCR – Correlated color temperature

SCN – Suprachiasmatic Nucleus

RGB – Additive Color Model (Red-Green-Blue)

CIE – International Commission on Illumination

LED – Light Emitting Diode

p[%] – Reflection Index

E_{av} – Average Illuminance

E_{min} – Minimum Illuminance

E_{max} – Maximum Illuminance

L_b – Backround illuminance, unit: cd x m^{-2},

L – Luminiance of the luminious parts of each luminaire, unit: cd x m^{-2}

ω – Solid angle of the luminious parts of each luminaire

ρ – Guth position index for each individual luminaire

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Introduction

In the past, for many years effect of the light on human body considered insignificant. Because of this, effect of light was not an important factor for lighting technology developers. However, since beginning of the 21st Century, scientists discovered that light does not serve only to get visual information but also it has a big influence on human body activities. [1]

Most of lighting systems which are used interior areas currently are constant lighting systems with fixed color temperature and illuminance. For instance, it is required to have fully concentration on places like working offices. For obtain this, luminaires with high color temperature are chosen. However, scientific researches show that continual application of luminaires with high color temperature makes people get tired faster and it causes the performance reduction. It is possible to say opposite situation for low color temperature applications. Most of time, home type interior areas where people are supposed to be relax have low color temperature lighting design. Continual application of low color temperature lighting makes people lazy and dizzy.

People are moving away from the natural human day-night rhythm day after day. It is important to observe significance of daylight by sense of illumination and color temperature. These parameters of the light change during the day. It is possible to simulate it by using artificial lighting sources. By doing this, people might obtain natural circadian rhythm and observe the positive effects of it.

It is considered sufficient daylight or any light which is similar to daylight increases the quality of life, improve the quality of sleep at night, increase the mental and physical performance during the day.

2) Technical standards and Requirements on Tunable White Luminaires Usage

2.1) European Standard EN12464-1 Lighting of indoor places

This European standard was approved by CEN on October 2002. It is prepared by Technical Committee CEN/TC 169 "light and lighting" This standard specifies requirements for most indoor work places in terms of quantity and quality of illumination. [2]

There is list of technical standard requirements for every possible indoor work place. There are three main parameters are defined for the requirement of each place. They are maintained illuminance (E_m), unified glare rating limit (UGR_I) and color rendering (R_a). Some part from this list can be seen on the Table.1

6.1	**Nursery School, play school**				
Ref.No.	**Type of interior, task or activity**	**E_m (lx)**	**UGR_L**	**R_a**	**Remarks**
6.1.1	Play room	300	19	80	
6.1.2	Nursery	300	19	80	
6.1.3	Handicraft room	300	19	80	
6.2	**Educational Buildings**				
Ref.No.	**Type of interior, task or activity**	**E_m (lx)**	**UGR_L**	**R_a**	**Remarks**
6.1.1	Classrooms, tutorial rooms	300	19	80	Lighting should be controllable
6.1.2	Classroom for evening classes and adult education	500	19	80	Lighting should be controllable
6.1.3	Lecture hall	500	19	80	Lighting should be controllable
6.1.4	Black board	500	19	80	Prevent specular reflections
6.1.5	Demonstration table	500	19	80	In lecture halls 750 lx
6.1.6	Art rooms	500	19	80	

Table.1 Sample Part of Technical Standards EN12464-1 for Interior Lighting [1]

7.1	Rooms for general use				
Ref.No.	**Type of interior, task or activity**	**E_m (lx)**	**UGR_L**	**R_a**	**Remarks**
7.1.1	Waiting Rooms	200	22	80	
7.1.2	Corridors: during the day	200	22	80	
7.1.3	Corridors: during the night	50	22	80	
7.1.4	Day rooms	200	22	80	
7.2	**Staff rooms**				
Ref.No.	**Type of interior, task or activity**	**E_m (lx)**	**UGR_L**	**R_a**	**Remarks**
7.2.1	Staff office	500	19	80	
7.2.2	Staff rooms	300	19	80	
7.3	**Wards, maternity wards**				
Ref.No.	**Type of interior, task or activity**	**E_m (lx)**	**UGR_L**	**R_a**	**Remarks**
					Prevent too high luminances in the patients' field of view.
7.3.1	General lighting	100	19	80	Illuminance at floor level
7.3.2	Reading lighting	300	19	80	
7.3.3	Simple examinations	300	19	80	
7.3.4	Examination and treatment	1000	19	80	
7.3.5	Night lighting, observation lighting	5	-	80	
7.3.6	Bathrooms and toilets for patients	200	22	80	
7.4	**Examination rooms**				
Ref.No.	**Type of interior, task or activity**	**E_m (lx)**	**UGR_L**	**R_a**	**Remarks**
7.4.1	General lighting	500	19	90	
7.4.2	Examination and treatment	1000	19	90	

Table.2 Sample Part of Technical Standards EN12464-1 for Interior Lighting [1]

2.2) Lighting Design Criteria

2.2.1) Illuminances at the Task Area

Average illuminance for each task should not fall below the value given by technical standards EN 12464. Values are calculated according to psycho-physiological aspects such as visual comfort and well-being, requirements for visual tasks, visual ergonomics, practical experience, safety and economy. [2]

There are situations where maintained illuminance is required to be increased. These situations are we when visual work is critical, accuracy or higher productivity is of great importance, task details are of unusually small size or low contrast, errors are costly to rectify, the visual capacity of the worker is below normal, the task is undertaken for an unusually long time. [2]

There are situations where maintained illuminance is supposed be decreased. These situations are when the task is undertaken for an unusually short time, task details are of an unusually large size or high contrast. [2]

The Illuminance of task area and illuminance of immediate surrounding area should have good balanced distribution of illuminance on the target illuminated area.

There is a given illuminance relationship between task area and immediate surrounding area on the Table.3.

Task Illuminance (lx)	Illuminance of Immediate Surrounding Areas (lx)
≥ 750	500
500	300
300	200
≤ 200	E_{task}
Uniformity: ≥ 0.7	Uniformity: ≤ 0.5

Table.3 Uniformities and relationship of illuminances of immediate surrounding areas to task area [2]

2.2.2) Distribution of Luminance

Its not only important the amount of illuminance, but also it is important how this total illuminance distributed over the target area. Well distributed illuminance effects the adaptation of the human eye to the task in a good way, It helps a person to concentrate to the main task and causes the increase of the efficiency. Very well balanced luminance increase the sharpness of vision, efficiency of the receptors of the eye, sensitivity of the contrast. In addition, distribution of the illuminance has an effect on visual comfort. If the illuminance is too way lower than it is supposed to be, It will cause non-stimulating working environment. If the illuminance is too way higher than it is supposed to be, then it will create exhaustion because of the constant re-adaptation on the eyes. In addition to this, high illuminance will increase the glare which will cause discomfort of a glare. [2]

There are some standards are defined by Technical Committee CEN/TC about the illuminance and the reflection on the surfaces. [2] According to the technical standards EN 12464, range of acceptable reflectance for the interior surfaces are given on the Table4.

Surface	**Minimum Value**	**Maximum Value**
Ceiling	0.6	0.9
Walls	0.3	0.8
Working planes	0.2	0.6
Floor	0.1	0.5

Table.4 Useful reflectance for the interior Surfaces according to Standard EN 12464 [2]

2.2.3) Discomfort Glare

Glare is a visual sensation caused by extreme and uncontrolled brightness. It can be annoying and uncomfortable.

Discomfort glare is the sensation of annoyance and disturbance caused by overly bright light sources. The level of annoyance is subjective. While young people have more tolerance to it, older people are more sensitive and get affected easily. [3]

Unified glare rating (UGR) is the rating of discomfort glare caused by the luminaires of indoor lighting. Installation of lighting system should be determined by using the unified glare rating method which is based on the formula(1) [2] given following;

$$UGR = 8\log_{10}\left(\frac{0,25}{L_b}\sum\frac{L^2\omega}{\rho^2}\right) \qquad (1)$$

L_b Backround illuminance, unit: cd x m^{-2},

L Luminiance of the luminious parts of each luminaire, unit: cd x m^{-2}

ω Solid angle of the luminious parts of each luminaire

ρ Guth position index for each individual luminaire

2.2.4) Color Appearance

It refers to apparent color of the light emitted. It is quantified by the correlated color temperature. CCT is the color temperature of a black-body radiator which to human color perception most closely matches the light from the lamp. [4] It is seen the color distribution of the light based on the change of CCT on the figure.2. CCT is specified in Kelvin.

Figure.1 Correlated Color Temperature [4]

Choice of color appearance matters to purpose of task, psychology, ambiance, design and anything considered to be natural. The following table (Table.5) includes examples showing the color temperature ranges of various light sources.

Light Source	**Color Temperature**
Candles	1900 - 2500
Lamps with tungsten filament	2700 - 3200
Daylight fluorescent lamps	2700 - 6500
High press. sodium vapor lamps	2000 - 2500
Halogen metal vapor lamps	3000 - 5600
High pressure mercury lamps	3400 - 4000
Moonlight	4100
Sunlight	5000 - 5800
Daylight	5800 - 6500
Overcast skies	6000 - 6900

Table.5 Color Temperature Ranges of Various Light Sources [4]

2.2.5) Color Rendering Index

Color rendering index (CRI) is ability of a light source to reveal the colors of various objects faithfully in comparison with an ideal or natural light source. Light sources which have high CRI is more requested for the lighting tasks with high color accuracy. Color rendering properties cannot be related by color temperature. The CRI is determined by the light source's spectrum. If certain ranges are missing from this spectrum, the corresponding color components cannot be reflected or seen. [4] CRI is the general term and R_a is accepted international color rendering index.

The maximum value of R_a is 100 which only can be given by the source to standardized daylight. Light sources with color rendering index is lower than 80 should not be used in interior places where people work or stay for longer periods. CRI values of some artificial light sources are given on the Table.6.

Light Source	CRI
Low-pressure sodium	0
Clear mercury-vapor	17
High-pressure sodium	24
Coated mercury-vapor	49
Halophosphate warm fluorescent	51
Halophosphate cool fluorescent	64
Tri-phosphor white fluorescent	73
Tri-phosphor cool fluorescent	76
Standard LED lamp	83
Quartz metal halide	85
High CRI LED Lamp (Blue LED)	95
Incandescent/halogen bulb	100

Table.6 Color Rendering Index Ranges of Various Light Sources [5]

2.3) Biological Effect of the Light

The non-visual information is received via light that falls onto our eyes and is conveyed via a nerve connection to the suprachiasmatic nucleus (SCN). The SCN is the central circadian for the day-night rhythm, for the control of the body temperature and many other functions. [6]

The effect of light on the biological rhythm depends on the intensity of light, the duration of exposure, the time regime, and the time of day, the spectral composition and the spatial distribution of light. Effects have been verified even for low illuminance levels.

It is seen that how the light penetrates to eye, then effect of the light on nervous system and the results which occurs on the Figure.2

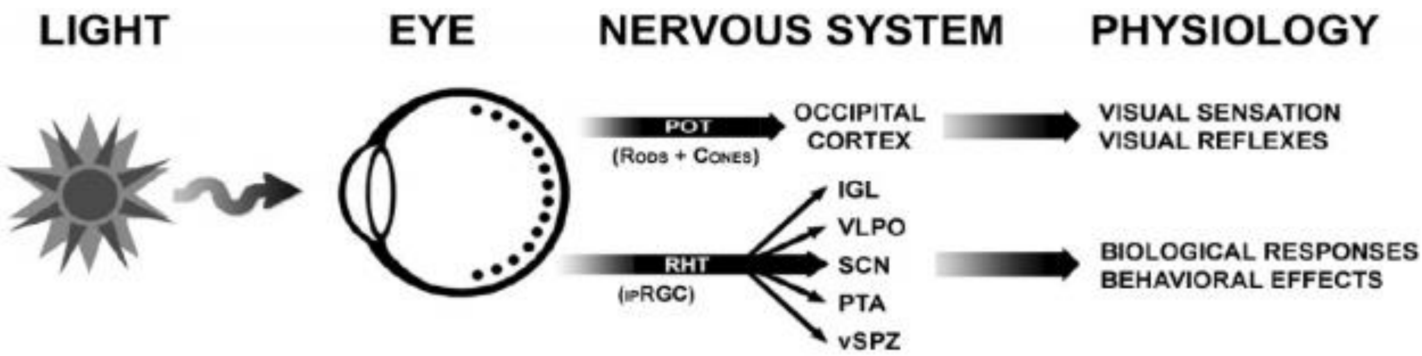


Figure.2 Neuroanatomy Diagram [6]

Effect of the light has known by sense of visual sensation for a long time. However, since 2000 s it is known that light has not only have effect on human body in the sense of visual way but also it is absorbed by hair roots and skin and this has a big effect on the mental and physical activity of a human. [1]

2.4) Lighting Design for Special Indoor Structures

Daylight loop is the most effective lighting design on the human body which is created by nature. When it comes to design of effective biological illumination, artificial lighting should suit the daylight form especially for indoor places where people spend their all day. For example; hospital operation rooms, patient rooms, offices, conference rooms, guest rooms, classrooms, production workspaces, homes etc. There are areas where the biological effects of the light are not considered as important parameter. For example; car parking areas, stairwells, storage rooms etc. [1]

The design requirements for biologically effective lighting highly depends on the task and purpose of the use. That is why it should be carefully designed in terms of vision, psychology, well-being and biological effects. Biological effects of the light are also generated by other light sources indoor area besides the main lighting design like displays and screens. They should be included to calculation as part of main lighting design.

It is not possible to generate all properties of daylight by using artificial light. UV radiation will be missing from general lighting. That is why there is no way to simulate daylight totally and its always recommended to use daylight in possible areas by using windows or spending time outside. [7]

Depending on the structure and its purpose of use, EN 12464-1 technical standard requirements should be implemented on the lighting design.

3) <u>Photometric Analysis of Spectrum and CCT of Tunable White Luminaire</u>

3.1) Spectral Sensitivity of the Human Eye

Wavelength range from 400nm to 700nm is called visible range because those are the wavelength range which human eyes are sensitive. [8] The cone cells of the human eye are sensitive to 3 wavelength ranges which the eye interprets as blue (narrow, with a peak near 419 nm), green (broader, with a peak near 531 nm) and red (also broad, with a peak near 558 nm). [8] Range of the visible spectrum of RGB for human eyes is given on the Figure.3.

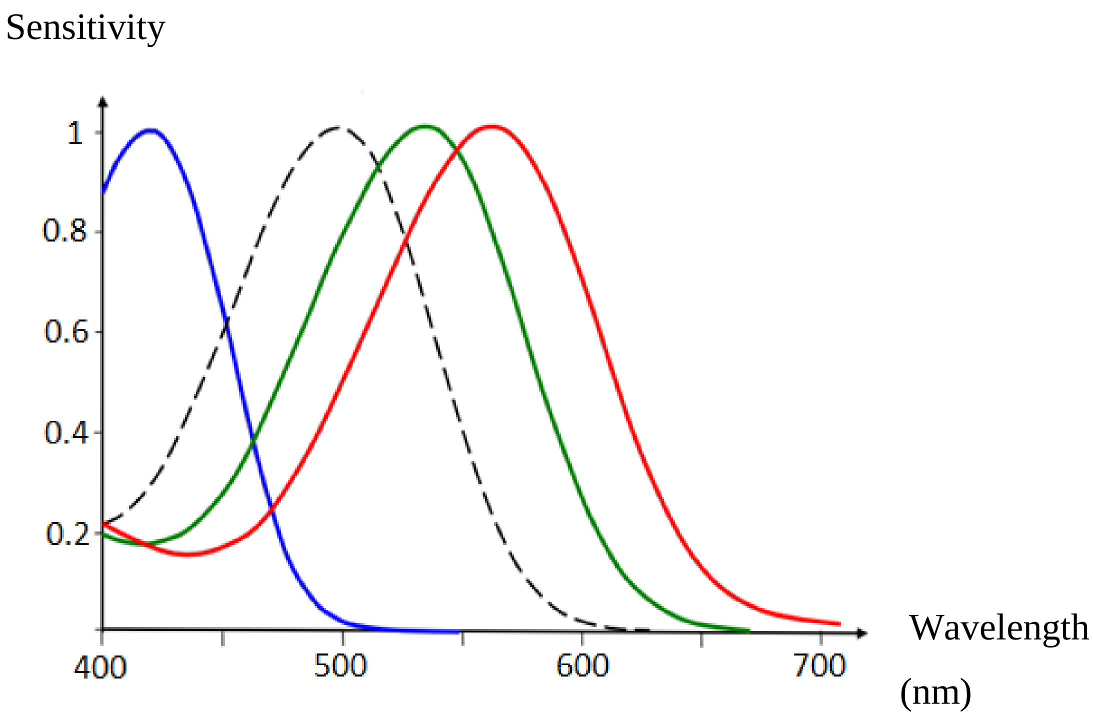


Figure.3 Spectral Sensitivity of the Human Eye for RGB [9]

On the Figure.3 it is seen spectral sensitivity of 4 types of the human eyes light receptors. Three cones (blue, red and green) are responsible for photopic vision (vision under well-lit conditions), while rod one is responsible for night vision (monochromatic vision in very low light). [18]

International Commission on Illumination (CIE) has established spectral sensitivity curves for the human eyes and standardized observation to maximum value of 1. For non-standardized curves maximum daytime vision is 683 lm/W and 1699 lm/W for the night vision. [4]

At the time of daytime vision, eyes are adapted to luminance greater than 30 cd/m^2 and spectral sensitivity curve with maximum 555 nm. [4]

At the time of nighttime vision, eyes are adapted to luminance lower than 10^{-3} cd/m^2 and spectral sensitivity curve with maximum 507 nm. [4]

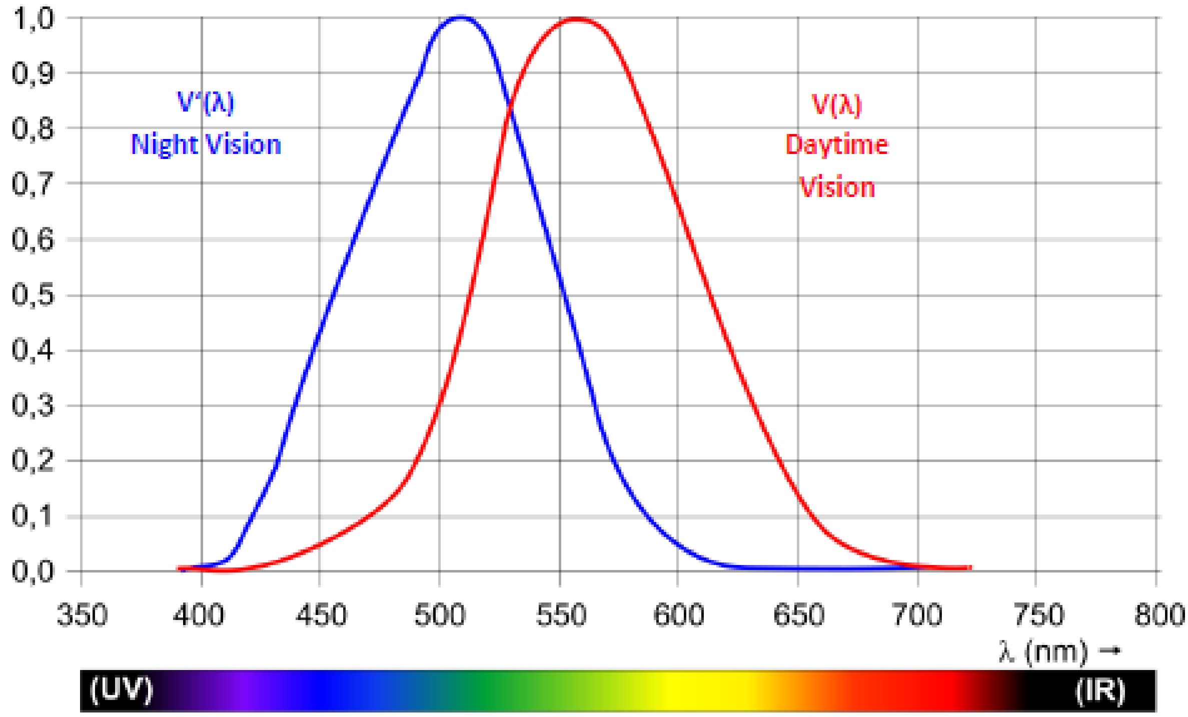


Figure.4 Spectral Luminous Efficiency of the Human Eye [4]

3.2) Tunable White LED Luminaire

Tunable white LED ‘s is the artificial light source which can produce light in different CCT (Correlated color temperature) values from warm color to neutral, and from neutral color to cool colors. It does not require permanent color temperature. Depends on the task and desire of the person, color temperature can be tuned for the periods determined. It does not only let the have control over the color temperature but also it lets the control intensity of the light independently.

