Energy and Circadian Assessment of a Combination Between Integrative Lighting and Daylight Harvesting

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Lund University

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The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Summary

In modern societies, people tend to spend up 90% of their lifetime indoors of which a big share is spent at work, this raises the demands for several aspects in terms of health and wellbeing. Several studies have proved that the quality of lighting has an impact on workers' health and performance. There is a network of circadian clocks in mammals that are reset with help of input and circadian signals that are delivered to the brain, a master clock at the top of this network that is located in the suprachiasmatic nuclei (SCN) is mainly controlled by ambient light. Intrinsically photosensitive retinal ganglion cells (ipRGC), which works as environmental irradiance detectors which senses light levels independently without the input from either rods or cones, is a proof of the non-visual pathway that affects the human physiology and psychology. The ipRGCs are responsible for transforming the information to the SCN which is located in the brain in order to help reset the circadian clocks.

A relatively new concept called integrative lighting is investigated in this study, the concept of integrative lighting is to support the circadian entrainment by varying in intensity and correlated colour temperature (CCT) during the course of a day in order to elicit a circadian response. Most of the integrative lighting systems that are available today are designed with the intention of supporting the circadian entrainment, which has led to lost or less focus on the energy consumption of such light source despite the fact that daylighting is free, and it stimulates the circadian entrainment better than any light source that are available today. Therefore, this study aims to investigate a combination of integrative lighting with daylight harvesting.

Earlier studies have shown that integrative lighting stimulates circadian entrainment. But since there were no studies that included the energy use, the objective of this study was to understand how integrative lighting systems in offices could be engineered to consume less energy than it does today with help of daylight harvesting, while still eliciting similar variations of melanopic over photopic (M/P) illuminance ratios.

The greater part of the results is consistent with previous research as they confirm that circadian entrainment is affected differently depending on the incoming light. Nonetheless, that M/P ratios were as desired in some cases and others not. Finally, yet importantly, a combination of integrative lighting and daylight harvesting was very beneficial in terms of energy as the energy demand significantly decreased. The time of the year turned out to be of great importance as the incoming light was different during different times of the year, which had a great impact on the results.

Abstract

This study deals with the health and wellbeing of humans who work in offices as well as the energy use for the lighting. The focus is on how integrative lighting and daylight harvesting can be combined in an attempt to reduce the energy consumption while still eliciting a circadian response for the workers.

The aim of this study is to investigate a combination of integrative lighting and daylight harvesting. Besides that, the study partly aims to make a literature review on the topic with the intention to find answers for unanswered questions for previous studies. The goal on the other hand is to understand how an integrative lighting system in offices could be engineered to consume less energy that it does today, while still eliciting similar variations of melanopic over photopic (M/P) illuminance ratios.

The research methods of this report included primary research of on-site measurements and observations as well as research of literature studies. Moreover, several modelling and simulation software’s within energy and non-visual effects of light were used and analysed in order to answer the research questions.

Literature on the subject along with technical information for the chosen light source has been a central and important part of the study, Adaptive Lighting for Alertness (ALFA) was a key factor in order to achieve optimum results. The results correlate with literature and previous research as they both confirm that the circadian entrainment is affected differently by different SPDs. The study shows that a combination of integrative lighting and daylight harvesting reduces the energy consumption, while the M/P ratios were both sufficient and insufficient depending on whether it is wintertime with overcast sky or summertime with clear sky.

Acknowledgments

To begin with, we would like to deeply thank our supervisor Niko Gentile (LTH). He has guided and supported us throughout the entire study, he has also shared a lot of his valuable knowledge within the topic that has contributed to an overall better outcome. His help kept us motivated and made it possible for us to fulfil the study.

We would also like to thank our Co-supervisor Jouri Kanters (LTH) that contributed with his knowledge regarding modelling and helped us with the license for ALFA.

Thanks to our examinator Thorbjörn Laike (LTH), for giving us constructive feedback that helped us put together the last and among the most important pieces of the project.

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Further thanks go to LTH for providing us with daylighting measurement tools that were used in this project.

Not least of all, we would like to express our gratitude to family, friends and other people that in one way or another supported us throughout this study, your support has kept us motivated and inspired us all the way to a complete project.

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Abbreviations

ADF	Average Daylight Factor
ALFA	Adaptive Lighting for Alertness
CCT	Correlated Colour Temperature
CIE	International Commission on Illumination
CRI	Colour Rendering Index
CS	Circadian Stimulus
DF	Daylight Factor
DA	Daylight Autonomy
EML	Equivalent Melanopic Lux
EPW	EnergyPlus Weather Format
IpRGCs	Intrinsically photosensitive Retinal Ganglion Cells
LED	Light Emitting Diodes
M/P Ratio	Melanopic/Photopic Ratio
PL	Photopic Lux
SAD	Seasonal Affective Disorder
sDA	Spatial Daylight Autonomy
SPD	Spectral Power Distribution
SCN	Suprachiasmatic Nuclei
WWR	Window-to-wall Ratio

Definitions

Correlated Colour Temperature (CCT)

CCT is an index mostly used to describe warmness (red-shifting) or coolness (blue-shifting) of a titularly white light source (Lechner, 2015).

Colour Rendering Index (CRI)

CRI gives general advice of how well a light source renders colour. The colour that appears on a surface depends on the CRI of the light source also, and the surface colour appears different with different light sources (Dubois et al., 2019).

Daylight Factor (DF)

The DF is described as the ratio of daylight illumination in a room at a given point on a horizontal plane from an unobstructed overcast sky, in relation to the total amount of illumination that would be accessible under an unobstructed hemisphere during overcast. DF is a static daylight metric, meaning that it only depends on architectural qualities and not on location and orientation (Acosta et al., 2018).

Daylight Autonomy (DA)

The DA describes the percentage of the year where daylight alone is sufficient for the occupants to perform their tasks. DA is measured on a grid for a minimum illuminance threshold and for a specific working schedule. DA is a dynamic daylight metric, meaning that it is climate based and as it depends on location, orientation and weather conditions (Reinhart et al., 2006).

Intrinsically photosensitive Retinal Ganglion Cells (ipRGCs)

The ipRGCs are defined as a subtype of ganglion cells that contain a blue light-sensitive photopigment called melanopsin with a peak sensitivity of approximately 482 nm, these cells work as environmental irradiance detectors which senses light levels through melanopsin independently without the need of input from neither cones nor rods (Chakraborty et al., 2021).

Illuminance

Illuminance represents the total amount of luminous flux incident per unit area, and it is measured in lux (Lechner, 2015).

Integrative Lighting

Lighting that supports circadian entrainment by varying in intensity and colour to result in a curve similar to daylight in order to elicit a circadian response (van Lieshout-van Dal et al., 2019).