Applications of white tunable LED is kind of new trend and it is not commonly used a technology yet. However, there are some applications made by companies about white tunable LED technology. Researches and improvement on this field is in progress.

Today ‘s white tunable LED applications usually provides to tune color temperature from 2700K to 6500K, +80 to +90 color rendering index, up to 10 dim levels. They provide user interfaces controlled by wall controllers or mobile applications controlled by bluetooth over smart phones and devices. [10]

3.3) Comparison of Daylight and Artificial Light

Daylight illuminance is around 111,000 lux on bright light, even it can reach to 1,000 – 2,000 lux on typical overcast day while the illuminance of the artificial light is much lower than that of natural light, between 500 – 1000 lux on the best condition. [1]

There is another parameter, while daylight has the full visible spectrum, artificial light cannot produce it.

From the sides of effect on human body, there are two cases where human body cannot be supplied by artificial lighting as much as the daylight. First one is the production of Vitamin D, second one is the human circadian system which regulates day-night rhythm.

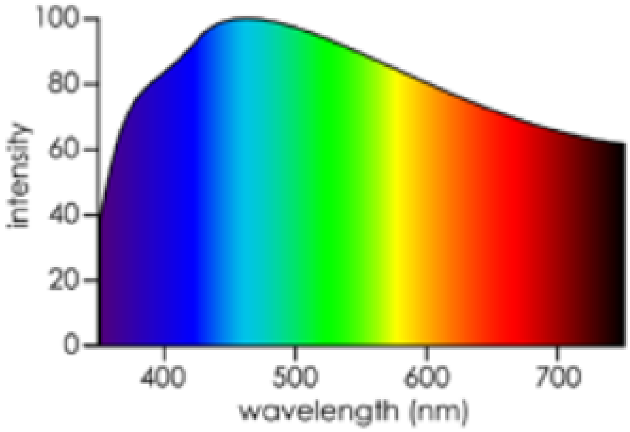


Figure.5 Spectrum Daylight [11]

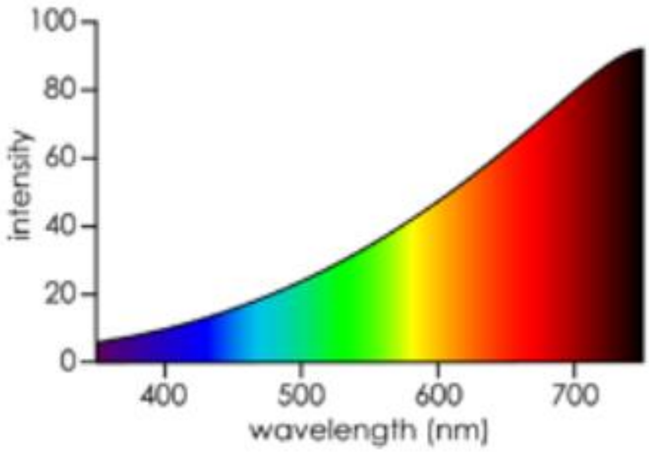


Figure.6 Spectrum Sunset [11]

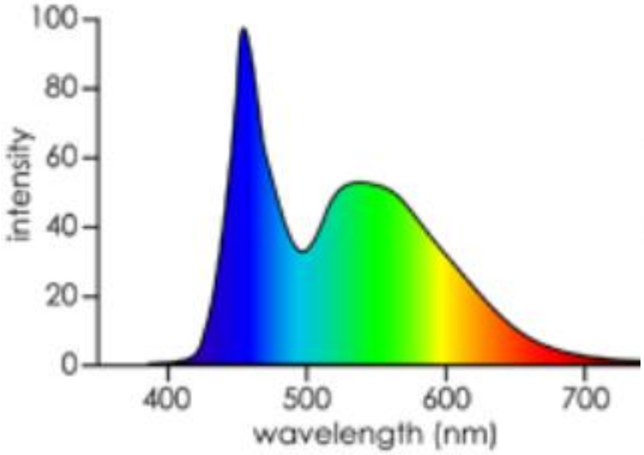


Figure.7 Spectrum Cool LED [11]

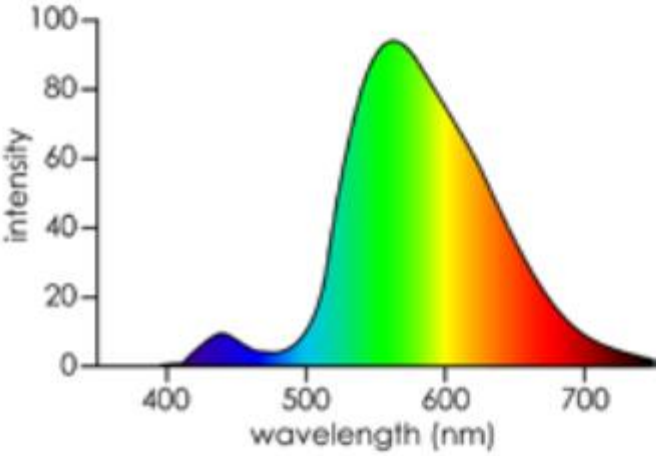


Figure.8 Spectrum Warm LED [11]

3.4) Spectral Power Distribution

Spectral power distrubition represents the radiant power emitted by a light source at each wavelength or band of wavelengths in the visible region of the electromagnetic spectrum. It is expressed by the unit of power occurs per a nanometer in one metersquare area. [$mW/m^2/nm$] [12]

Spectral power disribution curve shows the exact color output of a light source by charting the level of energy for visible range of the wavelengths of the spectrum. The curve also shows us color charecteristics of light source.

Spectral Power Distribution Comparison of Daylight and White LED

Daylight is the light source which covers the biggest range of visible wavelength color spectrum. The biggest difference of the daylight compared to artifical light sources are the high power distrubition on the side of ultraviolet spectrum.(Figure.9) While white LED light source has no power distrubition or very low on spectrum of ultraviolet side as it seems on the Figure.10.

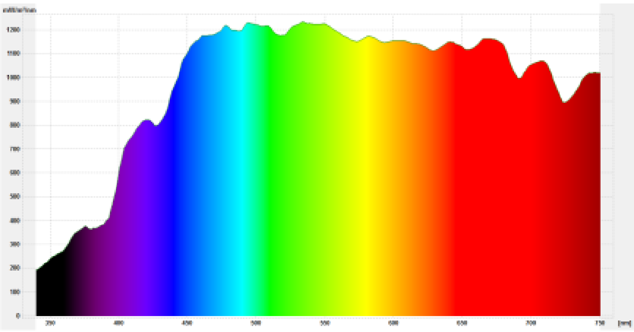


Figure.9 Noon Daylight CCT=5300K[4]

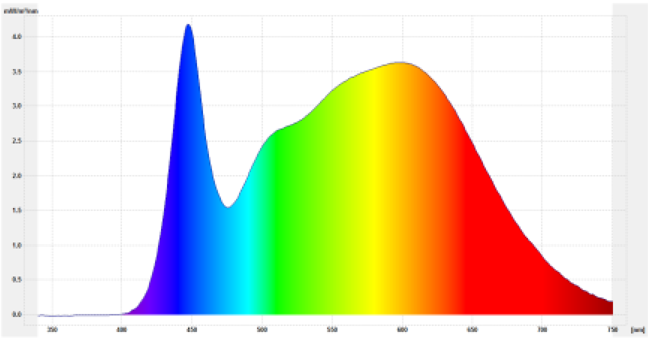


Figure.10 White LED CCT=4350K [4]

Spectral Photometer

Spectral photometer is a tool that capture the light and evaluate its many factors [4] which are;

- Illuminance [lux]
- Correlated color temperature -CCT [K]
- Spectral power distribution [mW/m²/nm]
- Color space chromaticity diagram
- Color rendering index – R_a [Max 100]
- Flicker
- Dominant & Peak wavelength [nm]

3.5) Spectrum Analysis and CCT of Tunable White Luminaire

3.5.1) Measurement Tools, Setup and Conditions

Tools

- Gossen Mavospec Base Spectral Photometer [13]

Applications	Daylight, LEDs, halogen and more
Illuminance [lux]	10 lx – 100 000 lx
CCT – color temperature	1600 K … 50 000 K (Duv > – 0.1)
Duv – color temperature difference relative to the Planckian locus	(1600 K < CCT < 50 000 K)
Color Rendering IES TM-30-15	Rf, Rg
CRI – color rendering index per CIE 13.3	Ra, Re, R1 – R15
Applications	Daylight, LEDs, halogen and more
Illuminance [lux]	10 lx – 100 000 lx
CCT – color temperature	1600 K … 50 000 K (Duv > – 0.1)

- HALLA, a.s. SANT 132-500K-15GFQ/TC

Color of the luminaires	White
Material	Aluminium
Lifetime	L80/B20 50 000 hours
Dimensions	842 mm × 66 mm × 92 mm

Type of optical system	Opal diffuser
Luminous flux	2020 lm ± 7 %
Temperature of chromaticity	2700 K - 6500 K Tunable White
Luminous efficacy	83 lm/W
Colour rendering index	80
UGR max. X=4H Y=8H, ϱ=70,50,20	22.7
Luminaire power input	24.4 W ± 7 %
Connection of the luminaires	Tunable White

Electrical voltage	220-240V

3.5.2) Setup and Measurement

White LED luminaire and the sensor of spectrum photometer is located on the same level of height. Distance between luminaire and spectrum photometer is set to 200 cm. The setup has been covered by black curtain to keep reflection of the light on the minimum level. White led luminaire is connected to tuning computer. Measurement has been done for 11 different levels of color temperature which are 3000-3200-3400-3600-3800-4000-4200-4400-4600-4800-5000K.

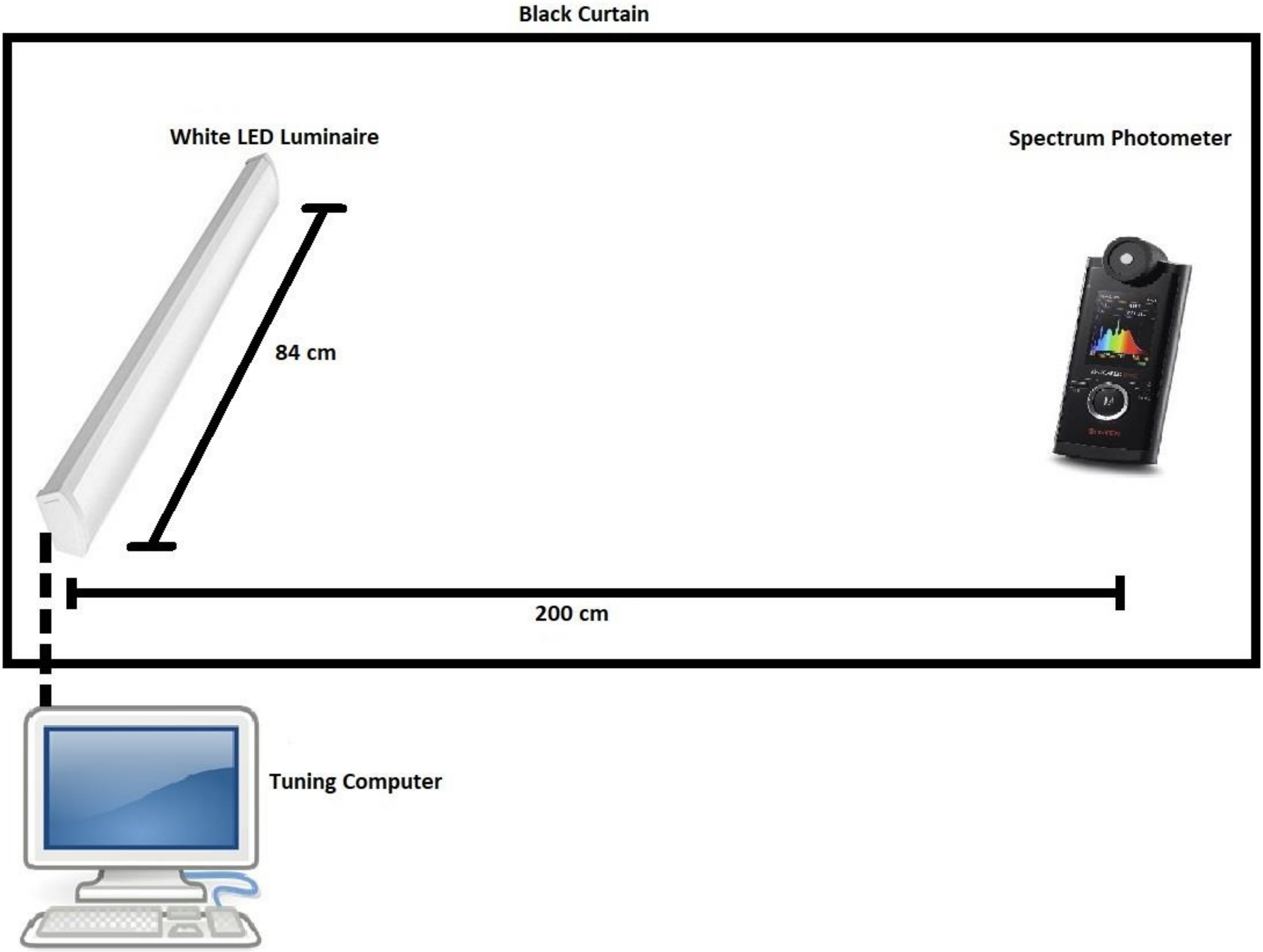


Figure.11 Model of Measurement Setup

3.6) Photometric Diagrams

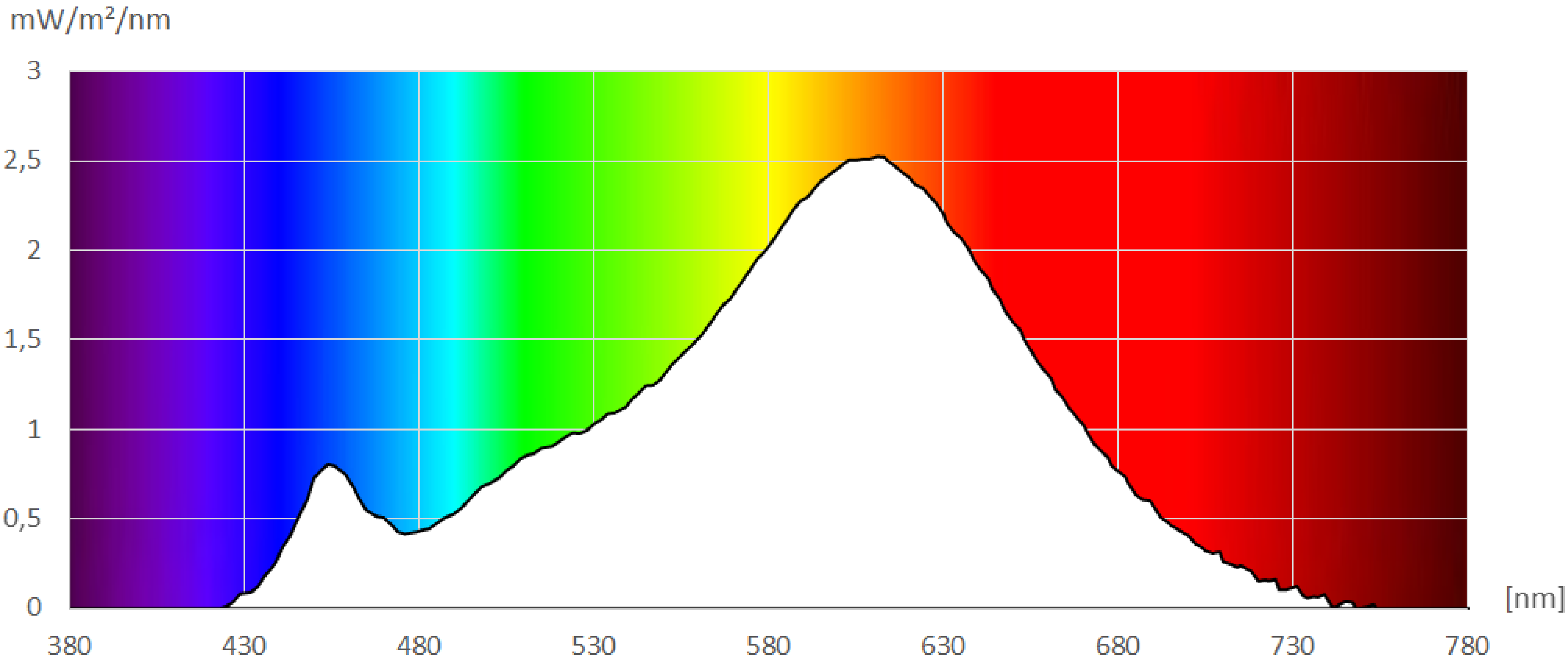


Figure.12 Photometric Diagram of tunable white luminaire at 3000K

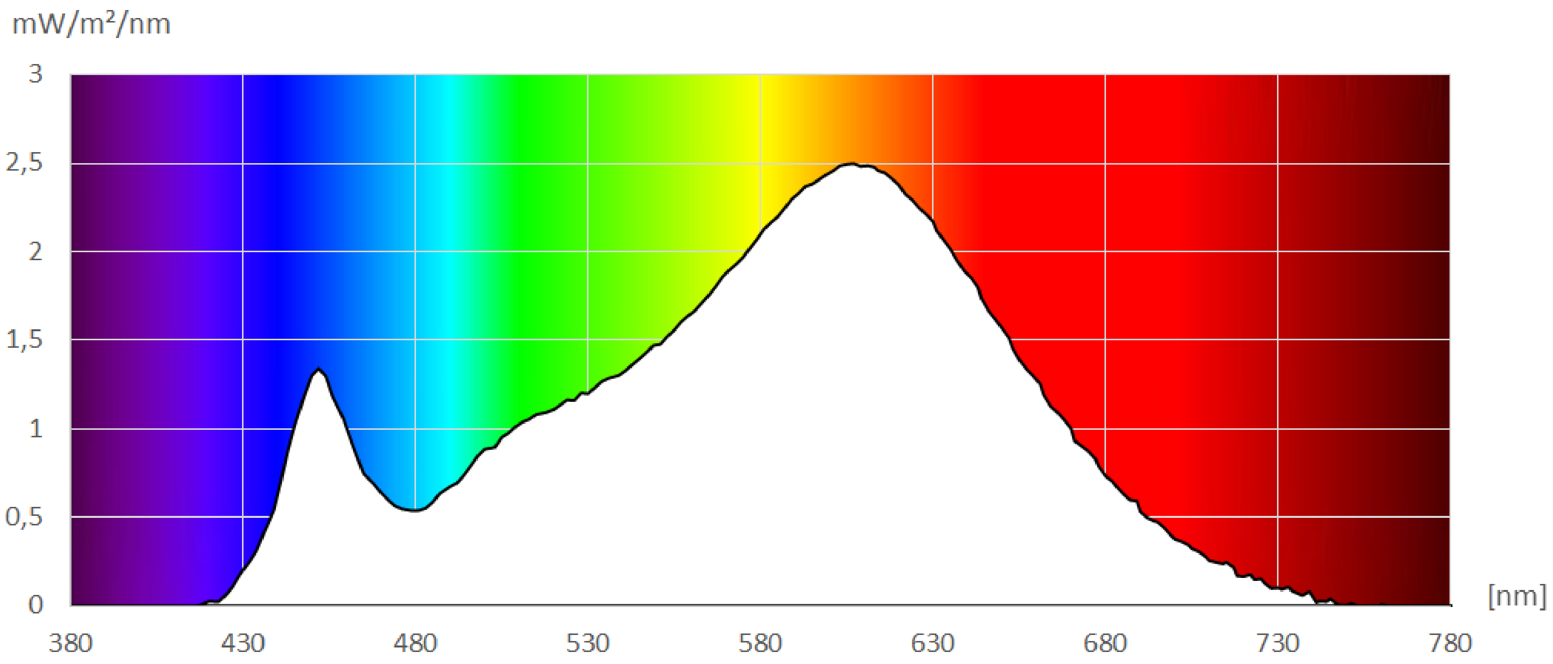


Figure.13 Photometric Diagram of tunable white luminaire at 3200K

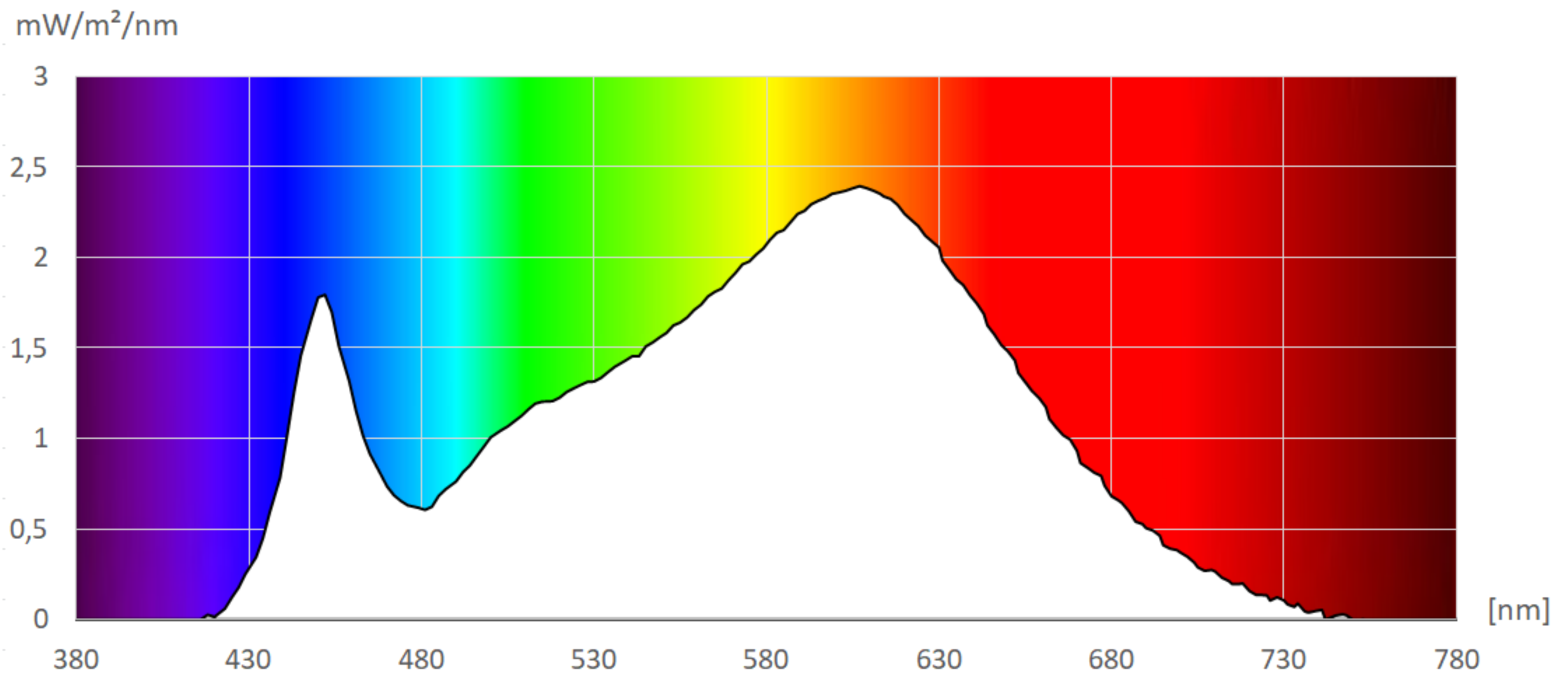


Figure.14 Photometric Diagram of tunable white luminaire at 3400K

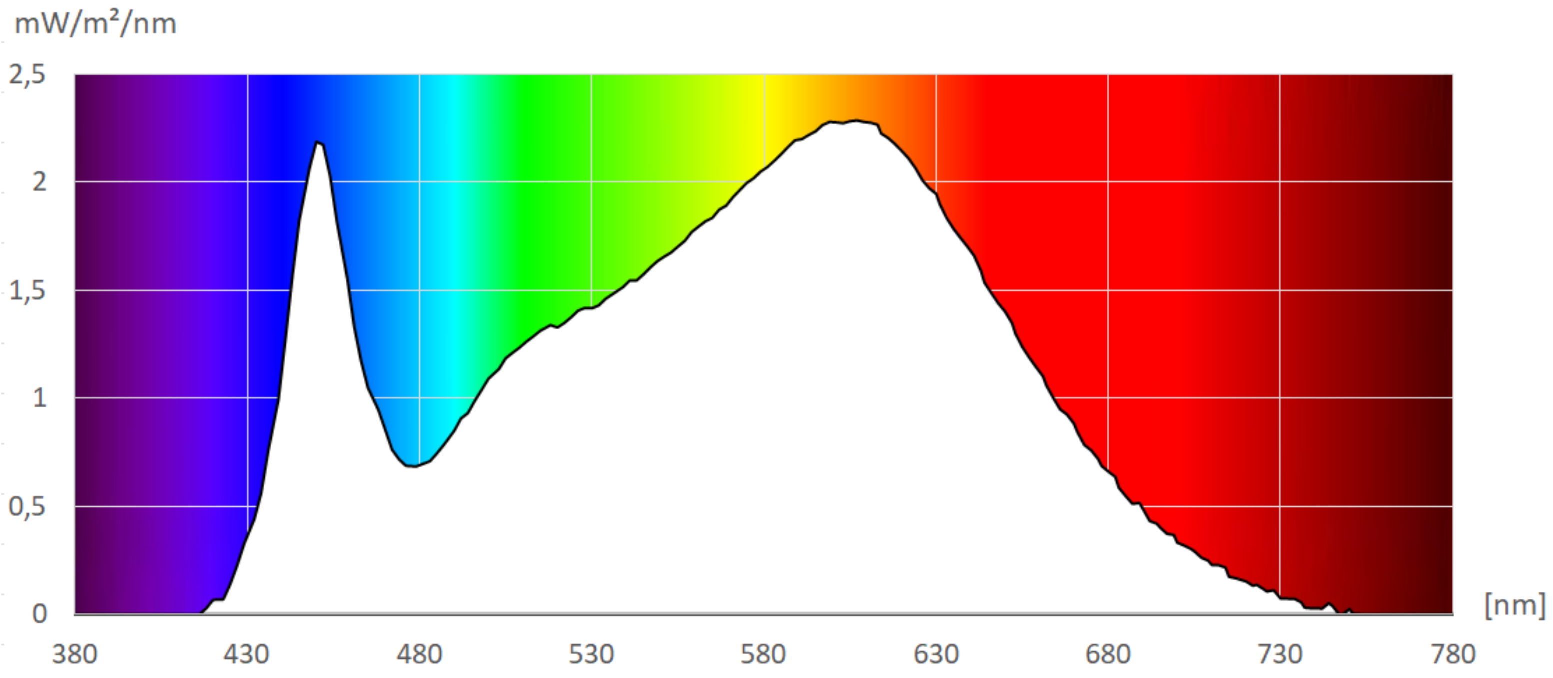


Figure.15 Photometric Diagram of tunable white luminaire at 3600K

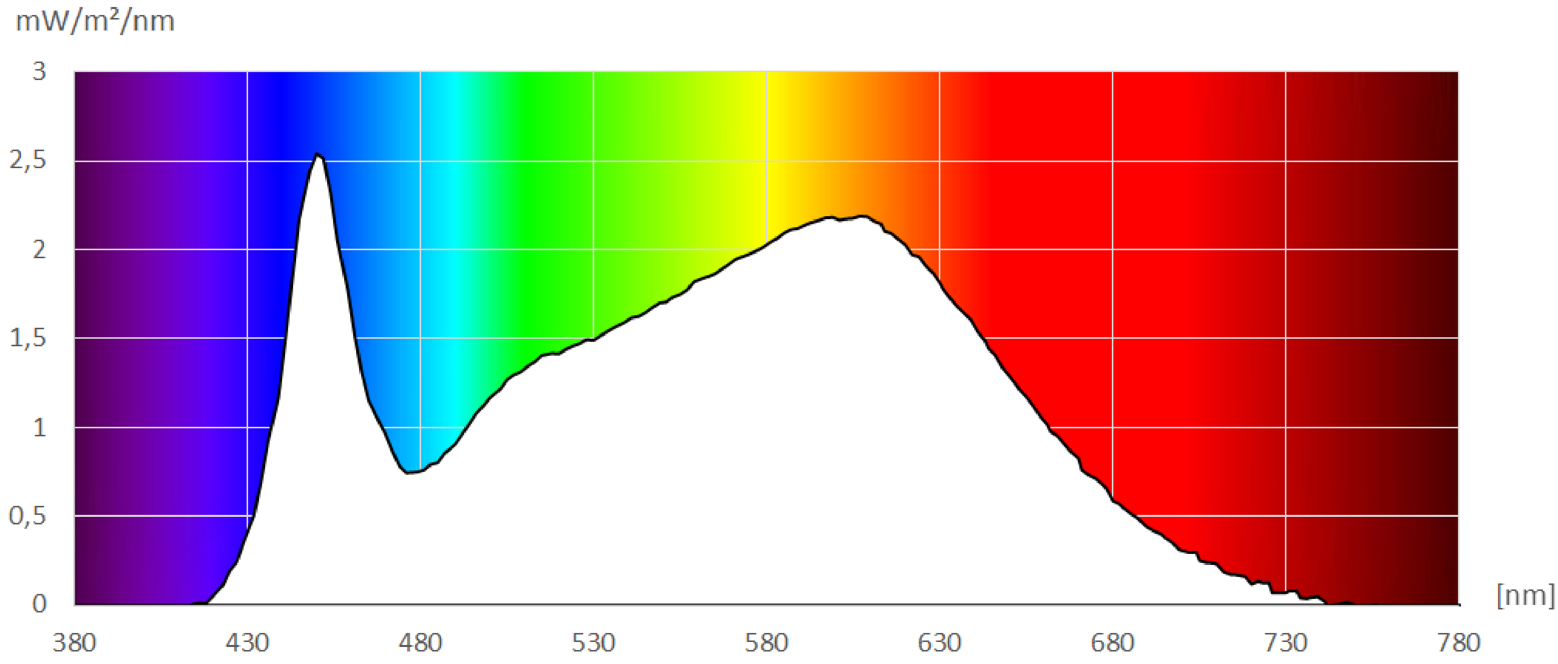


Figure.16 Photometric Diagram of tunable white luminaire at 3800K

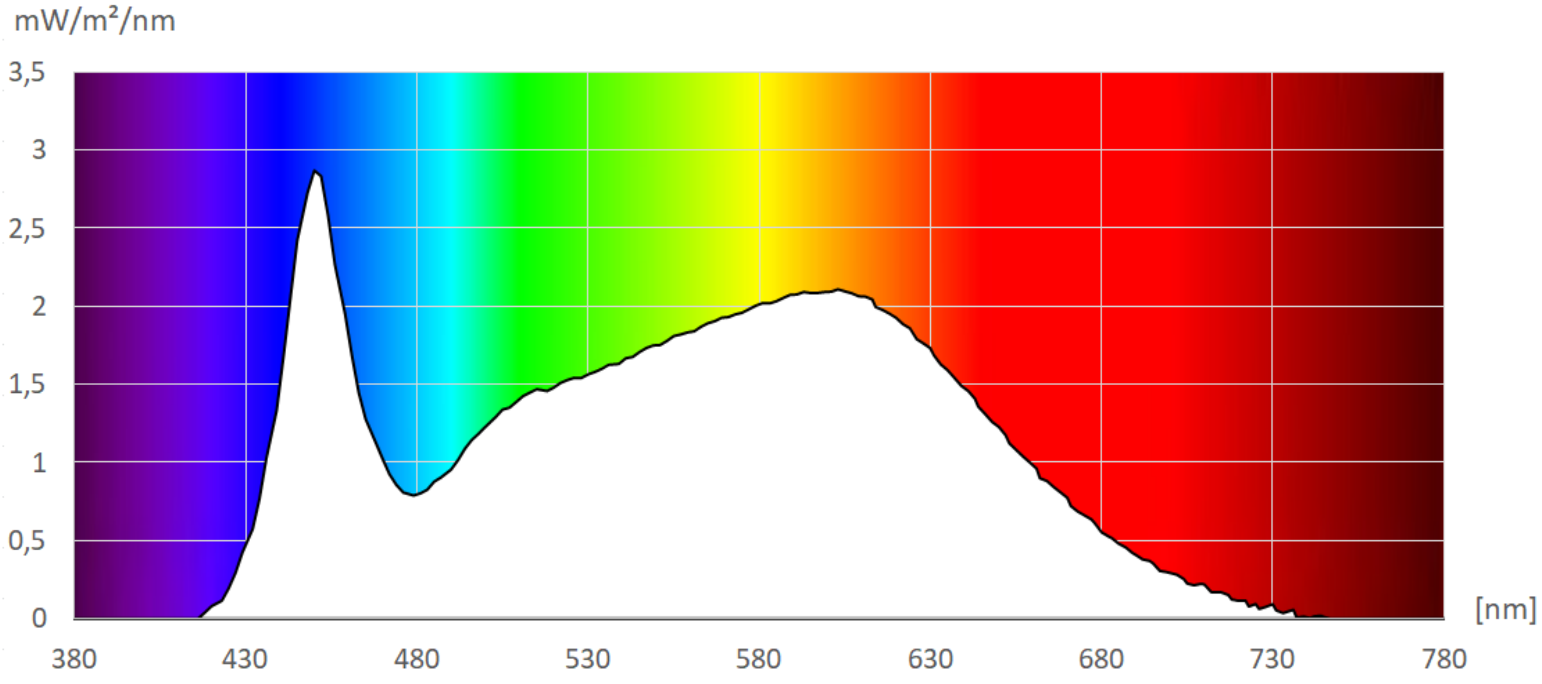


Figure.17 Photometric Diagram of tunable white luminaire at 4000K

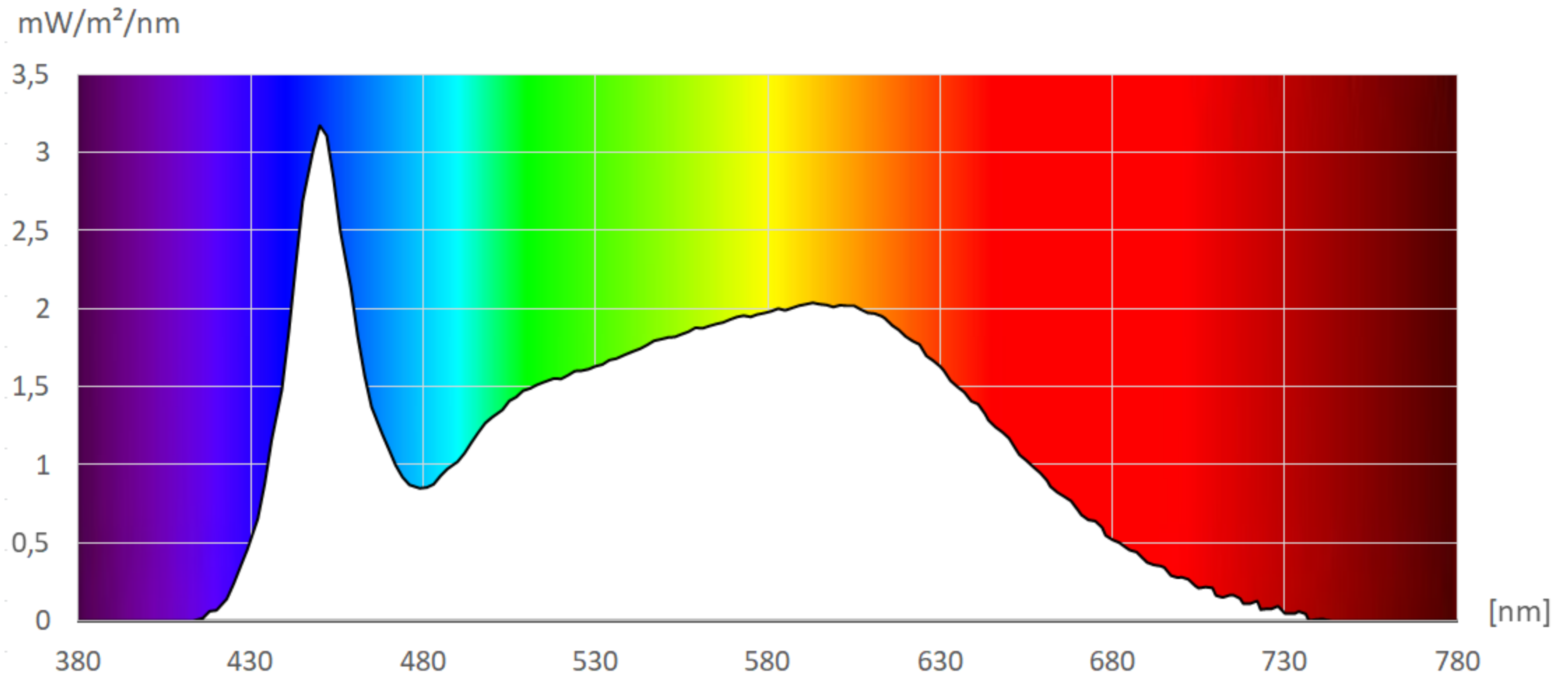


Figure.18 Photometric Diagram of tunable white luminaire at 4200K

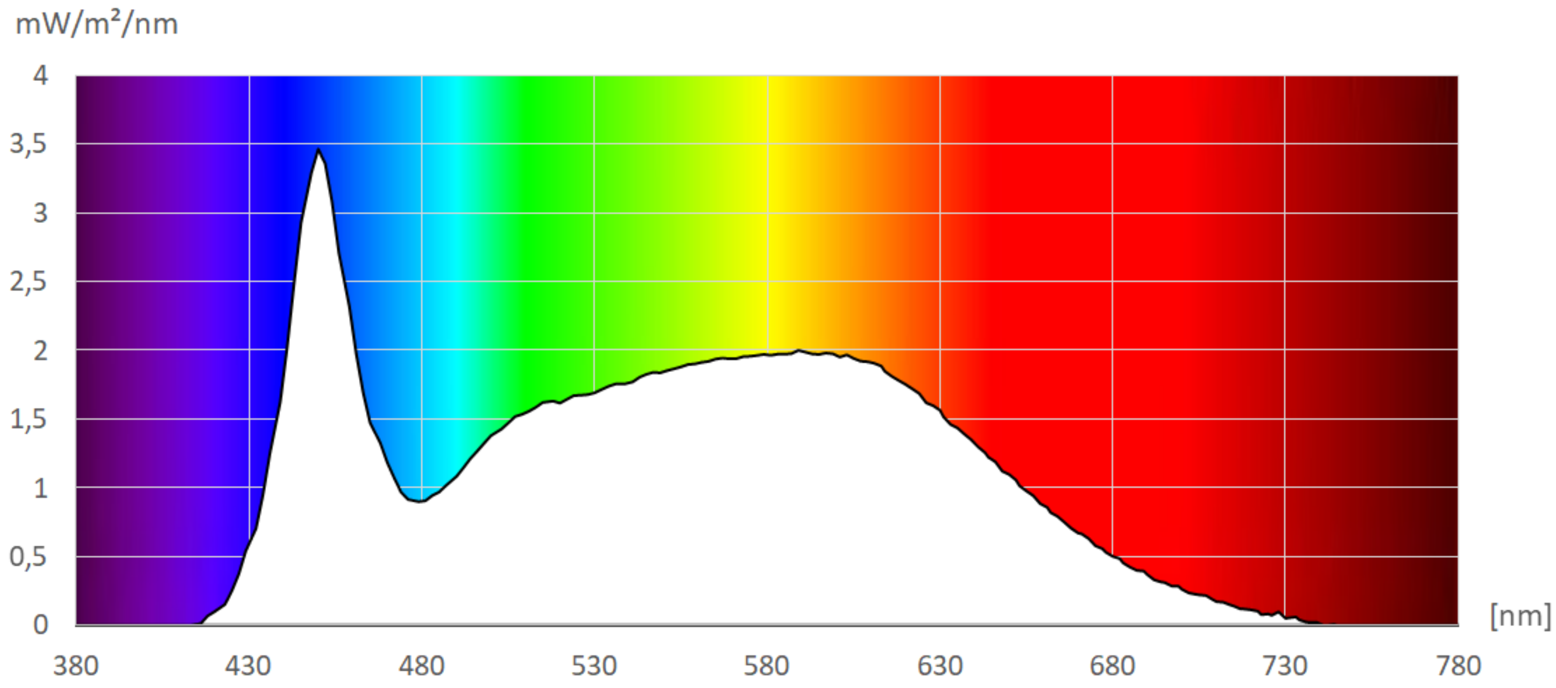


Figure.19 Photometric Diagram of tunable white luminaire at 4400K

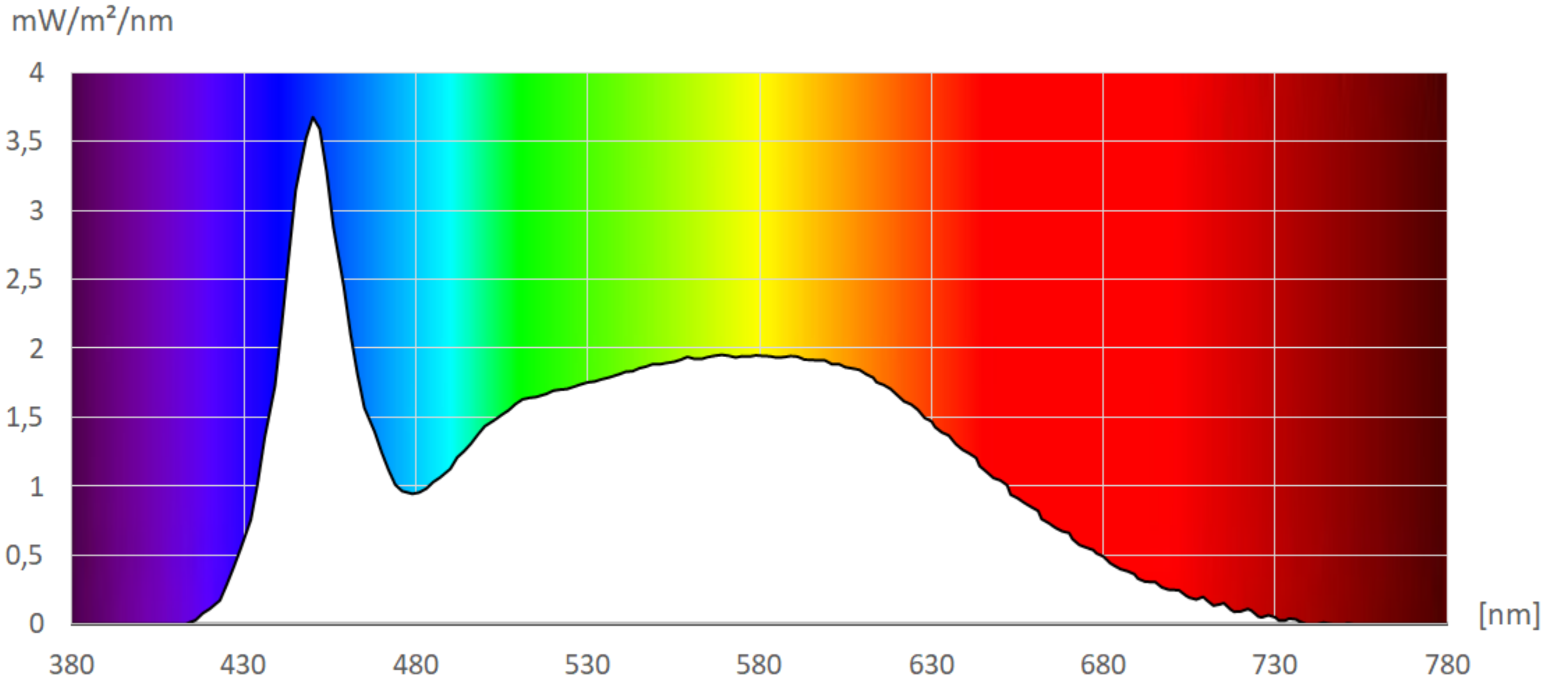


Figure.20 Photometric Diagram of tunable white luminaire at 4600K

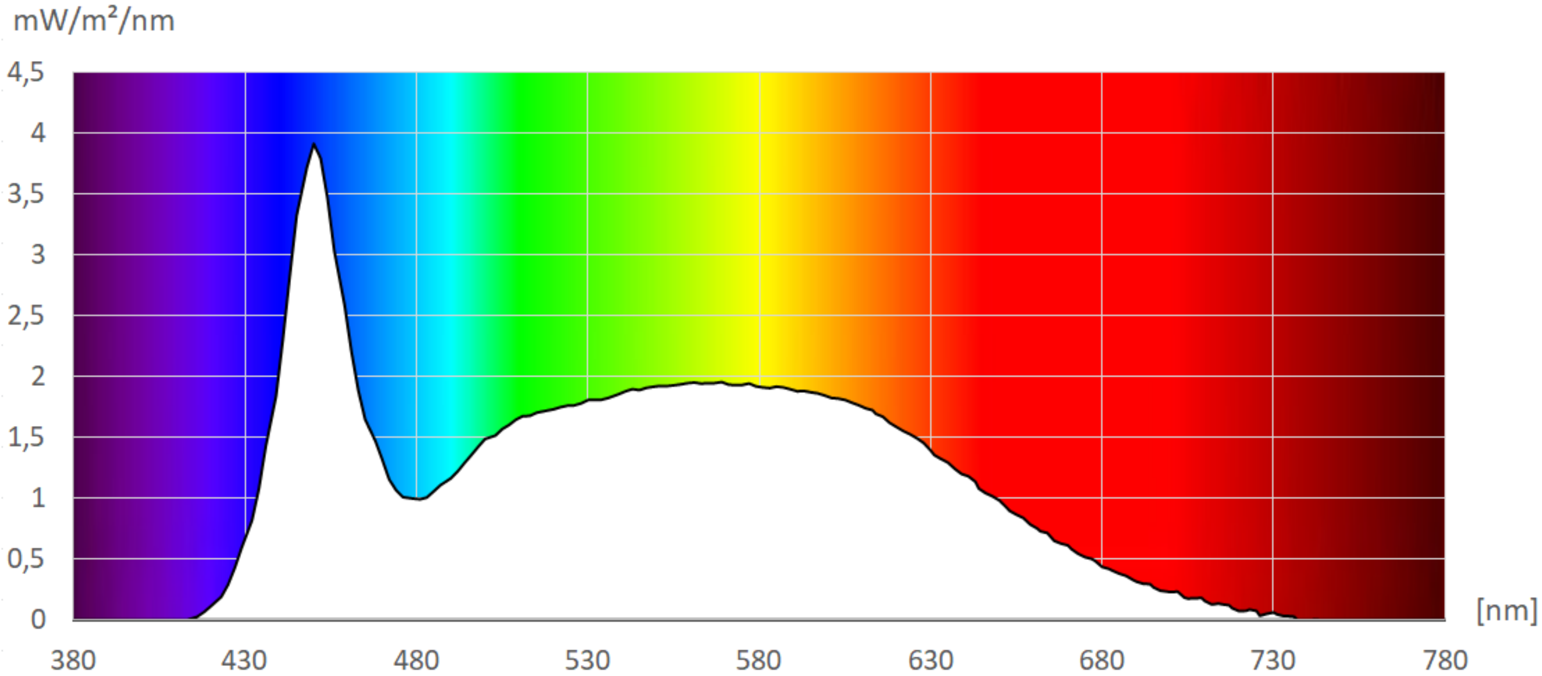


Figure.21 Photometric Diagram of tunable white luminaire at 4800K

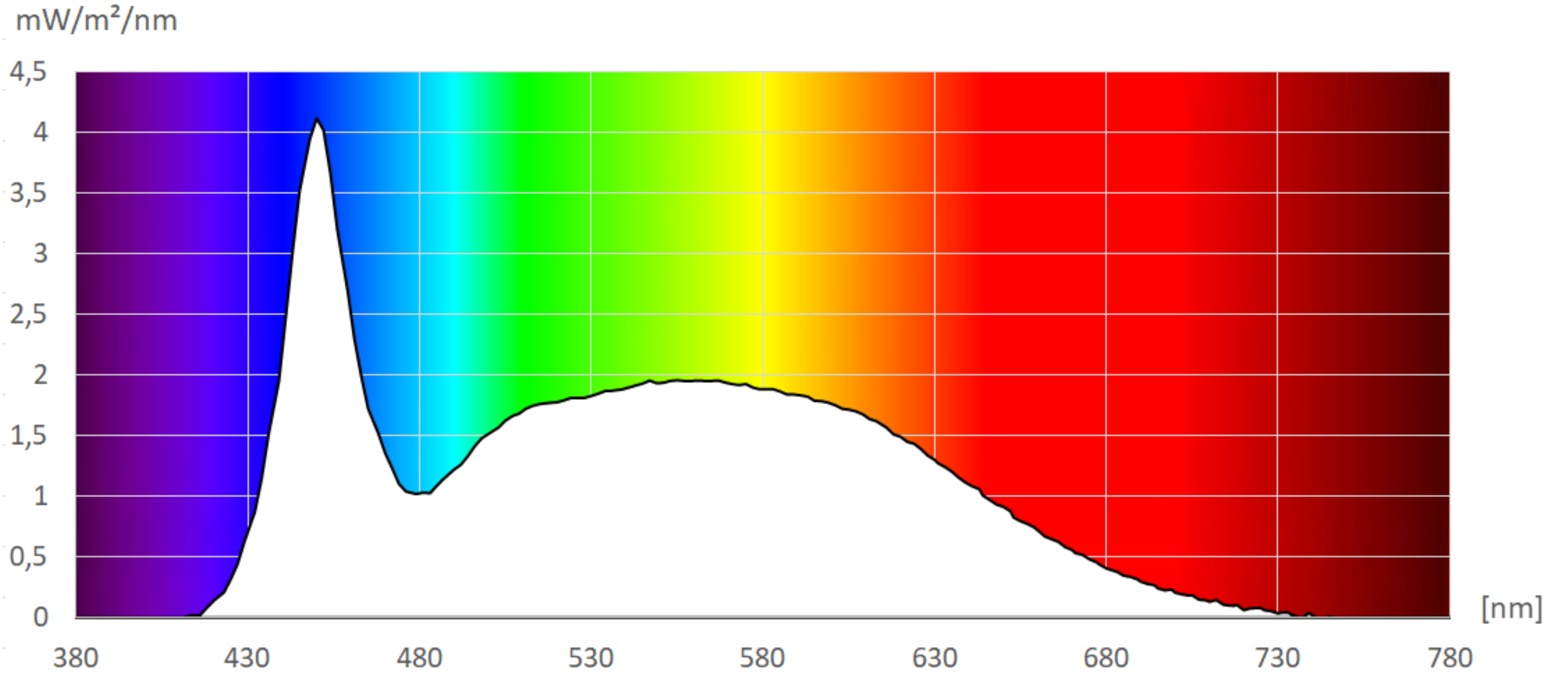


Figure.22 Photometric Diagram of tunable white luminaire at 5000K

It is seen on the diagrams that spectral power distribution of tunable white LED luminaire for 11 different correlated color temperature level between 3000 – 5000k by range of 200K between each measurement.

Spectrum of the chosen luminaire can produce light between approximately 415nm and 740nm. There is no light production on the range of ultraviolet and infrared side of the spectrum.

On the lower color temperatures warm color has produced mostly between 580 – 630 nanometers with maximum power slightly over 2,5 $mW/m^2/nm$ for 3000K. While increasing the color temperature it is seen light production on the warm color side of spectrum has began to decrease and It has got its minimum power for 5000K around 2 $mW/m^2/nm$.