Luminous Flux

Luminous flux is the total amount of light that is emitted by a light source and it is measured in lumen (Lechner, 2015).

M/P Ratio

It describes the ratio between melanopic and photopic illuminance. M/P ratio is commonly used to indicate whether the lighting may provide calming, alerting or neither effects on users.

Seasonal Affective Disorder (SAD)

A depressive disorder common in higher latitudes, shortened photoperiods and decreased exposure to sunlight results in affective dysregulation and a disorder of biological rhythms (Akram et al., 2020).

Spatial Daylight Autonomy (sDA)

The part of an analysis area that fulfils the requirements of minimum daylight illuminance level for specific occupancy hours per year (Kazanasmaz et al., 2016).

Spectral Power Distribution (SPD)

SPD represents the radiant power that is emitted by a light source at each wavelength in the visible part of the electromagnetic spectrum (Chuang, n.d.).

Zeitgeber

Environmental cycles which synchronizes an endogenous clock that drives the circadian rhythms (Caldart et al., 2020).

1 Introduction

The circadian entrainment in mammals is controlled by biological oscillators which include a master clock located in the SCN. This oscillation has a duration of approximately 24 hours, which means that in order to synchronize with the surrounding environment, the circadian entrainment needs to be entrained by virtue of Zeitgeber (“time giver”) signals, for instance the day-night cycle (Golombek and Rosenstein, 2010). The main synchronizer of the human biological clock is light, it has the ability to shift the phase of the circadian entrainment as well as regulating the quality of our sleep (“Ocular Lighting Effects on Human Physiology, Mood and Behaviour,” 2003). According to Dubois et al., (2019), daylight provides dynamic changes that have a positive effect on the activation state on people, specifically in indoor work environments. Furthermore, these dynamic changes are hard to achieve with electric illumination. However, in this modern society, humans tend to spend more than 90% of their time indoors of which about 60% is spent at home (Cooper et al., 2021; Mannan and Al-Ghamdi, 2020). The total amount of time spent indoors makes the quality of lighting of big importance, whether it comes from daylighting or artificial lighting because it affects occupant’s health, wellbeing and performance in workspaces through visual and non-visual light perception (Chen et al., 2020). Photobiological studies confirm that poor lighting quality could result in health and wellbeing issues such as SAD, cardiovascular disease and low energy, desynchronized circadian clocks and sleep problems (Parsaee et al., 2020).

According to Lechner (2014), artificial lighting is responsible for the consumption of about 25% of the electricity that is consumed by all buildings and around 40% is consumed by commercial buildings which makes the topic of big importance. The importance of occupants' health and wellbeing in offices is becoming more recognized and has led to the development of something called integrative lighting, or also commercially called human-centric, circadian, biodynamic and healthy lighting (Parsaee et al., 2020). The idea of integrative lighting is to support circadian entrainment by varying in intensity and spectral composition to result in a curve similar to daylight in order to elicit a circadian response (van Lieshout-van Dal et al., 2019). In order to trigger circadian entrainment, integrative lighting systems are required to deliver higher illuminances in comparison to traditional systems which may result in an even higher energy consumption. This may lead to backfire issues in regard to energy use, although integrative lighting is generally designed with efficient LEDs which is considered to be energy efficient in comparison to other light sources.
Earlier studies with reference to integrative lighting has investigated integrative lighting in relation to how it affects the circadian entrainment. This study will focus more on the energy consumption and the possibilities to reduce it by combining integrative lighting with daylight harvesting while still satisfying the circadian entrainment for office workers.

1.1 Objective and Research Questions

The aim of this study is to investigate whether a combination of integrative lighting, daylighting and daylight harvesting control system (artificial lighting is dimmed according to available daylight) can provide both circadian response and energy saving. Since Integrative lighting is a young technology, not much have been evaluated on how to integrate it with daylighting. Beside the experimental part, the study provides a literature review on the topic.

The circadian entrainment is naturally stimulated by the dynamic changes in daylight which provides a natural and biological environment for humans. However, the majority of integrative systems that are available today are designed to support the circadian system under electric lighting conditions only, despite the fact that daylight provides a free circadian stimulation. The thesis hypothesis is that a combination of good daylighting design together with a daylight-linked integrative lighting system could efficiently support circadian entrainment and reduce the energy consumption in comparison to a traditional integrative lighting system. The objective of this work is therefore to understand how integrative lighting in offices could be engineered to consume less energy than it does today with help of daylight harvesting, while still eliciting similar variations of melanopic over photopic (M/P) illuminance ratios.

The specific research question is: could a combination of daylight harvesting and integrative lighting result in similar M/P profiles, while saving energy?

1.2 Scope and Delimitation

The scope of this study was to find a way for integrative lighting to consume less energy while still stimulating the circadian entrainment in humans. This project was limited to one office throughout the entire research period, located in Helsingborg, Sweden (56°01'34"N 12°42'48"E). EML and M/P ratio are the circadian metrics that have been measured for a type of integrative lighting; the focus was on three different CCTs and different daylighting conditions. In regard to energy, only energy from electric lighting has been considered in this study.

1.3 Overall approach

This study is carried out through a quantitative method by conducting field measurements and simulations, building site visits and measurements as well as a literature review.
The literature review was made on previously published research within the field was conducted. The scope was to get a good understanding of relevant concepts and current status of scientific knowledge on the thesis topic.

2 Theoretical Background

In mammals, a network of circadian clocks is responsible for controlling the behavioural and physiological processes, they are reset with help of inputs and circadian signals are delivered to the brain (Pevet and Challet, 2011). The top of the network is a master clock located in the SCN which is mainly reset by ambient light (Liu et al., 2019; Pevet and Challet, 2011). The most prominent zeitgeber of the circadian system is light. It is known that the intensity and wavelengths of light, among others, has an impact on the rhythms of the melatonin synthesis and clock gene expression in the central oscillator of most mammals (Liu et al., 2019) see Figure 1.

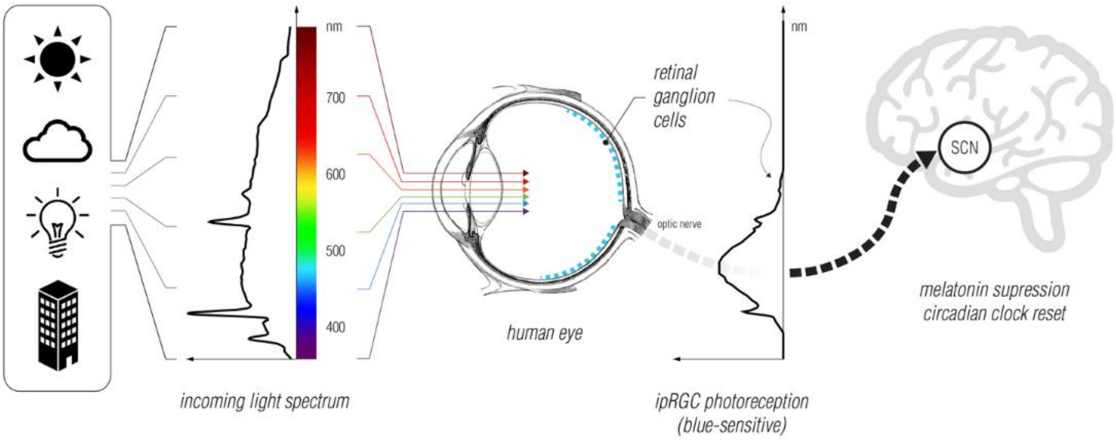


Figure 1: Explanation of how light is absorbed by the human eye and then perceived by the brain. Image from www.solemma.com Published with permission from Solemma team.

Circadian disruptions and deviation may occur if a certain environment does not provide appropriate light stimuli to the occupant (Nie et al., 2020). An appropriate light stimulus is considered to have high intensity and high CCT (blue-enriched light) during the morning, and lower intensity and lower CCT (red-shifted) lighting during the afternoon. Integrative lighting could be used to help stimulate the circadian entrainment in environments where it is necessary, as varies in CCTs ranging from 2700K - 6500K trying to result in a similar curve as natural light (van Lieshout-van Dal et al., 2019).
The following chapters covers relevant concepts and definitions for this study in order to get a deeper understanding of the reports content.

2.1 Natural and Artificial Lighting

Daylight is a combination of both direct and indirect electromagnetic radiation from the sun, which is changed by various reflections and filtered through the atmosphere. The availability and duration of daylight depends on several factors such as geographical locations, time of the year and atmospheric conditions (Wirz-Justice et al., 2020). The light that the human eye responds to makes up a small part of the electromagnetic spectrum (Figure 2) which is between 380 to 740 nm (Dubois et al., 2019). According to Dubois et al., (2019), the following are the some of the most obvious benefits of daylighting:

- better visual performance,
- stimulation of the circadian entrainment,
- reduction of stress, feeling of security and connection,
- increased productivity (relevant for workspaces and schools),
- high luminous efficacy (lumens/Watts) resulting in energy savings,
- improved architectural quality and improved space perception,
- improved image of the building (through environmental certification).

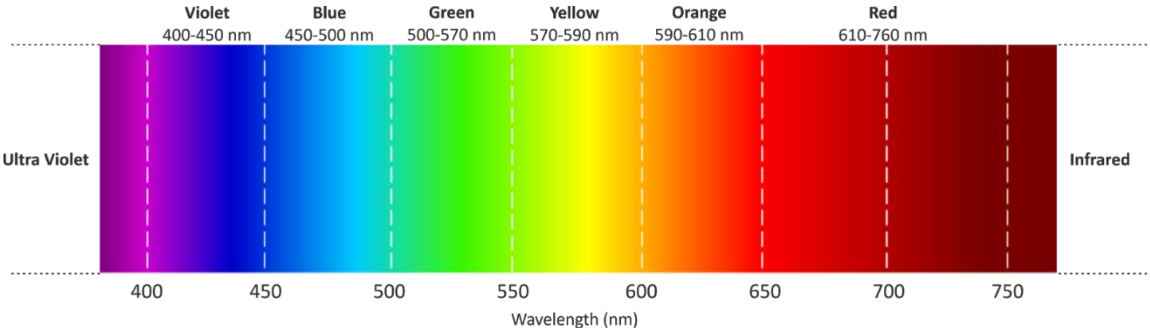


Figure 2: The humanly visible part of the electromagnetic spectrum.

Daylight provides a wide and continuous SPD which changes during and across days, during different weather and sky conditions as well absolute power in the form of irradiance. Furthermore, it changes in colour, diffuseness and direction and polarity (Wirz-Justice et al., 2020).

In a modern society where people spend up to 90% of their time indoors, electric lighting is necessary in buildings where daylight access is limited as it blurs the distinction between day and night as well as benefiting the circadian entrainment (Acosta et al., 2019). But despite that, artificial lighting lacks the ability to stimulate the circadian entrainment in the same way natural daylight does. For instance, traditional artificial lighting is not dynamic and does not change in CCT and does not render colours as good as daylight (Wilson and Tregenza, 2011). It is important to keep in mind that daylighting should be the main source of illumination when designing a building, meaning that artificial lighting should only be used as a complement to daylighting considering that daylighting is free and benefits humans in a better way that artificial lighting does (Dubois et al., 2019).

2.2 Effects of light

According to (Dubois et al., 2019), there are three main pathways through which daylighting affects human physiology:

- visual (through rods and cones)
- direct skin absorption
- non-visual effects which have an impact on the circadian entrainment as well as other neuronal pathways

(Bisenga et al., 2015) states that the discovery of the ipRGC in the 1990s is proof of a non-visual pathway of light which influences human physiology and psychology. The ipRGCs are defined as a subtype of ganglion cells that contain a blue light-sensitive photopigment called melanopsin with a peak sensitivity of approximately 482 nm, these cells work as environmental irradiance detectors which senses light levels through melanopsin independently without the need of input from neither cones nor rods (Chakraborty et al., 2021). This specific type of ganglion cell is responsible for transmitting signals to the SCN which is located in the brain. Despite that, 2% of all the ganglion cells are photosensitive and the density of photopigments in ipRGC is approximately 10 000 times smaller compared to rod and cone pigments. With that being said, a relatively bright light is necessary in order to obtain effective signals (Figure 3) from the ipRGC cells (van Bommel, 2019).

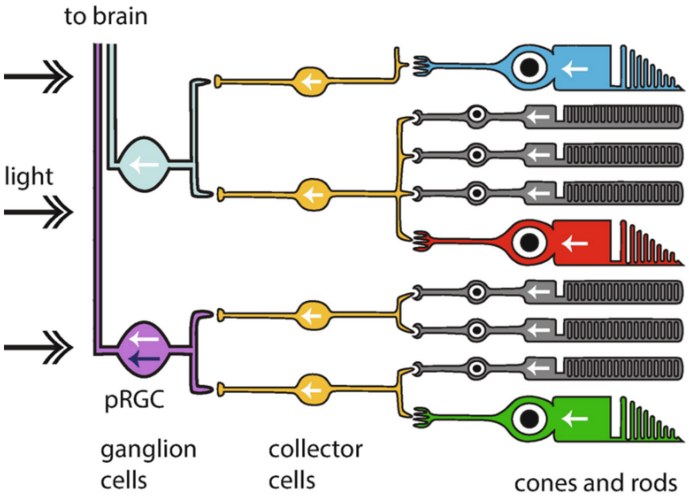


Figure 3: Illustration of a part of the photoreceptor cells including iPRGC. The white arrows show how the signals reach the brain as a result of the transformation of light which is incident on cones and rods. The blue arrow shows the light which is incident on the iPRGC. Source: NON VISUAL BIOLOGICAL MECHANISM 1. Published with permission from the owner.