On the contrary, cool color light has produced mostly between 430 – 480 nanometers with minimum power around 0,8 $mW/m^2/nm$ for 3000K. While increasing the color temperature from 3000 to 5000K, It is seen light production on the cool color side of spectrum has began to increase and it has got its maximum power for 5000K around 3.9 $mW/m^2/nm$.

3.7) CIE 1931 Color Space Chromaticity Diagram

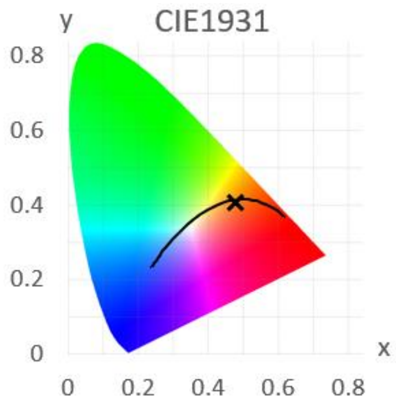


Figure.23 CIE at 3000K

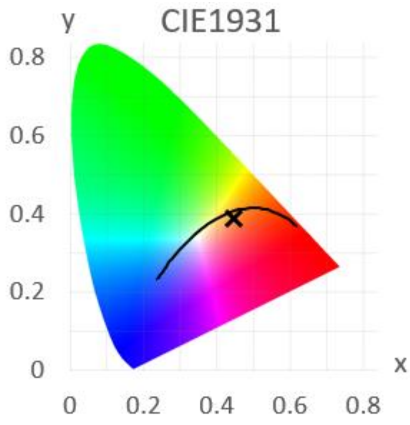


Figure.24 CIE at 3200K

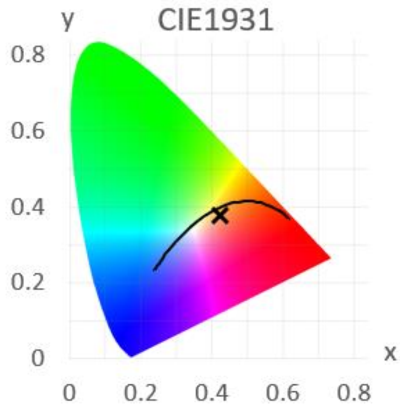


Figure.25 CIE at 3400K

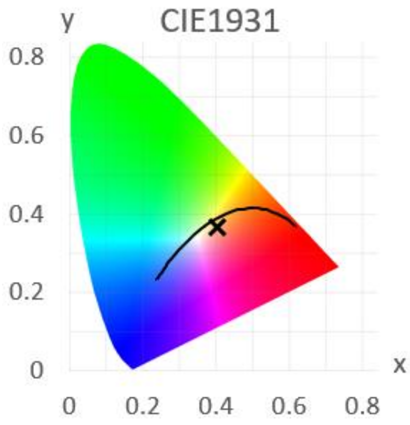


Figure.26 CIE at 3600K

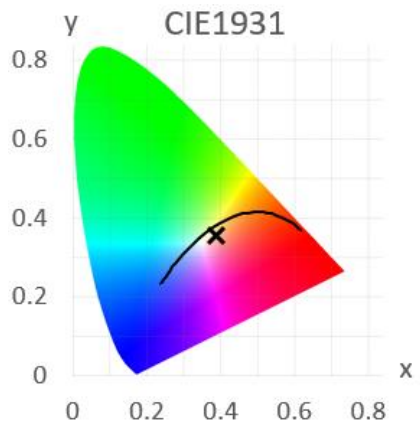


Figure.27 CIE at 3800K

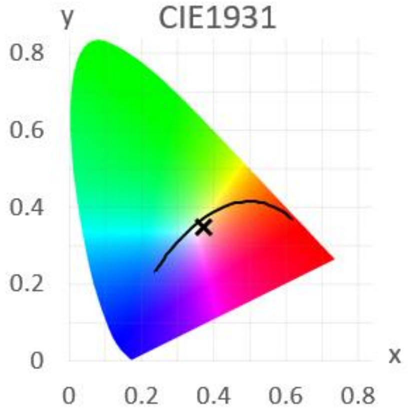
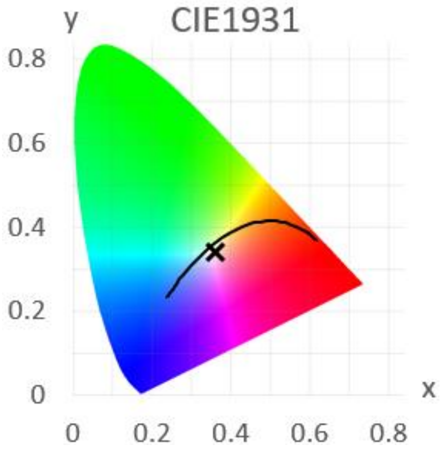
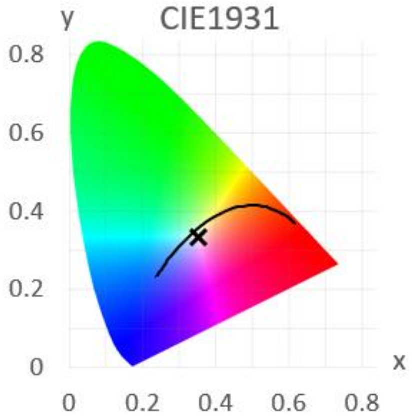


Figure.28 CIE at 4000K





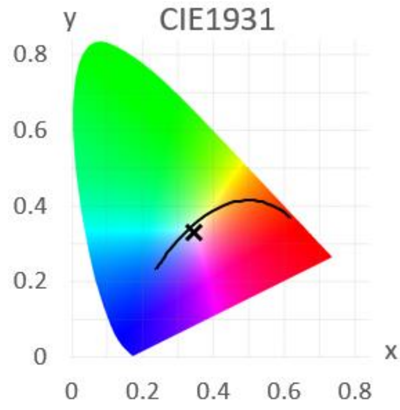
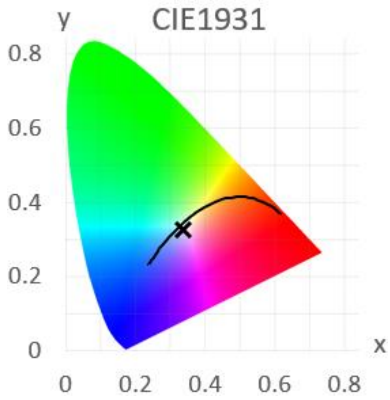


Figure.29 CIE at 4200K **Figure.30** CIE at 4400K **Figure.31** CIE at 4600K



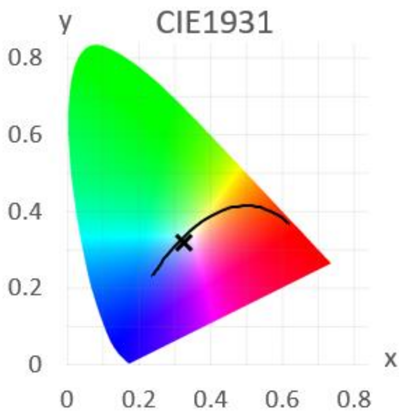


Figure.32 CIE at 4800K **Figure.33** CIE at 5000K

The acronym CIE stands for International Commission on Illumination which is the international authority on light, illumination, color, and color spaces. [17] On 1931, this specific color space has born. CIE chromaticity diagram is itself a color triangle based on fictitious. The axis which are X, Y, and Z, which plot on the diagram at, respectively, (1,0), (0,1), and (0,0).The outer curved boundary is the monochromatic locus, with wavelengths shown in nanometers. [17]

On the measurements it is seen lower color temperature lighting (3000K) has color close the red spectrum which includes yellow tones. When increase the color temperature, especially after the 4000K color temperature it is seen the movement of the light color on the color space chromaticity diagram shifts to the left side where the blue color space is located.