Studies on animals and humans confirm that short wavelength radiations help stimulating psychological responses correlated to the neuroendocrine and neurobiological systems such as resetting the timing of the circadian pacemaker, sleep and wakefulness, hormone suppression and production, body temperature, metabolism (Bellia et al., 2011; Dubois et al., 2019).

2.3 Circadian Entrainment

Human biological functions are regulated by the circadian system with an approximate schedule of 24-hours in order to guarantee synchronization between the outer environment and the internal events in the body (Zheng et al., 2021). This synchronization is essential in order to regulate several physiological and psychological aspects in humans such as cellular processes, mood and behaviour (Carmon, 2020; Sadria and Layton, 2021) The circadian entrainment has a duration that fluctuates somewhere in the range of 23.5 and 24.7 hours, though the normal average is about 24.2 for grown-ups with good health (Carmon, 2020).

This confirms that there is a natural phase shift between the 24-hour duration of a conventional day and the internal circadian clock. Therefore, it is necessary for the human body to have a day-to-day reset in order to fluctuate parallelly with the external environment (Carmon, 2020).

2.4 Physiological processes

The circadian entrainment ensures the right functioning of several physiological processes over a period of 24 hours by the release of different hormones as well as regulating other indicators such as body temperature and alertness (Carmon, 2020). In addition to that, there are several body properties that are affected by the circadian entrainment, among those are blood pressure, liver function and production of new cells (van Bommel, 2019).

However, blue-enriched light in the morning has a biologically alerting effect which makes the cortisol hormone rush in early mornings and then slowly decrease until it reaches very low levels during night-time. Quite the opposite happens early evening time as the sky becomes redder which allows the melatonin synthesis to begin (Carmon, 2020; Dubois et al., 2019), see Figure 1.

A healthy person should barely have any melatonin in their body during the daytime. The melatonin level should gradually rise and reach its maximum level around 2-3 hours after midnight. In contrast to that, the cortisol levels should approximately be at their lowest point around midnight (van Bommel, 2019). These hormones are of particular importance since they regulate sleep and alertness, and they are directly affected by light stimulus. Cortisol, which is sometimes referred to as the energy or stress hormone, increases the glucose level in the body (blood sugar) in order to provide the system with energy as well as improving the immune system. If cortisol levels reach a higher level than required, the body will feel inefficient and exhausted. Melatonin on the other hand, which is sometimes referred to as the sleep hormone, induces sleep and slows down several bodily processes (van Bommel, 2019). Figure 4 shows a typical example of daily rhythms in the bodily system over a 2-day period.

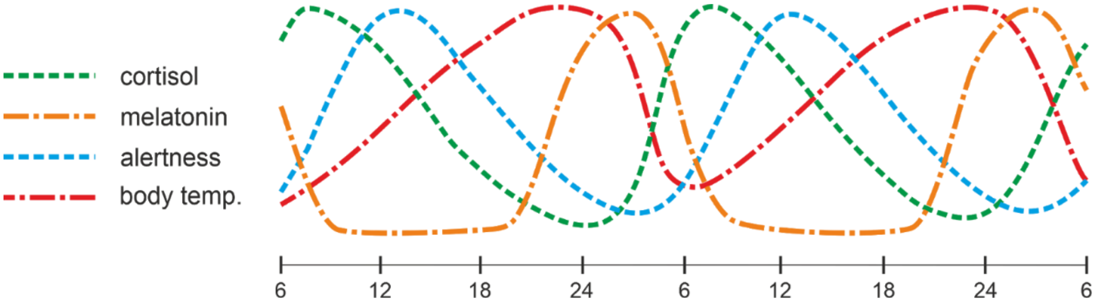


Figure 4: Daily rhythms in the bodily system over a 2-day schedule. Adapted from CIE.

2.5 Equivalent Melanopic Lux

EML is one of the proposed circadian metrics that is used to measure the non-visual biological effects that light has on humans. Traditional lux is measured to the cones while EML is measured to the iPRGCs since it is based on the melanopsin sensitivity of iPRGCSs in the retina. The EML has its basis in the spectral action curve of the photopigment melanopsin, the method that it is calculated through involves the SPD of a specific light source as well as the normalized values for the melanopic curve on different wavelengths (Enezi et al., 2011). EML measurements are taken on a vertical plane at an eye level of the occupant ("Standard | WELL V2," 2020). This is quite different from traditional lighting design for visual performance, where most of current metrics are measured on the horizontal work plane.

2.6 Melanopic/Photopic Ratio

The ratio between melanopic and photopic illuminance describes the circadian efficacy of a light source. For instance, two light sources with the same visual brightness could have two totally different M/P ratios. A greater M/P ratio is preferred during morning and midday since it indicates a higher potential to suppress melatonin secretion (Konis, 2018). ALFA, a software for circadian lighting design, introduces the following thresholds:

- Alerting, blue colour (M/P > 0.9)
- Calming, (M/P < 0.35)
- Neither (0.35 < M/P <0.9)

2.7 Correlated Colour temperature

CCT is an index mostly used to describe the colour appearance of titularly white light source (Lechner, 2014). A light source with a CCT around 2700 K appears as yellowish white and is commercially available labelled as warm, a light source with a CCT around 4000 K has a blueish white appearance which is commercially labelled as cold while and a clear blue sky shows around 10 000 K in CCT (Dubois et al., 2019), see Figure 5.

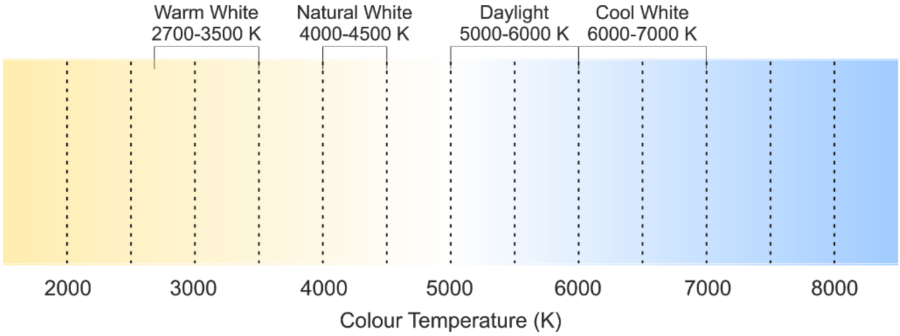


Figure 5: Basic illustration over how different CCTs appear as in colour.