Measurement Table

Set Color Temperature (K)	Measured Color Temperature (K)	Illuminance (lux)	Color Rendering Index (R_a)	Dominant Wavelength (nm)	Peak Wavelength (nm)
3000	2645	113.2	83	583	610
3200	2965	120.8	85.3	583	606
3400	3317	123.24	87.2	583	606
3600	3653	125.19	88.2	582	606
3800	4018	126.26	88.6	582	449
4000	4374	126.8	88.6	581	449
4200	4748	127.69	88.5	579	449
4400	5125	128.89	88	576	449
4600	5506	129.22	87.8	535	449
4800	5877	129.44	87.4	488	449
5000	6339	129.09	86.5	484	449

Table.7 Results of the Measurement

As it seems on Table.7, Color temperature for tunable white LED luminaire set between 3000 and 5000K and measured color temperatures are between 2645 and 6339K which has almost 2 times larger spectrum of color temperature. Measured lumen per square meter and color temperature has an exact ratio between each other. While for 3000K color temperature its measured 113.2 lux, It is increased to 129.09 lux for 5000K of color temperature.

4) <u>Project and Operating Schedule of Lighting System with Tunable White Luminaire</u>

4.1) Lighting Design for Classrooms

Learning by listening and writing, having exams, tests, group works are often completed tasks in classrooms. Getting high concentration and avoiding errors while reading, writing and taking a test is possible by using correlated color temperatures over 5000K and higher illuminances. When there is a case of group work, communication or being taught simultaneously, is it necessary to use correlated color temperature lower than 3000K and also lower illuminances to reduce tiredness and make relaxed learning atmosphere. Figure.34 illustrates the lighting design of a classroom.

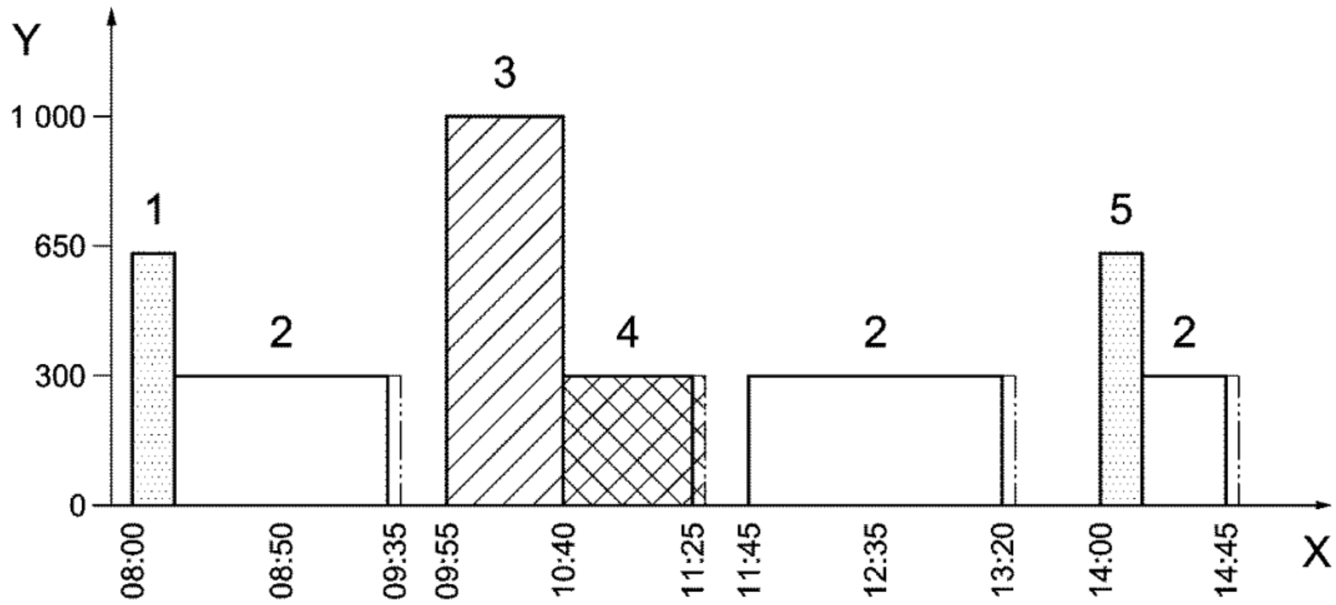


Figure.34 Tunable Lighting Design Diagram of Classroom [1]

X Time of the day

Y Illuminance, unit: lux

Time Zone 1 (08:00 – 08:10)

Morning activating light: High correlated color temperature and slightly over than average illuminances is used for activate the human body right from the very first lesson. – 12000K

Time Zone 2 (08:10 – 09:35)

Standard lesson light: While entire class is being taught simultaneously, average correlated color temperature and relatively lower illuminance is used. – 4000K

Time Break (09:35 – 09:55)

Time Zone 3 (09:55 – 10:40)

Test lighting: Illuminance and color temperature should be increased during the time of the test where high concentration is needed. – 6000K

Time Zone 4 (10:40 – 11:25)

After test lighting: Students are anxious after the test. They should calm down and relax. Application of low illuminance and low warm color temperature restores and creates learning atmosphere again. – 2700K

Time Break (11:25 – 11:45)

Time Zone 2 (11:45 – 13:20)

Standard lesson light. – 4000K

Time Lunch Break (13:20 – 14:00)

Time Zone 5 (14:00 – 14:10)

After the lunch break activation light: Students feel sleepy after having the lunch. High color temperature and high illuminance application activates the people. – 12000K

Time Zone 2 (14:10 – 14:45)

Standard lesson light. – 4000K

4.2) Lighting Simulation of Classroom with Tunable White Luminaire

Room

Dimensions of the room;

- Width : 7.6 meter
- Length : 11 meter
- Height : 2.8 meter

Dimensions of the desk;

- Height: 0.75 meter

Maintenance plan method;

- Ambient conditions: Clean
- Maintenance level : Every 2.5 years

Room Surfaces;

- Ceiling;

1. Reflection : %70
2. Color : White

- Walls;

1. Reflection : %50
2. Color : White

- Floor;

1. Reflection : %20
2. Color : White

Lighting Setup

Features of the luminaire;

- Code: HALLA, a.s. SANT 132-500K-15GFQ/TC
- Number of luminaires: 84 Pieces
- Luminous flux (Luminaire): 1850 lm
- Luminous flux (Lamps): 1850 lm
- Luminaire Wattage: 24.9 W
- Luminaire classification according to CIE: 79

Layout Plan ;

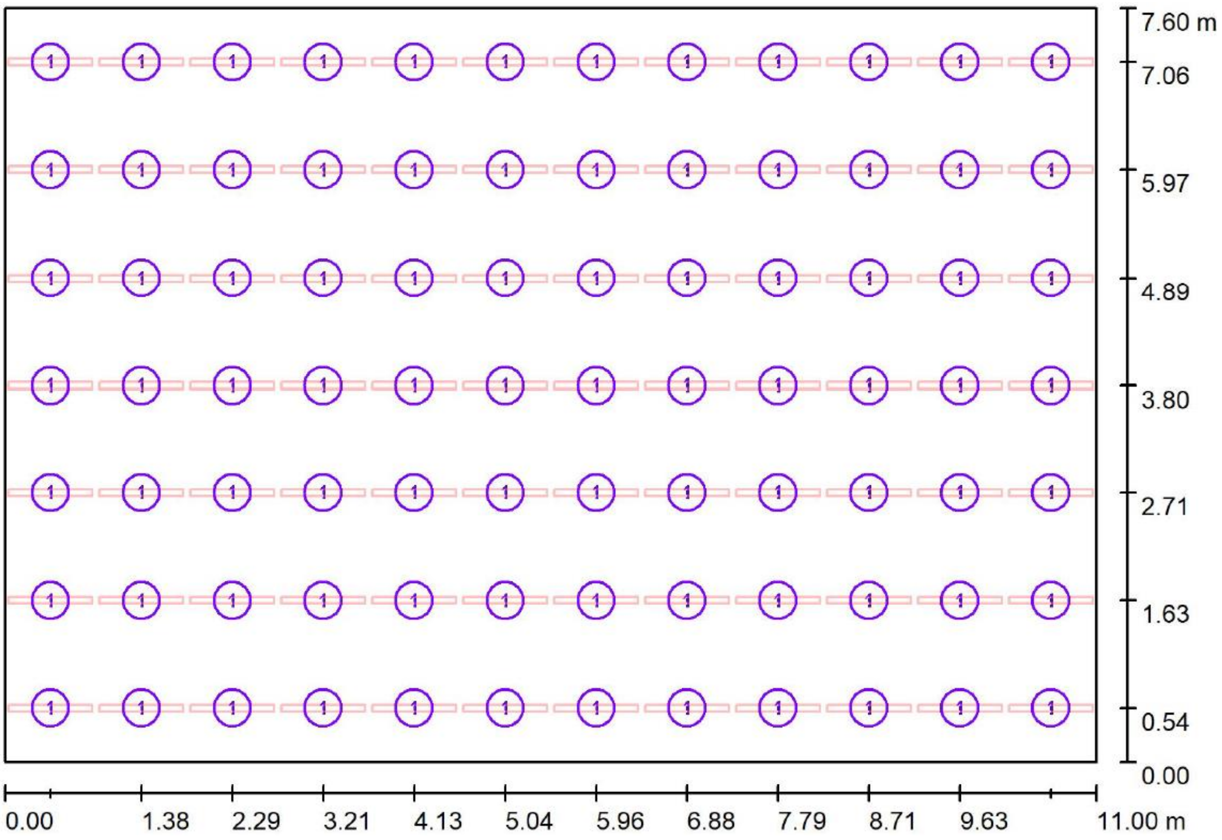


Figure.35 Layout Plan of the chosen Tunable White Luminaire

Luminous emittance

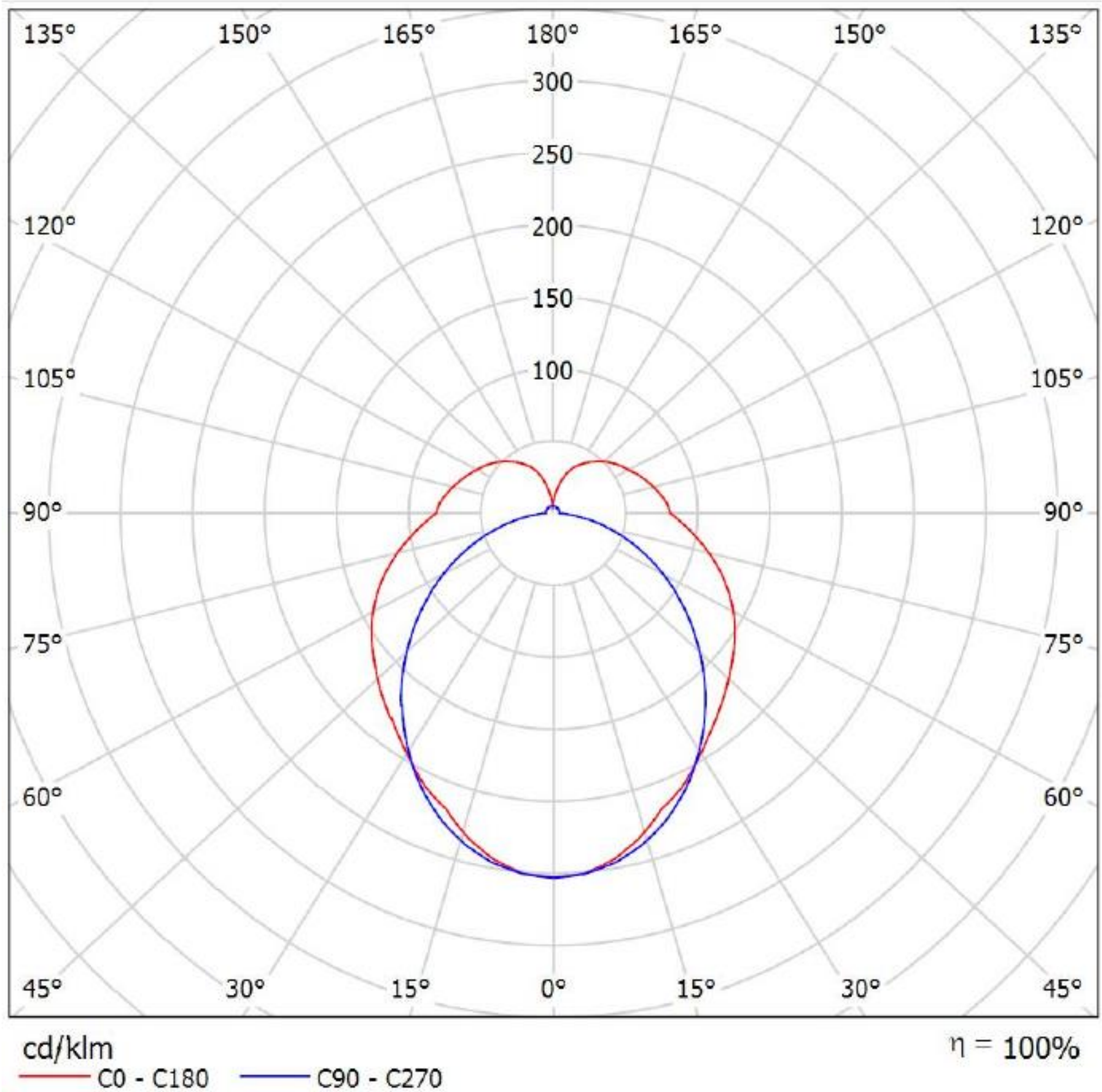


Figure.36 Luminous emittance Curves of HALLA, a.s. SANT 132-500K-15GFQ/TC

Lighting Condition 1 (Time Zone 3)

This is the lighting condition which is designed to get continuous concentration where students take tests or tasks which needs high concentration for longer periods. This is also the lighting condition which requires the highest amount of illuminance. That is why lighting installation is made for this required value as maximum. It requires 1000 lux and 6000K color temperature. Correction factor (percentage reduction of full luminous flux and power consumption of whole lighting system) is set to 1 and obtained 1007 lux on the desk surface.

Surface	ρ [%]	E_{av} [lx]	E_{min} [lx]	E_{max} [lx]
Desk	/	1007	652	1174
Floor	20	904	618	1075
Ceiling	70	533	277	1790
Walls (4)	50	700	422	2329

Table.8 Illuminance Distribution for Lighting Condition 1

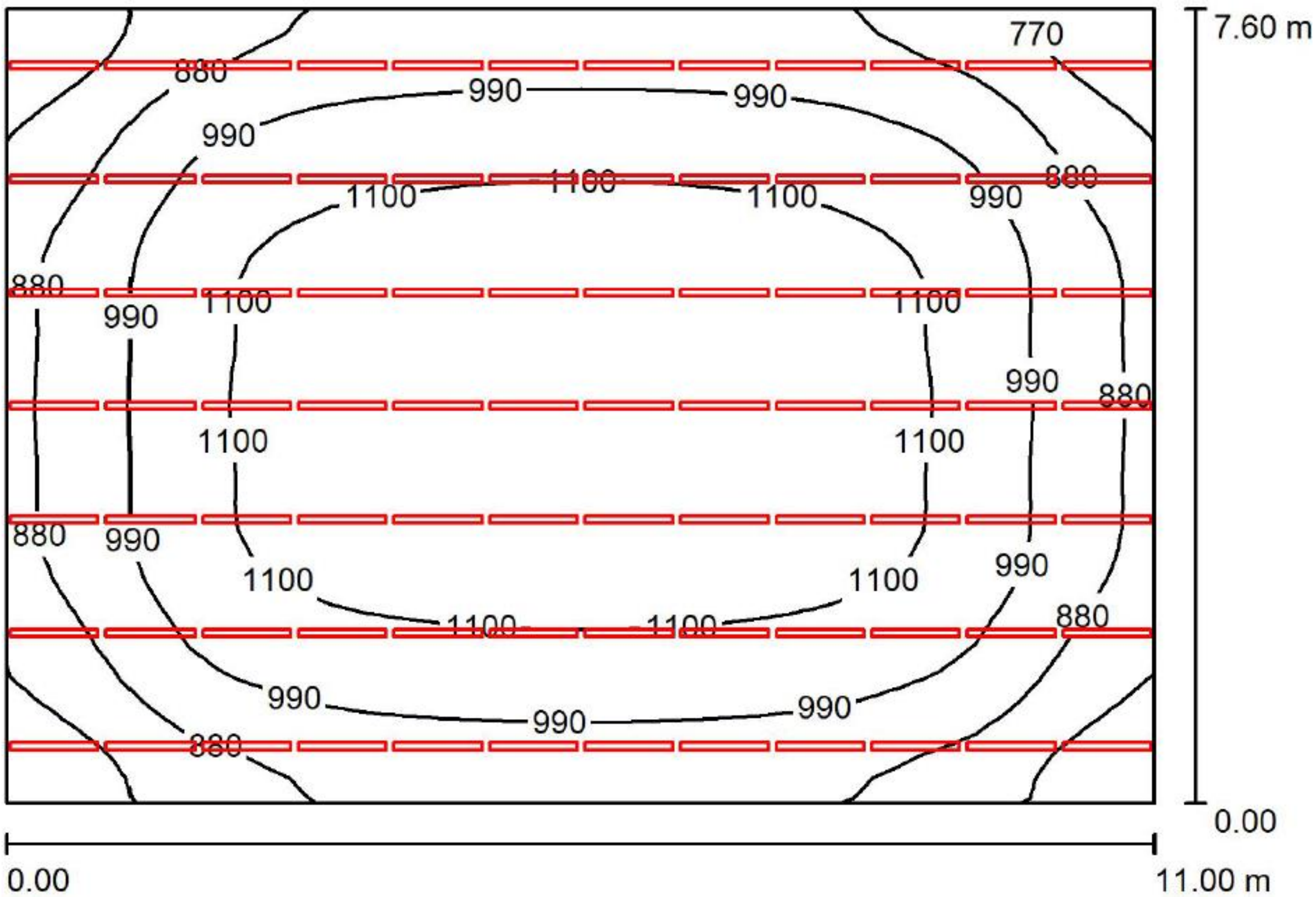


Figure.37 Light Distribution for Lighting Condition 1

Lighting Condition 2 (Time zone 1 – 5)

This is an activation lighting condition which is supposed to activate students for the following task which requires a concentration. It requires Illuminance 650 lux and 12000K color temperature. On the simulation lighting setup is tuned to observe 650 lux on the surface of the desk which is the target point. Correction factor (percentage reduction of full luminous flux and power consumption of whole lighting system.) is set to 0.65 and has obtained 655 lux on the desk surface.

Surface	ρ [%]	E_{av} [lx]	E_{min} [lx]	E_{max} [lx]
Desk	/	655	424	763
Floor	20	587	402	699
Ceiling	70	346	180	1164
Walls (4)	50	455	274	1514

Table.9 Illuminance Distribution for Lighting Condition 2

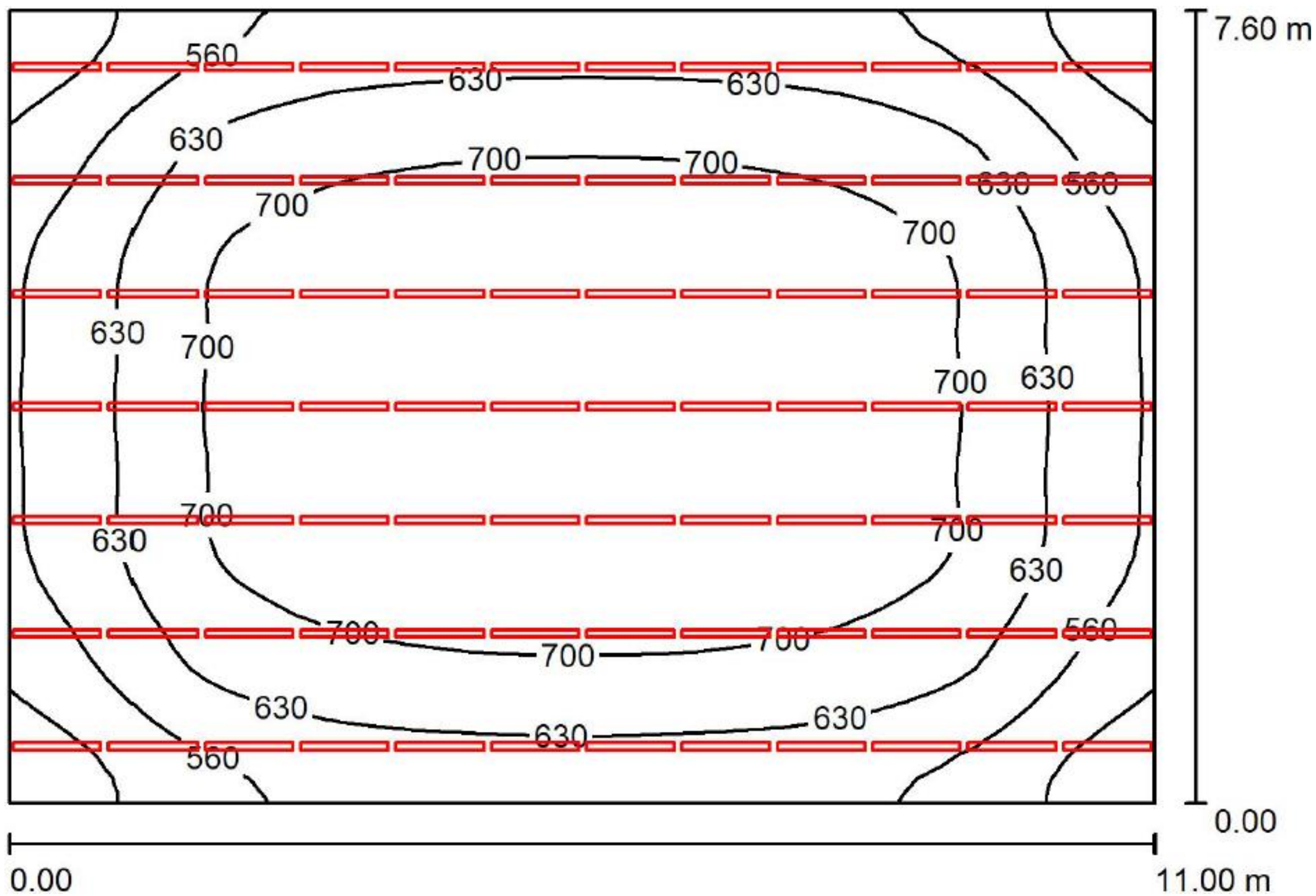


Figure.38 Light Distribution for Lighting Condition 2

Lighting Condition 3 (Time Zone 2)

This is the lighting condition where students are being taught simultaneously. For the standard lessons, it requires illuminance 300 lux and 4000K. Correction factor (percentage reduction of full luminous flux and power consumption of whole lighting system.) is set to 0.3 and has obtained 302 lux on the desk surface.

Lighting Condition 4 (Time Zone 4)

After examination period it requires 300 lux and 2700K color temperature.

Surface	ρ [%]	E_{av}[lx]	E_{min}[lx]	E_{max}[lx]
Desk	/	302	196	352
Floor	20	271	186	322
Ceiling	70	160	83	537
Walls (4)	50	210	127	699

Table.10 Illuminance Distribution for Lighting Condition 3 and 4

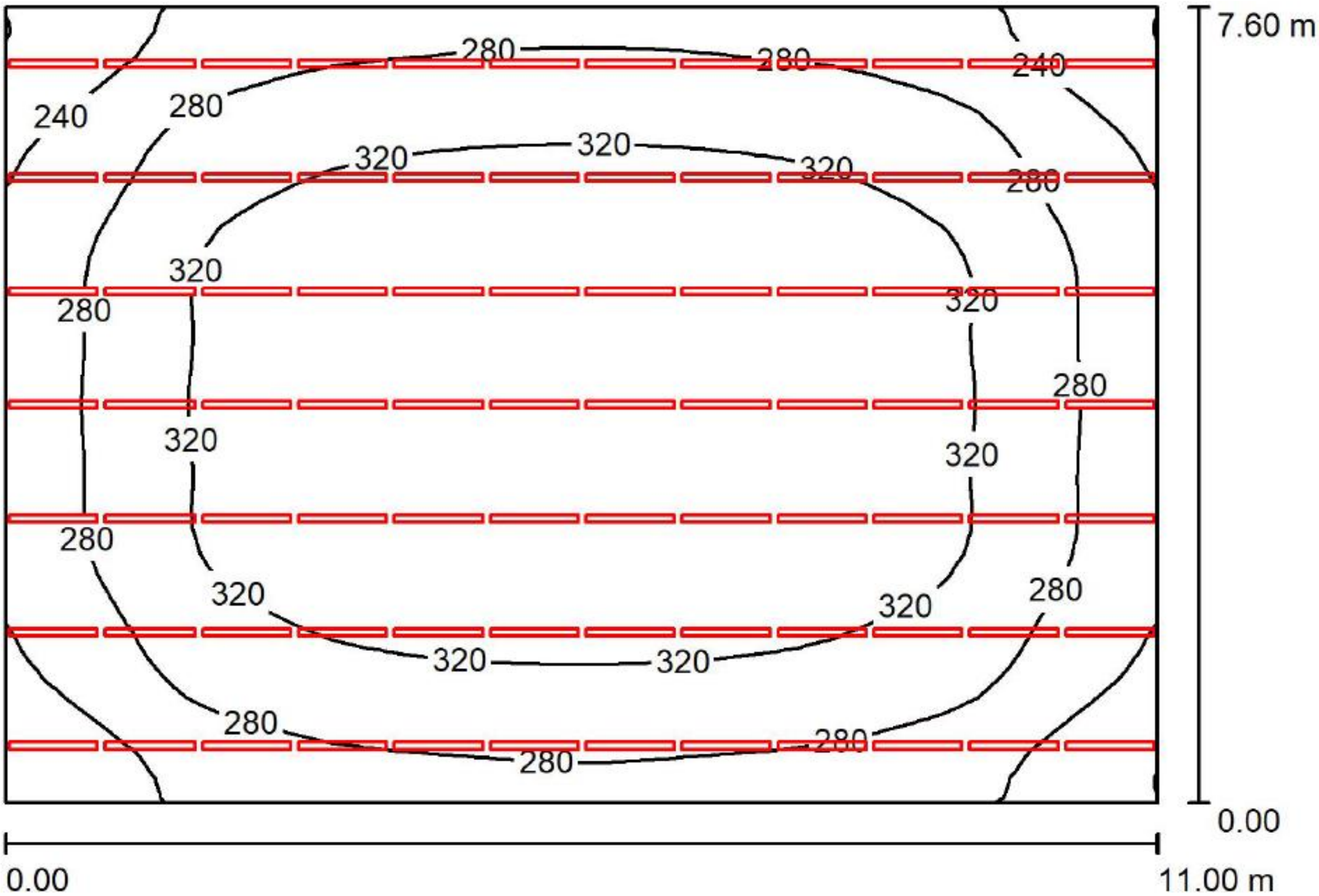


Figure.39 Light Distribution for Lighting Condition 3 and 4

4.3) Power Consumption

In this section, power consumption of the tunable white luminaire lighting design system for the classroom has been calculated. Because of the variable illumination values for the different lighting time zones, according to the formula, φ = 4 π.lm [17], luminous flux changes. As a result of this, total power consumption of the luminaire changes. As results of Dialux simulation, on the Table.11 12 and 13, It is seen the power consumption values for each luminaire and total system power consumption for lighting conditions 1,2,3 and 4.

Designation(Correction Factor)	Pieces	Φ Luminaire [lm]	Φ Lamps [lm]	P [W]
HALLA, a.s. SANT 132-500K-15GFQ/TC (1.000)	1	1850	1850	24.9
	84	155400	155400	2091.6

Specific connected load: 25.02 W/m^2 = 2.48 W/m^{2}100 lx (Ground area: 83.60 m^2)

Table.11 Power Consumption of Lighting Condition 1

Designation(Correction Factor)	Pieces	Φ Luminaire [lm]	Φ Lamps [lm]	P [W]
HALLA, a.s. SANT 132-500K-15GFQ/TC (1.000)	1	1200	1200	16.2
	84	100800	100800	1360.8

Specific connected load: 16.28 W/m^2 = 2.49 W/m^{2}100 lx (Ground area: 83.60 m^2)

Table.12 Power Consumption of Lighting Condition 2

Designation(Correction Factor)	Pieces	Φ Luminaire [lm]	Φ Lamps [lm]	P [W]
HALLA, a.s. SANT 132-500K-15GFQ/TC (1.000)	1	550	550	7.4
	84	46200	46200	621.6

Specific connected load: 7.44 W/m^2 = 2.48 $W/m^2$100 lx (Ground area: 83.60m^2)

Table.13 Power Consumption of Lighting Condition 3 and 4

It is seen on the table.9, 10 and 11 that decreasing the luminous flux also decreases the power consumption. For each lighting zone, there is different periods of use during the day of lighting the classroom. To understand total energy consumption, it is necessary to calculate energy consumption for each time zone.

On the Table.12 It has been showed the total energy consumption of tunable white luminaire lighting of a classroom for one day.

	Time Zone 1	Time Zone 2	Time Zone 3	Time Zone 4	Time Zone 5	Total
Time (hour)	0.16	3.58	0.75	0.75	0.16	5.4
Power (watt)	1360.8	621.6	2091.6	621.6	1360.8	
Energy (hourwatt)	217.73	2225.33	1568.7	466.2	217.73	4695.7

Table.14 Energy Consumption of Tunable Lighted Classroom for one day

For the standard lighting without tunable design luminance is defined as 300 lux by technical standards. In this case the total energy consumption for standard lighting is 3353 watthour per a day.

Adaptation of Tunable LED White Luminaire to Real Life Conditions

According to technical standards EN_12464-1, photometry analysis measurement and software simulation, lighting design for real life installation for a classroom is given to the table-1. As it seems on the table most values are matching between required and obtained. There is only one condition which doesn't match totally is the required color temperature for lighting condition 2. Only clear sky daylight can reach such a high color temperature. With today's technology highest color temperature can be obtained from artificial light is around 7000K.

	Lighting Condition 1	**Lighting Condition 2**	**Lighting Condition 3**	**Lighting Condition 4**
Required Color Temperature (K)	6000	12000	4000	2700
Set Color Temperature (K)	4800	5000	3800	3000
Obtained Color Temperature (K)	5877	6339	4018	2645
Required Illuminance (lux)	1000	650	300	300
Obtained Illuminance (lux)	1007	655	302	302
Required Minimum R_a	80	80	80	80
Obtained R_a	87.4	86.5	88.6	83
Required UGR	19	19	19	19
Obtained UGR	20	20	20	20

Table.15 Required and Obtained Lighting Design Parameter for Each Lighting Condition

5) Applications of Tunable White Luminaires

Nowadays tunable white luminaires are not commonly used however, there are applications exist. There is the list of current and future applications of tunable white luminaires are given on the below. [15]

- Relax or energize classroom students
- Make a home or apartment more appealing for prospective tenants
- Treat certain medical conditions, like sleep disorders
- Improve the feel of a room after it has been redesigned
- Make people feel warmer or cooler depending on the outside temperature
- Balance the human circadian rhythm (24-hour biological clock) to enhance mood, health and alertness at the proper times of day
- In Restaurants using cool colors in breakfast and warmer colors in dinner time
- Increase the efficiency of office workers

6) Conclusion

After standard LED lights started being used commonly, tunable LED luminaires became a trend lastly which is still improving. Advantages of these systems is giving more ability of control to people over the illuminance and correlated color temperature.

Firstly, it is measured the color temperature of HALLA, a.s. SANT 132-500K-15GFQ/TC tunable white luminaire model in 11 levels between 3000-5000K. As a result, It is obtained color temperatures between 2600-6400K. This range of CCT covers biggest part of required CCT for classroom lighting. However, in one lighting condition it requires 12000K which is not possible to reach such a value by any artificial light with today's technology. On the other hand, It is obtained color rendering index between 83 and 88.6 R_a while technical standards EN_12464-1 requires minimum 80 R_a.

Secondly, lighting simulation of a classroom is created to obtain lighting intensity over the classroom. Lighting design setup is made according to maximum required illuminance lighting condition which is 1000lux. For obtain other lighting conditions dimming is used that requires 650lux and 300lux. 84 Pieces of luminaires is used. Power consumption of tunable lighting has not remarkable difference compared to permanent lighting of the same light source. HALLA, a.s. SANT 132-500K-15GFQ/TC is a luminaire which is connected to each other serially. On the process of design installation of luminaires, it is supposed to use as many luminaires as possible in the same row and keep the number of rows less.

Total energy consumption of the classroom which is designed by tunable white lighting has little bit more energy consumption than the standard lighting system with permanent illuminance and CCT. Main reason of the difference is the high required illuminance on some time zones for activate and increase concentration of the students.

Benefits of this project is lighting design and application of certain white tunable luminaire model (HALLA, a.s. SANT 132-500K-15GFQ/TC) according to the technical standarts EN_12464-1.

In conclusion, researches and experiments has shown applications of tunable white luminaires have many positive effects on the human health, related to this their day-night rhythm, efficiency and concentration. Given these realities, tunable white luminaire technology is improving by investments and researches of many companies. In soon future it will be commonly used be a big part of interior lighting of our lives.

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8) Appendix

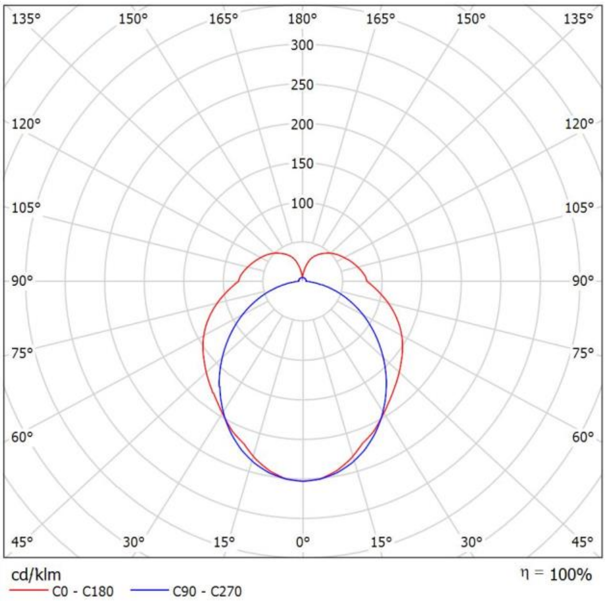
Operator
Telephone

Fax

HALLA, a.s SANT 132-500K-15GFQ/TC /Luminaire Data Sheet

See our luminaire catalog for an image of the luminaire.

Luminous emittance 1:



Luminaire classification according to CIE:
79 CIE flux code: 40 68 88 79 100

Luminous emittance 1:

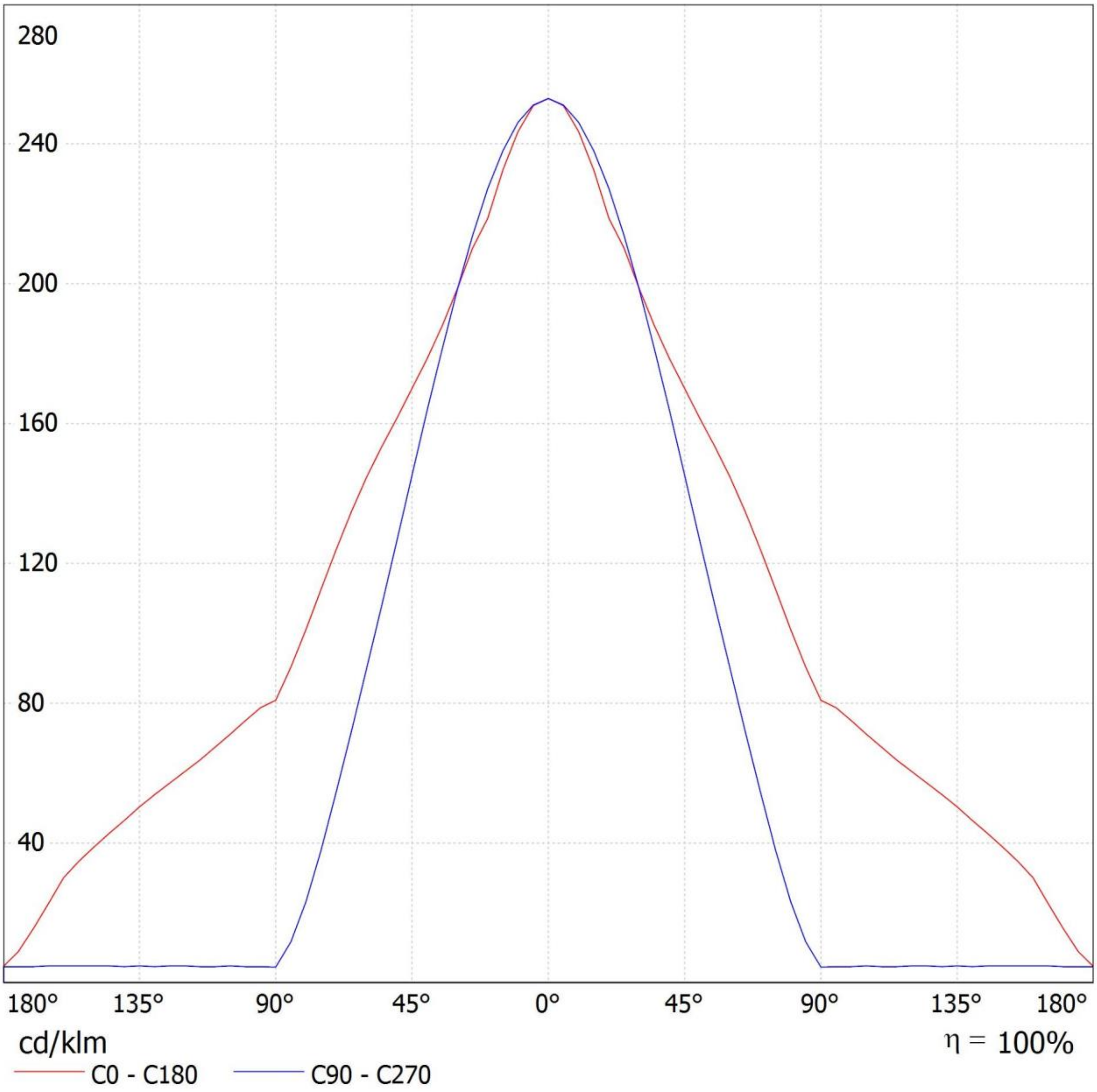
Glare Evaluation According to UGR

ρ Ceiling		70	70	50	50	30	70	70	50	50	30
ρ Walls		50	30	50	30	30	50	30	50	30	30
ρ Floor		20	20	20	20	20	20	20	20	20	20
Room Size X	Y	Viewing direction at right angles to lamp axis					Viewing direction parallel to lamp axis				
2H	2H	16.6	17.8	17.2	18.4	19.0	16.1	17.3	16.7	17.8	18.5
	3H	18.7	19.7	19.3	20.3	21.0	17.6	18.6	18.2	19.2	19.9
	4H	19.7	20.7	20.3	21.3	22.0	18.1	19.1	18.8	19.7	20.5
	6H	20.7	21.6	21.3	22.2	23.0	18.6	19.5	19.2	20.1	20.9
	8H	21.1	22.0	21.8	22.7	23.4	18.7	19.6	19.4	20.2	21.0
	12H	21.6	22.4	22.3	23.1	23.9	18.8	19.6	19.5	20.3	21.1
4H	2H	17.2	18.2	17.8	18.8	19.5	16.8	17.8	17.4	18.4	19.1
	3H	19.5	20.3	20.1	21.0	21.7	18.4	19.3	19.1	19.9	20.7
	4H	20.6	21.4	21.3	22.1	22.9	19.1	19.9	19.8	20.6	21.4
	6H	21.8	22.5	22.5	23.2	24.0	19.7	20.4	20.4	21.1	21.9
	8H	22.4	23.0	23.1	23.7	24.5	19.9	20.5	20.6	21.3	22.1
	12H	22.9	23.5	23.6	24.2	25.1	20.1	20.6	20.8	21.4	22.2
8H	4H	20.9	21.5	21.6	22.3	23.1	19.6	20.2	20.3	21.0	21.8
	6H	22.3	22.8	23.0	23.6	24.4	20.4	20.9	21.1	21.7	22.5
	8H	23.0	23.5	23.8	24.2	25.1	20.7	21.2	21.5	21.9	22.8
	12H	23.7	24.1	24.5	24.9	25.8	21.0	21.4	21.8	22.2	23.1
12H	4H	20.9	21.5	21.7	22.2	23.1	19.7	20.3	20.5	21.0	21.9
	6H	22.4	22.8	23.1	23.6	24.5	20.6	21.1	21.4	21.8	22.7
	8H	23.2	23.5	23.9	24.3	25.2	21.0	21.4	21.8	22.2	23.1
Variation of the observer position for the luminaire distances S											
S = 1.0H		+0.1 / -0.1					+0.1 / -0.1				
S = 1.5H		+0.2 / -0.2					+0.2 / -0.3				
S = 2.0H		+0.2 / -0.4					+0.3 / -0.6				
Standard table		BK09					BK06				
Correction Summand		7.4					4.2				
Corrected Glare Indices referring to 1850lm Total Luminous Flux											