2.8 Spectral Power Distribution

SPD is the function of wavelength that describes the amount of optical radiation emitted by a light source in a part of a spectrum. It can also describe the optical radiation reflected by an object or transmitted from a transparent or semi-transparent object(Chuang, 2014). When it comes to colours, SPD is often used to describe an object's colour characteristics since optical properties like transmittance, reflectance and absorbance are usually dependent on the specific wavelength (McCluney, 2014).

2.9 Integrative Lighting

Integrative lighting is defined as artificial lighting that changes in intensity, spectrum and temporal characteristics that aims at adapting buildings lighting to individuals physical and mental health in order to stimulate circadian entrainment (van Lieshout-van Dal et al., 2019). This type of light source produces both direct and indirect light with bluish colour and higher illuminance in morning time and changes more towards a warmer red colour in the evening. Moreover, it produces colour temperatures ranging from approximately 2700 to 6500 K trying to result in a similar curve as natural light (van Lieshout-van Dal et al., 2019)

2.10 WELL Standard

WELL building standard is a system based on performance that measures, certifies and monitors features of the built environment that impact human wellbeing and health through air, water, nourishment, light fitness, comfort and mind ("Standard | WELL V2," 2020). WELL is managed and administered by the International WELL Building Institute and is a public benefit corporation that aims to improve human health and wellbeing through the built environment ("Standard | WELL V2," 2020).

The concept from WELL is the light concept, which is divided into 8 features, each feature has requirements that need to be achieved in order to gain points. The total sum of the points decides which level you reach in the WELL building standard later on. The 8 features are the following:

- Light exposure and education.
- Visual lighting design.
- Circadian lighting design.
- Glare control.
- Enhanced daylight access.
- Visual balance.
- Electric light quality.
- Occupant control of lighting.

The main feature from WELL for this study was the "Circadian Lighting Design". This feature seeks to provide occupants with appropriate exposure to light in order to maintain circadian health and adjust the circadian entrainment with the day-night cycle. Furthermore, WELL standard suggests that at least one of the following requirements are met in working areas:

a. 200 EML should be present at 75% or more of the workstations in work areas, this light level may include daylight and is at least present between the hours 09.00 AM - 1.00 PM for all the days of a year.
b. 150 EML or greater for all workstations where electric lighting provides the maintained illuminance on a vertical place facing forward in order to simulate the view of the occupant.

3 Methodology

This chapter describes the overall methodology and analysis that were used in this study in three different parts. Chapter 3.1 describes the investigation of the office and its current situation in terms of reflectance measurements on site and daylight simulations. Chapter 3.2 introduces the software that has been used in order to fulfil the project. Chapter 3.3 examines the annual energy use and the combination of integrative lighting with daylight harvesting. The impact of the light source on the circadian entrainment is covered in the same chapter. Finally, chapter 3.4 presents the certification system WELL Standard and its requirements for circadian lighting design.

The implementation of the method for the entire study is shown in Figure 6.

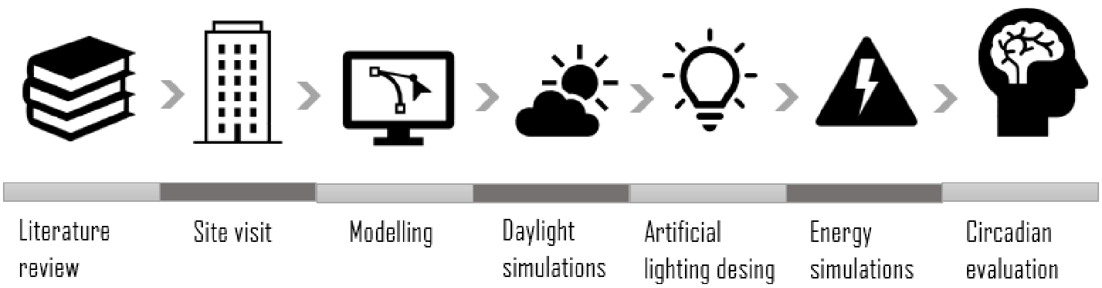


Figure 6: The workflow of the method used in the study.

3.1 Daylight Analysis of Current Situation

Figure 7 and Figure 8 shows the office that has been investigated in this study, which had a floor area of 34 m^2. The yellow box in Figure 8 shows the part of the building that was chosen for the study. The windows in the yellow box are the only source of daylight and they are oriented towards the southwest.

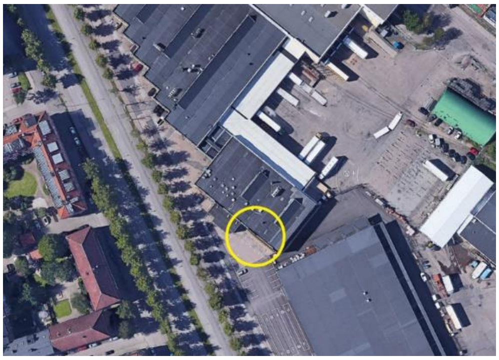


Figure 7: Aerial view of the office yellow circle.

Figure 8: Elevation view of the office in yellow box.

The study was carried out with the original layout and furnishing of the office. Figure 9 shows a simplified illustration of the original layout that was used during the entire project.

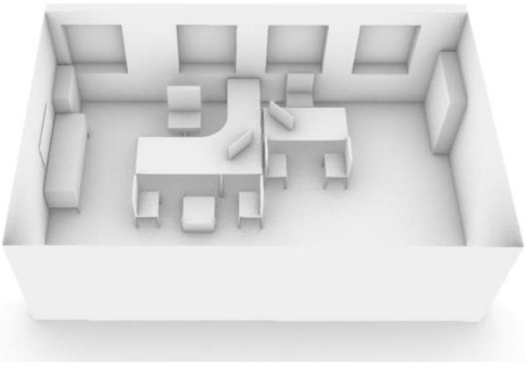


Figure 9: Office layout that was used for the simulations.

3.1.1 Subjective evaluation and observation

A site visit was conducted in order to measure the photopic reflectance (V(λ)) of all surfaces in the office. In this first site visit, the surfaces were considered diffusive, and they were measured with a luminance meter and a reference plate of known reflectance. Note that some surfaces with different properties were considered as one in the study. For instance, books on a bookshelf were not measured and were instead considered as part of the bookshelf and were given the same reflectance value as the bookshelf itself in the simulations. Figure 10 and Figure 11 show the tools that were used to measure the reflectance.