Operator
Telephone
Fax

HALLA, a.s. SANT 132-500K-15GFQ/TC / LDC (Linear)

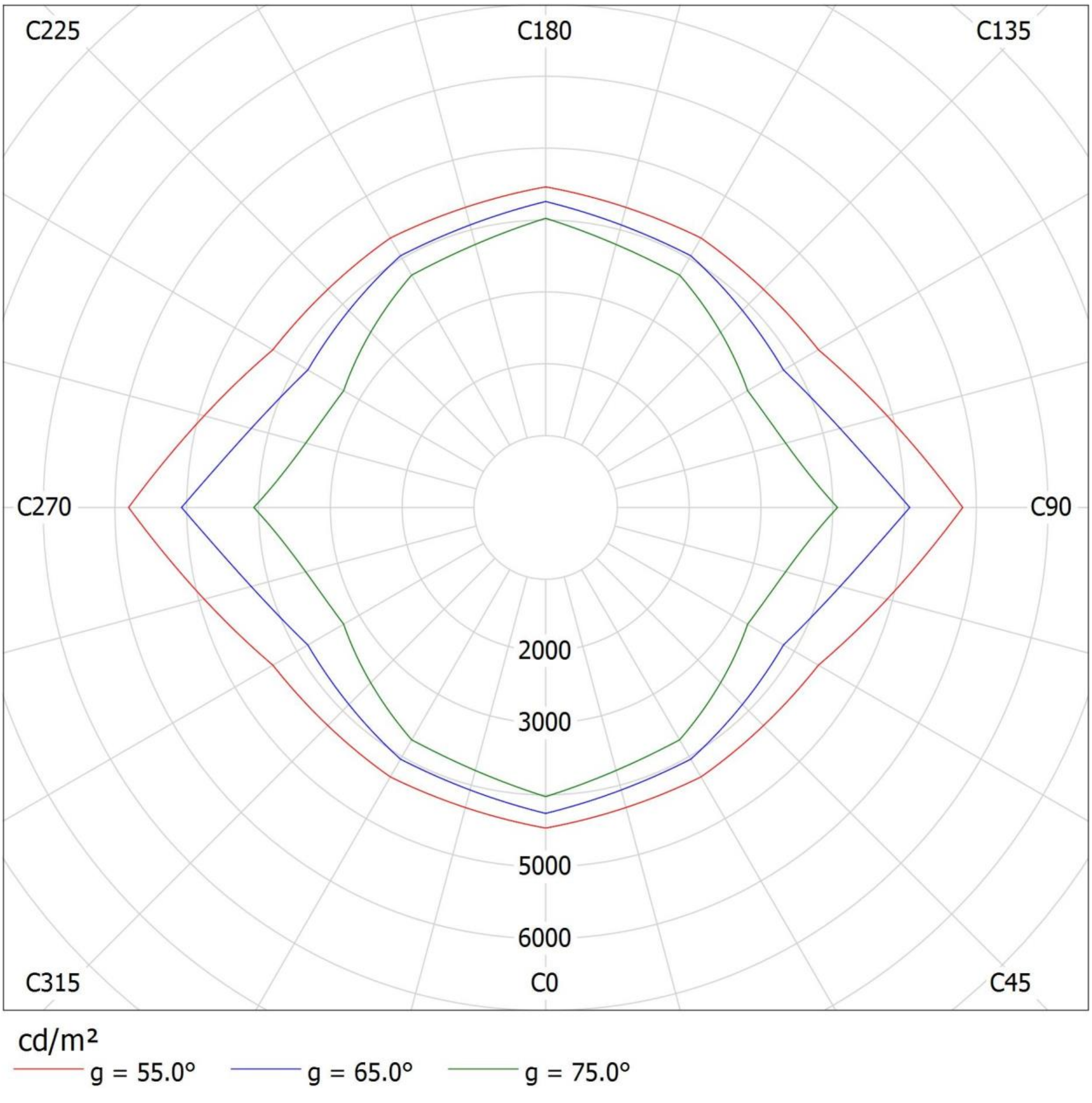
Luminaire: HALLA, a.s. SANT 132-500K-15GFQ/TC Lamps: 1 x LED 2700-6500K



Operator
Telephone
Fax

HALLA, a.s. SANT 132-500K-15GFQ/TC / Luminance Diagram

Luminaire: HALLA, a.s. SANT 132-500K-15GFQ/TC Lamps: 1 x LED 2700-6500K



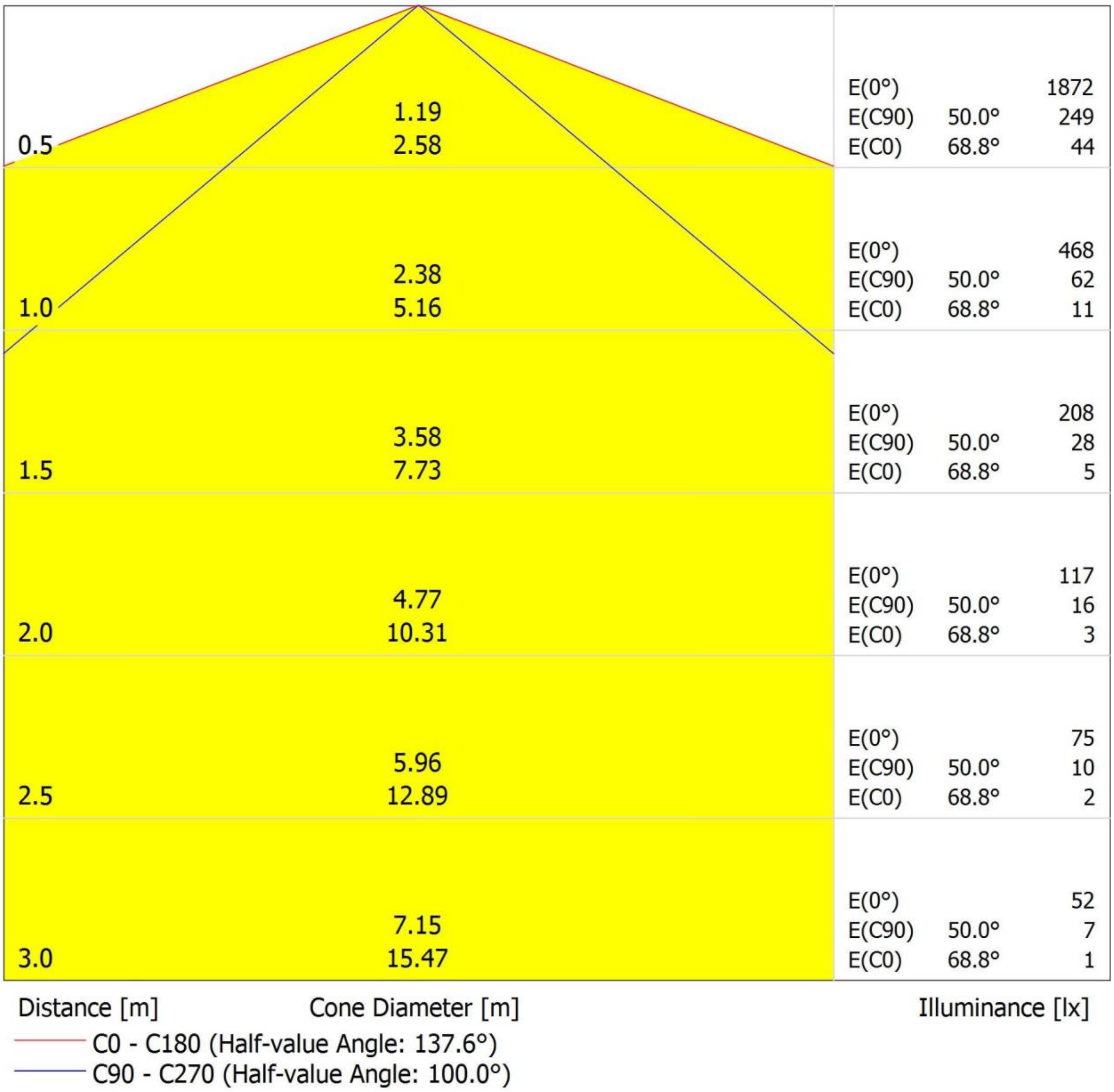
Operator
Telephone

Fax

HALLA, a.s. SANT 132-500K-15GFQ/TC / Cone

Diagram

Luminaire: HALLA, a.s. SANT 132-500K-15GFQ/TC Lamps: 1 x LED 2700-6500K



Operator
Telephone

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HALLA, a.s. SANT 132-500K-15GFQ/TC / Luminous intensity table

Luminaire: HALLA, a.s. SANT 132-500K-15GFQ/TC Lamps: 1 x LED 2700-6500K

Gamma	C 0°	C 15°	C 30°	C 45°	C 60°	C 75°	C 90°
0.0°	253	253	253	253	253	253	253
5.0°	251	251	251	251	251	251	251
10.0°	243	244	244	245	246	246	246
15.0°	233	233	234	235	237	238	238
20.0°	219	219	220	223	225	226	227
25.0°	210	209	209	210	211	212	214
30.0°	199	198	197	196	195	197	198
35.0°	188	186	185	181	178	180	181
40.0°	179	176	173	169	164	164	164
45.0°	170	166	162	156	149	147	145
50.0°	162	157	152	143	133	130	126
55.0°	153	148	142	130	118	113	108
60.0°	145	138	132	118	104	97	90
65.0°	135	128	121	105	90	81	72
70.0°	124	117	109	93	76	65	55
75.0°	113	105	97	80	63	50	38
80.0°	101	94	86	68	50	37	23
85.0°	90	83	76	58	41	26	12
90.0°	81	76	71	52	33	19	4.54
95.0°	79	68	57	43	30	17	4.67

Values in cd/klm

Operator
Telephone

Fax

HALLA, a.s. SANT 132-500K-15GFQ/TC / Luminous intensity table

Luminaire: HALLA, a.s. SANT 132-500K-15GFQ/TC Lamps: 1 x LED 2700-6500K

Gamma	C 0°	C 15°	C 30°	C 45°	C 60°	C 75°	C 90°
100.0°	75	65	55	42	30	17	4.67
105.0°	71	62	53	41	30	17	4.90
110.0°	67	59	50	40	30	17	4.67
115.0°	64	56	48	39	29	17	4.67
120.0°	60	53	46	37	29	17	4.90
125.0°	57	50	43	36	28	16	4.90
130.0°	54	47	41	34	27	16	4.67
135.0°	50	44	38	32	26	16	4.90
140.0°	46	41	36	30	25	15	4.67
145.0°	43	38	33	28	23	14	4.90
150.0°	39	34	30	25	19	12	4.90
155.0°	35	31	27	22	17	11	4.90
160.0°	30	26	23	18	14	9.45	4.90
165.0°	23	20	17	14	11	8.18	4.90
170.0°	16	14	12	10	8.94	6.80	4.67
175.0°	8.94	8.14	7.33	6.87	6.42	5.54	4.67
180.0°	4.67	4.67	4.67	4.67	4.67	4.67	4.67

Values in cd/klm

Operator
Telephone

Fax

HALLA, a.s. SANT 132-500K-15GFQ/TC / Luminance Table

Luminaire: HALLA, a.s. SANT 132-500K-15GFQ/TC Lamps: 1 x LED 2700-6500K

Gamma	C 0°	C 15°	C 30°	C 45°	C 60°	C 75°	C 90°
0.0°	8421	8421	8421	8421	8421	8421	8421
5.0°	7902	7908	7945	8014	8109	8222	8350
10.0°	7330	7356	7436	7576	7766	7986	8241
15.0°	6752	6787	6895	7104	7387	7705	8084
20.0°	6180	6219	6346	6611	6973	7386	7892
25.0°	5826	5826	5924	6175	6537	7033	7657
30.0°	5444	5444	5551	5764	6099	6663	7394
35.0°	5135	5113	5207	5367	5655	6273	7100
40.0°	4896	4844	4915	5066	5353	5959	6805
45.0°	4717	4635	4683	4780	5019	5612	6483
50.0°	4569	4463	4494	4526	4697	5268	6150
55.0°	4461	4322	4329	4292	4388	4926	5811
60.0°	4364	4198	4186	4083	4107	4599	5470
65.0°	4257	4069	4044	3877	3826	4247	5073
70.0°	4141	3927	3884	3661	3544	3878	4631
75.0°	4024	3788	3733	3448	3249	3461	4066
80.0°	3914	3662	3602	3260	2983	3045	3409
85.0°	3847	3582	3527	3144	2811	2730	2760

Values in Candela/m².

HALLA, a.s. SANT 132-500K-15GFQ/TC / Data sheet emergency lighting

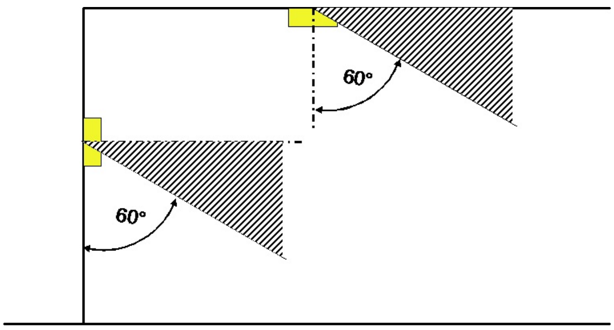
Luminaire: HALLA, a.s. SANT 132-500K-15GFQ/TC

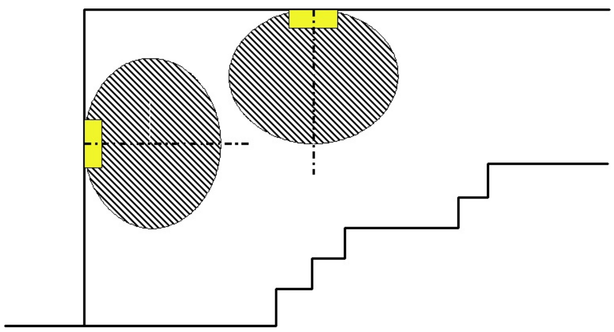
Lamps: 1 x LED 2700-6500K

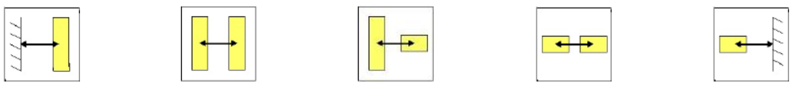
Color rendering index:	80
Luminous flux:	1850 lm
Correction Factor:	1.000
Emergency lighting factor:	1.00
Emergency lighting luminous flux:	1850 lm
Light output ratio:	100.00
Light output ratio (lower hemisphere):	78.69
Light output ratio (upper hemisphere):	21.31

Glare valuation (Maximum luminous intensity [cd])

	C0	C90	C0 - C360
Gamma 60° - 90°	267.6	166.4	267.6
Gamma 0° - 180°	468.0	468.0	468.0







Distance table for even escape routes
Mounting Height [m]

2.00	5.09	12.85	11.42	10.09	4.17
2.50	6.34	15.99	14.21	12.54	5.17
3.00	7.39	18.66	16.62	14.69	6.05
3.50	7.75	19.66	17.66	15.73	6.44
4.00	8.04	20.53	18.59	16.67	6.79

Operator
Telephone

Fax

Room 1 /

Maintenance plan

Regular maintenance is essential for an effective lighting installation. It is the only way to limit the light loss over the installation's life time.
The minimum values of the illuminance specified in the EN 12464 are maintenance values, i.e. they are based on a new value (at installation) in a maintenance to be prescribed. The same is of course true also for the values calculated in DIALux. They can therefore be reached only if this basic maintenance plan is diligently carried out.

General room information

Environment conditions of room:	Clean
Maintenance interval of room:	Every 2.5 years.

Field Arrangement / HALLA, a.s. SANT 132-500K-15GFQ/TC

Influence of the room surfaces by reflection:	medium
(1.6 < k <= 3.75) Flux distribution: indirect	Direct /
Maintenance interval of luminaires:	Annually
Luminaire type:	Closed IP2X (acc. CIE)
Annual burning time (in 1000 hours):	2.58
Replacement interval lamps:	Annually
Lamp type: CIE)	Tri-phosphorus fluorescent lamp (acc.
Spot lamp replacement:	Yes
Room surface maintenance factor:	0.87
Luminaire maintenance factor:	0.88
Lamp lumen maintenance factor:	0.93
Lamp survival factor:	1.00
Light loss factor:	0.71

Please observe the corresponding instructions of the respective manufacturers when maintaining luminaires and lamps.