Figure 10: Universal photometer.

Figure 11: Reflectance reference.

The reflectance values from the site visit were used to navigate and find appropriate materials on a spectral material database (http://Spectraldb.com). There, the materials were selected based on their type, reflectance, colour, specularity and roughness, trying to find those closer to the actual materials in the office. The spectral definition of materials values was necessary in order to run circadian simulations with higher accuracy.

3.1.2 Static and Dynamic Daylight Simulations

As a first step, daylight metrics such as DF, ADF, DA and sDA were simulated in order to get a perception of the office's current daylight situation. The DA and sDA were measured at two different thresholds, 300 lux and 500 lux as these are common thresholds depending on the tasks. 300 lux were used for everything around the workstation and 500 lux for the workstations. DA and sDA simulations were run with a height of 0.76 m from floor level. The DF was 0% at some points in the grid due to furniture that happened to be placed at the coordinates of the grid point, therefore the ADF was the most equitable way of presenting the DF. All simulations were performed with all the furnishing inside (see Figure 9). The results are presented in Table 1.

Table 1: Illumination in the office from daylight.

ADF	DA (500)	sDA (500)	DA (300)	sDA (300)
2.42%	53.21%	48.41%	66.17%	95.24%

3.2 Artificial Lighting

The artificial lighting in this study is not the original light source in the office, the original light source is fluorescent tubes which was excluded from the study. They were replaced with an integrative lighting ceiling system consisting of LED ceiling panels from LEDVANCE GmbH called "BIOLUX HCL PANEL, 600 ZB 43W 2700K-6500K", see Figure 12.

Figure 12: BIOLUX HCL PANEL, 600 ZB 43W 2700K-6500K. Published with permission from LEDVANCE AB.

The system is able to run with 3 different CCTs, 2700 K, 4000 K and 6500 K. The luminous flux changes with CCT. When running on 2700 K, luminaire has a luminous flux of 3960 lm while it delivers 4400 lm for both 4000 K and 6500 K. First, the system was dimensioned to satisfy visual requirements, namely, to deliver 500 lux on the working space. Then, the following integrative lighting "recipe" was decided for the variation of CCT for the ceiling panels:

- 6500K between 08.00 - 11.00
- 4000K between 11.00 - 14.00
- 2700K between 14.00 - 17.00.

This division was chosen because 6500K is more alerting and should therefore be the one used early in the morning to help people get started with their activities, 4000K is neither alerting or calming and were therefore more suitable for these hours. Finally, 2700 is a warm colour which were considered as calming and were therefore most suitable for the hours by the end of the workday.

In either way, the light distribution curve for the chosen ceiling panel does not change with the dynamic changes in CCT and it is as shown in Figure 13.

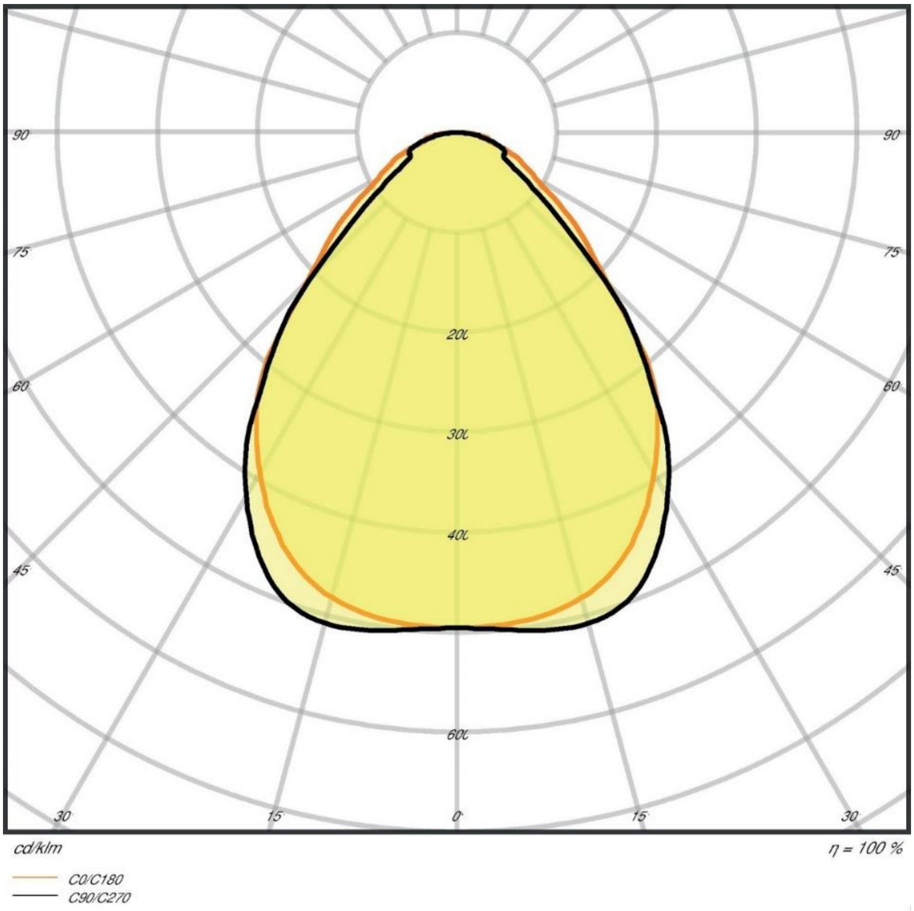


Figure 13: Light distribution curve for BIOLUX HCL PANEL, 600 ZB 43W 2700K-6500K. Published with permission form LEDVANCE AB.

Table 2 presents the technical specification for the chosen light source.

Table 2: Technical data of the light source.

Nominal Wattage	43 W
Type of Operation	External LED Driver
Nominal Rated Voltage	220-240 V
Power Factor λ	≥0,90
Output Current	1100 mA
CCT	2700 K - 4000 K - 6500 K
CRI	>90
Light Colour	Warm White/Cool White/Cool Daylight
Light Flux	3960 lm – 4400 lm - 4400 lm
Luminous Efficacy	95 lm/W
Spreading Angle	80,00 º

3.3 Software and Tools

Several software and tools were used in order to fulfil the study. The office was modelled in Rhinoceros 3D. Once the office was modelled, Grasshopper, which is a graphical algorithm editor that works as a plugin for Rhinoceros 3D, was used to create and run scripts for the simulations by using Honeybee and Ladybug plugins. EnergyPlus Weather Format (EPW) from www.climate.onebuilding.org for Helsingborg, Sweden was used for the dynamic simulations that were location dependent.

ALFA, one of the two currently available circadian lighting design software, was used for calculating the EML for different scenarios. ALFA works as a plugin to Rhinoceros 3D and was used in this study to evaluate the non-visual effects of light. Visualizations and pictures extracted from ALFA were fisheye pictures in RGB and Falsecolor for EML and Photopic illuminance (PL). Besides that, simulations for EML, and M/P ratio were simulated as well. Note that the reflectance values that were used in ALFA were values from the spectral database (http://Spectraldb.com). The spectral definition for the sky is given by ALFA; since there is not standard yet on spectral sky definitions, this could have a significant impact on the results.

The Lucas Toolbox which was created by Lucas et al. (2014) enabled conversions and calculations that are related to the non-visual effects of light. The SPD values for the chosen light source were collected from a database for relative SPDs (https://www.doi.org/10.11583/DTU.12783389). Further on, the values that were extracted from the toolbox were used to calculate the equivalent melanopic illuminance (EML) over photopic illuminance (M/P) ratio. Thereafter, the light source with the closest M/P ratio to the chosen light source in this study was used as an input in ALFA for each CCT. Note that

ALFA is a pretty limited software and therefore, values for M/P ratios in the software were chosen similarly to the ones that were calculated from Lucas Toolbox. The SPDs that were collected from the database for relative SPDs were not the same SPDs that were used in ALFA, those are the real SPDs which could not be inserted in the software. See Figure 14, Figure 15 and Figure 16 for different CCTs of the ceiling panel.

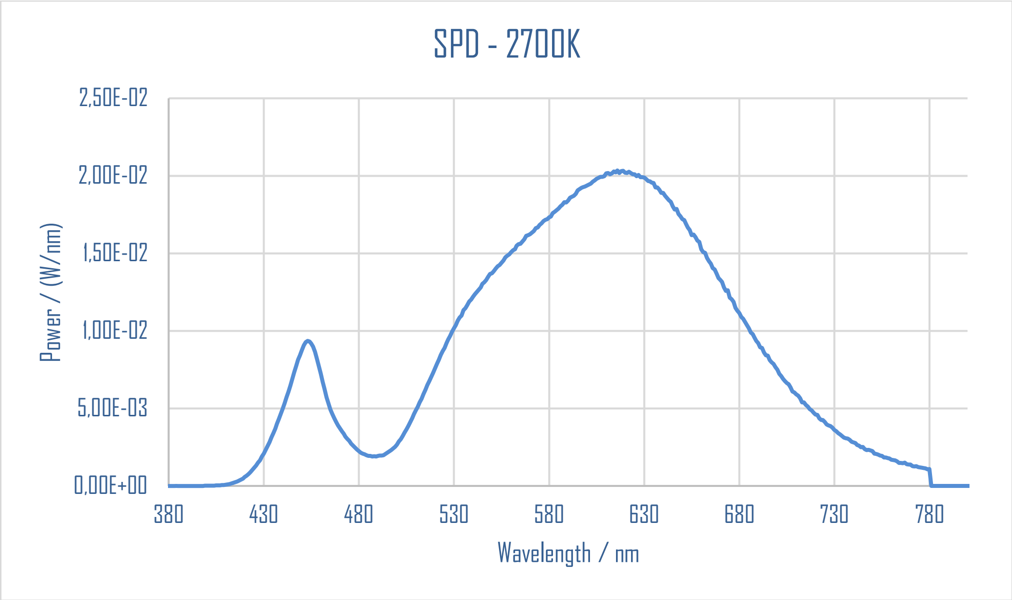


Figure 14: SPD for the 2700K CCT.

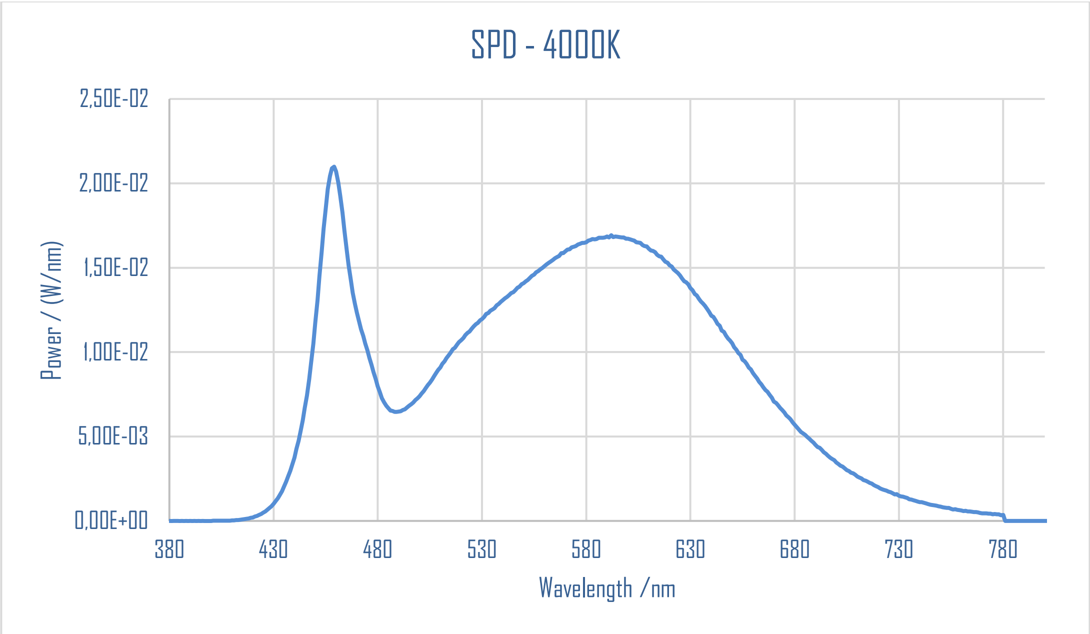


Figure 15: SPD for the 4000K CCT.