Operator
Telephone

Fax

Room 1 / Photometric Results

Total Luminous Flux: 155400 lm Total Load: 2091.6 W

Boundary Zone: 0.000 m

Surface	Average illuminances [lx]			Reflection factor [%]	Average luminance [cd/m²]
	direct	indirect	total		
Desk	639	369	1007	/	/
Floor	549	355	904	20	58
Ceiling	271	262	533	70	119
Wall 1	446	291	737	50	117
Wall 2	345	298	643	50	102
Wall 3	446	292	738	50	117
Wall 4	345	304	649	50	103

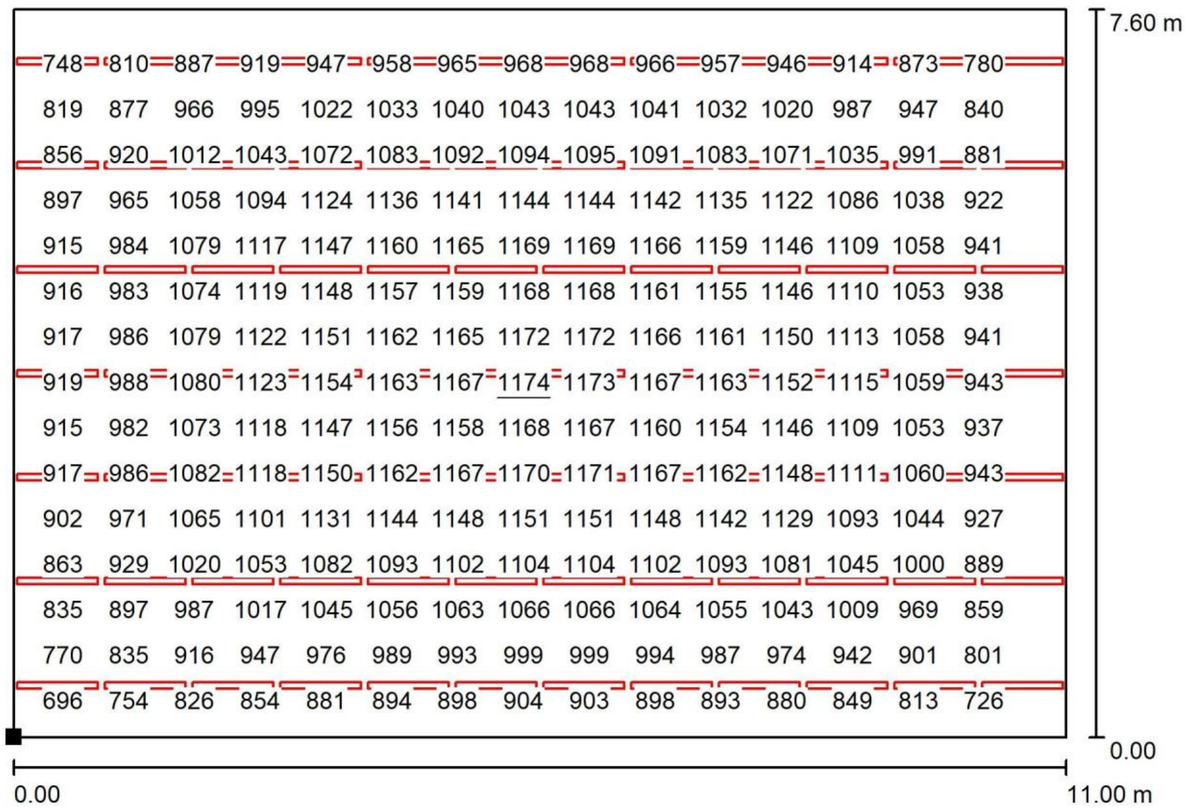
Uniformity on the working plane u0: 0.647 (1:2)

E_{min} / E_{max}: 0.556 (1:2)

UGR	Lengthways-	Across	to luminaire axis
Left Wall	22	20	
Lower Wall	21	20	

(CIE, SHR = 0.25.)

Illuminance Quotient (according to LG7): Walls / Working Plane: 0.755, Ceiling / Working Plane: 0.529. Specific connected load: 25.02 W/m² = 2.48 W/m²/100 lx (Ground area: 83.60 m²)



Values in Lux, Scale 1 : 79

Not all calculated values could be displayed. Position of surface in room:

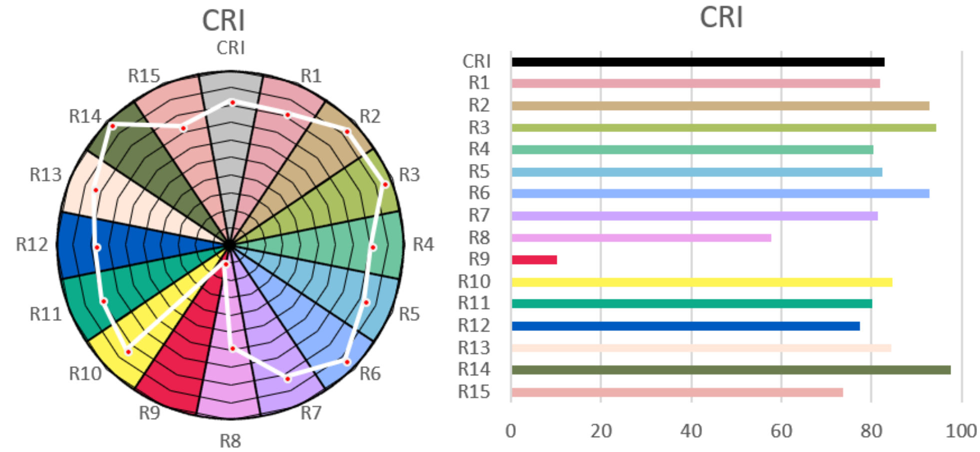
Marked point:

(0.000 m, 0.000 m, 0.750 m)

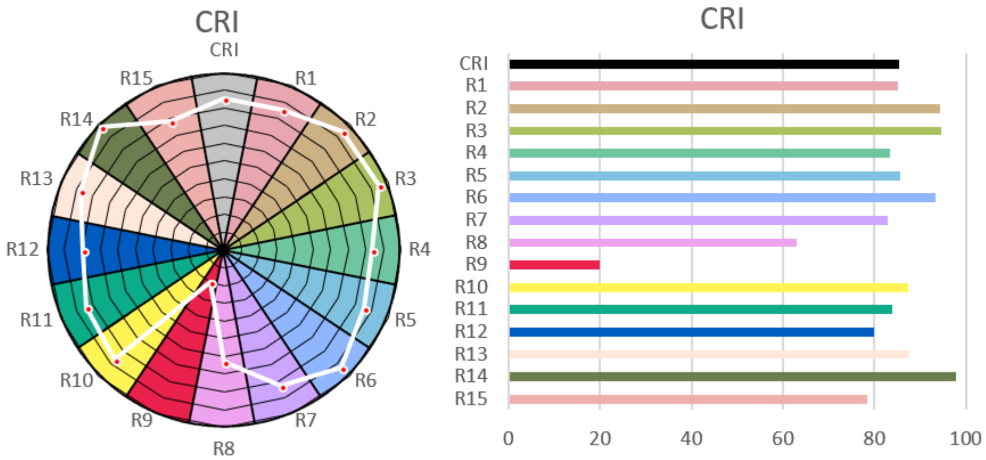
Grid: 32 x 32 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	Emin / Emax
1007	652	1174	0.647	

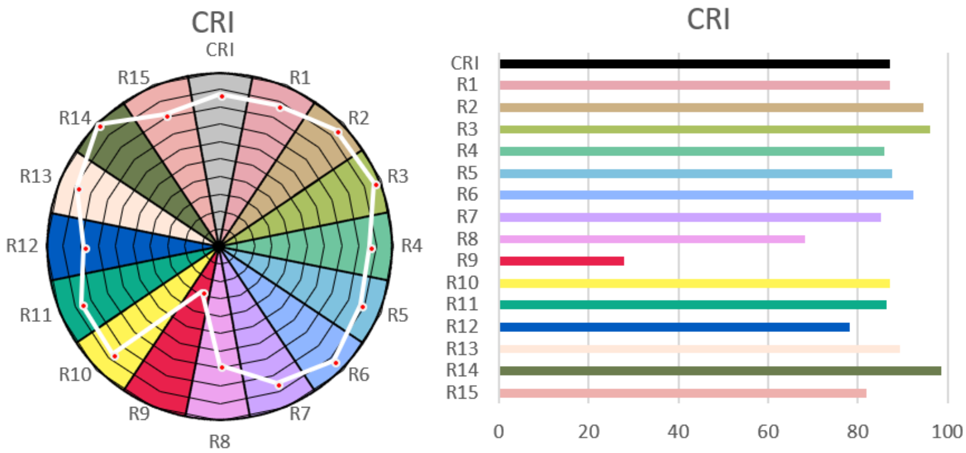
Color Rendering Index Graphs and Values of Measurement



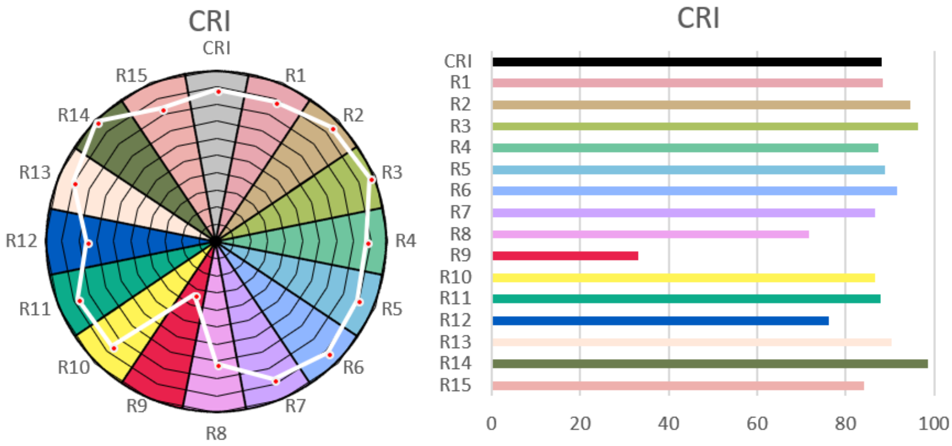
CCT = 3000K



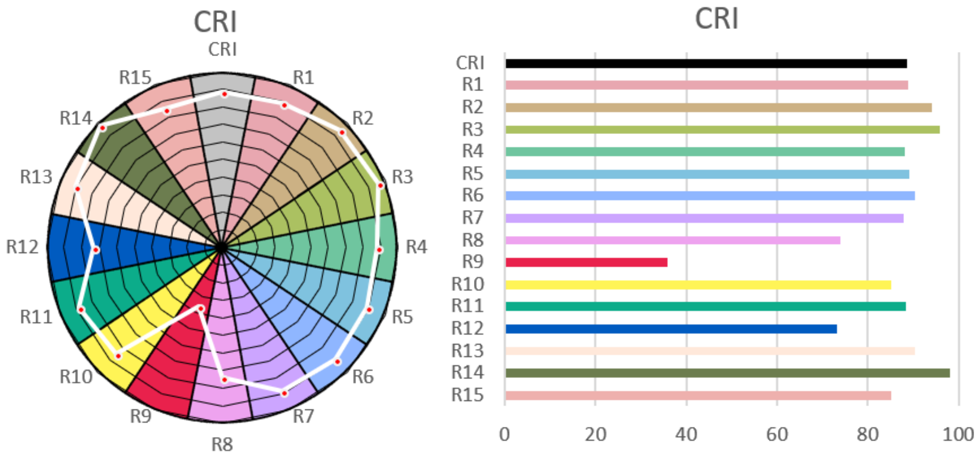
CCT = 3200K



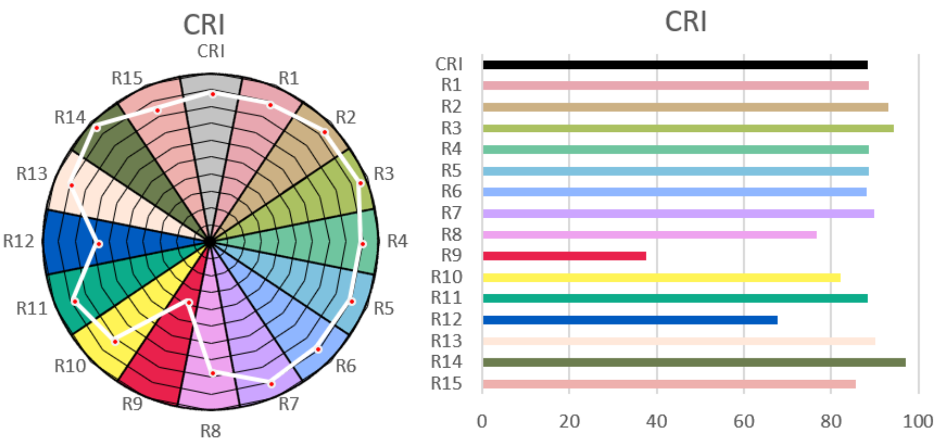
CCT = 3400K



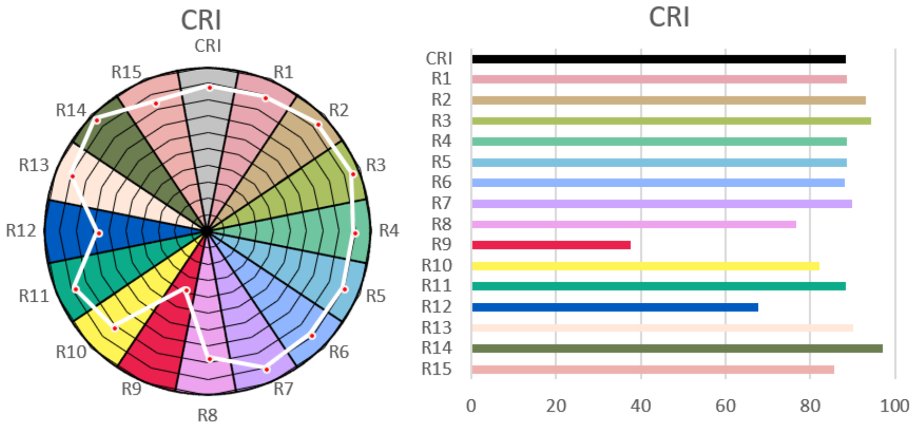
CCT = 3600



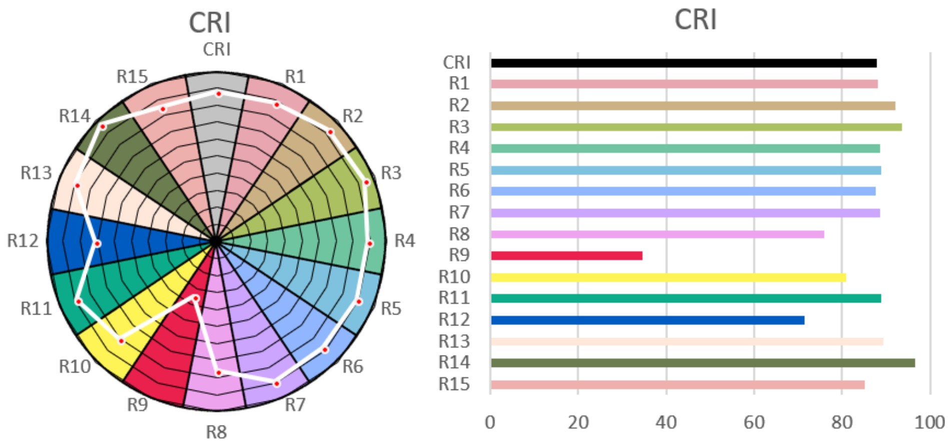
CCT = 3800



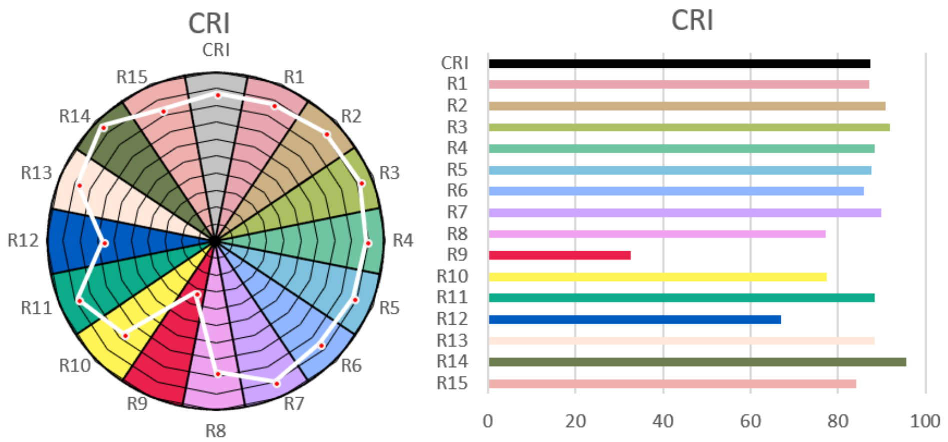
CCT = 4000



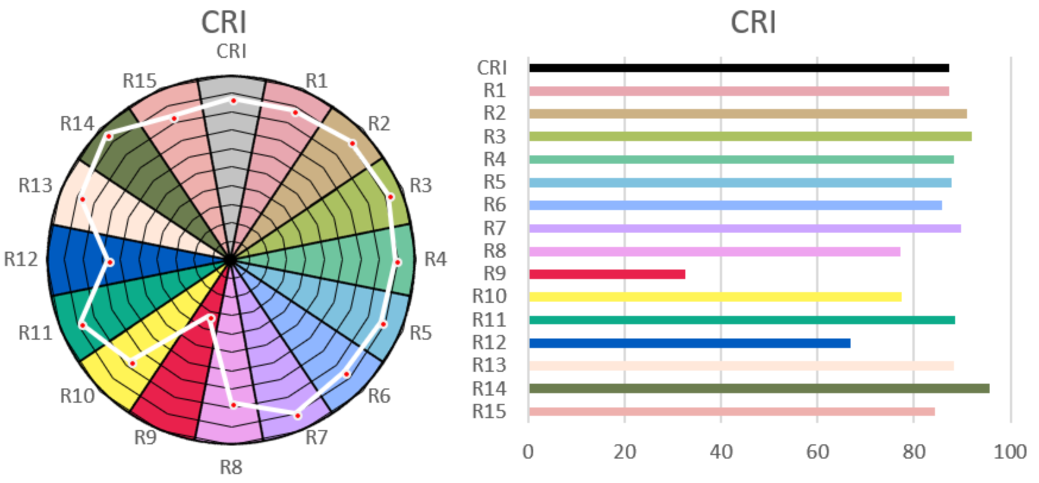
CCT = 4200



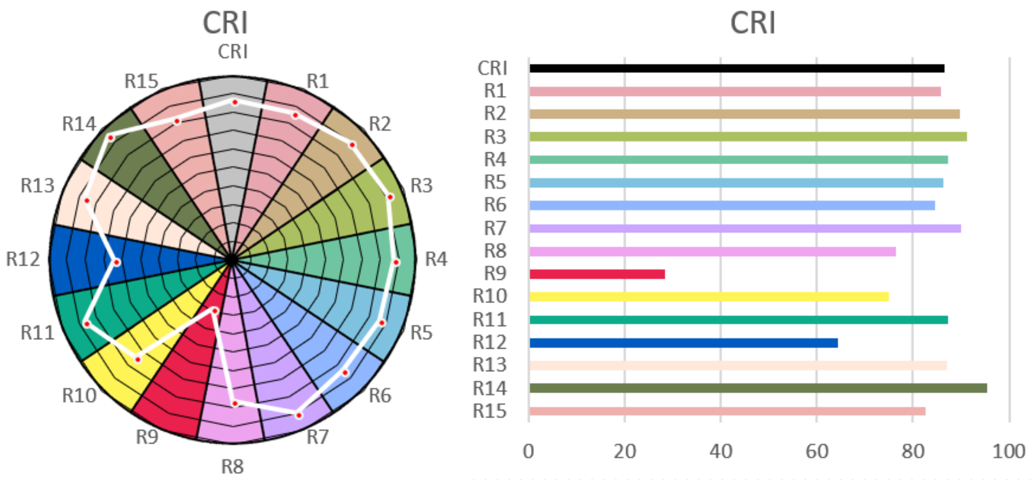
CCT = 4400



CCT = 4600



CCT = 4800



CCT = 5000