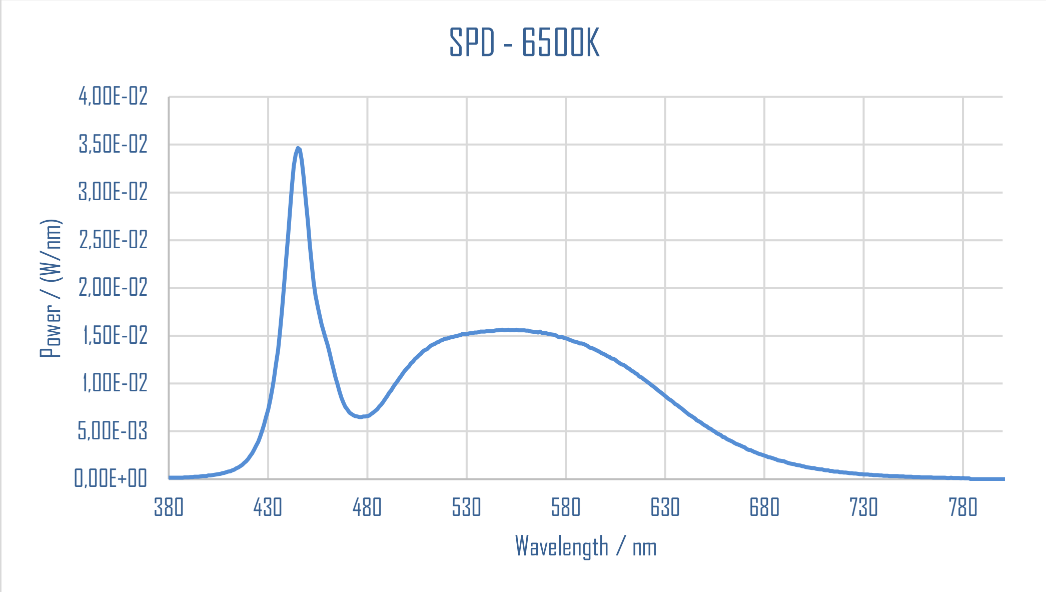


Figure 16: SPD for the 6500 CCT.

3.4 Analysis of Energy Use and Integrative Lighting Combined with Daylight Harvesting

The implementation of the method was mainly divided into three different steps. This process was necessary to reach the goal of the study which was to reduce the energy use while still stimulating the circadian entrainment in humans, since – to date - this cannot be handled by a single software.

The first part was placement and dimming of the lamps, which was conducted with respect to the threshold of 500 lux of horizontal illuminance or the workstations and 300 lux for the surroundings. This is in agreement with traditional artificial lighting design for workplace, as defined by ("Ljus och belysning - Belysning av arbetsplatser," 2003).
Once the placement and dimming of the lamps were determined, the power (W) for each lamp was multiplied with the total amount of lamps in the office and the dimming percentage in order to get the energy use.

The annual energy use was the second step of the process where the annual demand for the lamps was calculated. The third and final step was to investigate the non-visual effects for each one of the chosen simulation days. This process was used in order to make comparisons of the M/P ratios for when the lamps were dimmed and when they were running on 100% without any dimming. The occupancy schedule used in the simulations was between 08.00-17.00.

3.4.1 Artificial Lighting Design

The lamps were placed in a symmetrical way that could supply all the surfaces in the room with at least 300 lux except for the workstations where 500 lux had to be delivered to ensure a good working environment in the office. Once the lamps were placed, they were dimmed down to the lowest possible level while still fulfilling the requirements for illuminance. Since the chosen light source had the same luminous flux for the CCTs 4000 K and 6500 K, the dimming was only necessary in two cases even though the study investigates three different cases during a day.

The first simulation that was run after determining the coordinates for the lamps was for the base case where the lamps were running on 100% all the time. Note that the lamps that are used in this study are not adapted to the office, these lamps can be used in any office where the occupants want to improve their circadian entrainment. Having said that, it was therefore necessary to dim all the lamps for all simulations, where artificial light was used without daylight harvesting as well as artificial lighting combined with daylight harvesting. Running simulations with artificial lighting without daylight harvesting was to investigate if they could provide the required illumination. In normal cases, it would not have been necessary to dim the lamps while running on the lowest CCT (2700 K), instead it would only be necessary to dim the lamps for when running on higher CCTs (4000 K and 6500 K) with higher luminous flux in order to maximize the use of the ceiling panels efficiency.

3.4.2 Annual Energy

The second step was to calculate the annual energy demand for the lamps by using the results from the first step. The number of lamps along with the dimming percentage were used in the script, the energy demand for the lamps during occupation hours was calculated in this step. Thereafter, the energy for the lamps was calculated for the time where the 500 lux on the horizontal plane was not achieved by daylight only. With that being said, the lamps were only used with a certain dimming percentage when the illumination from daylight could not deliver 500 lux on the workstations in order to fulfil the requirement. This was achieved by using a sensor (see Figure 17) in the script that sensed when the illumination indoors did not reach the required threshold. For instance, daylight delivers 300 lux when 500 is required, it means that the remaining 200 lux is supplied by the lamps in order to reach the 500 lux threshold.

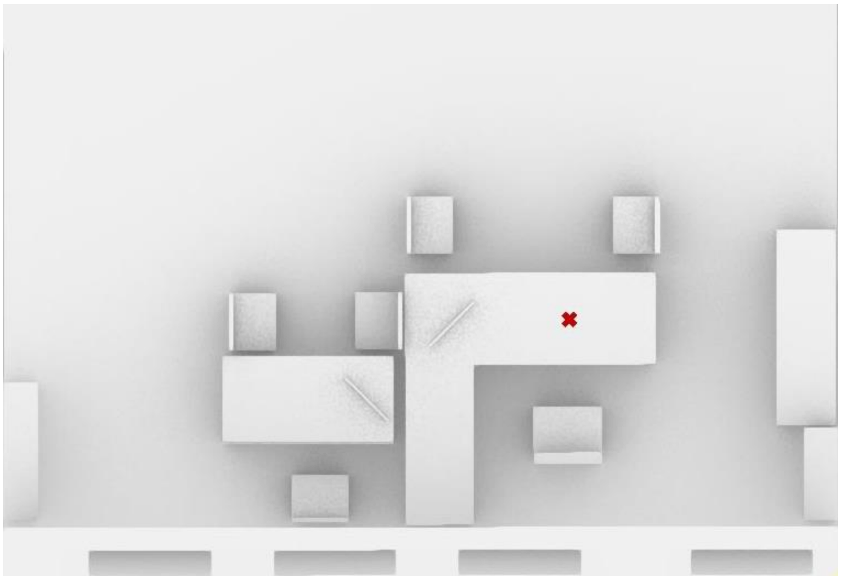


Figure 17: The red X on the table shows the placement of the sensor with a height of 0.76m.

What was challenging in this step was to divide the calculation in two parts, one part where certain luminous flux was used from 08.00 - 11.00 am with a certain percentage of dimming. The second part was to calculate with different luminous flux for the h11.00 - 17.00. Finally, all the results were added together to get the annual energy demand for the case where the sensor was used and the case where the lamps were turned on all the time during occupancy hours.

3.4.3 Simulations for Circadian Entrainment

The M/P ratio, EML and PL were investigated for the vernal and autumnal equinox as well as the summer and winter solstice to get a better understanding of the possibility for daylight harvesting during different times of the year, considering that daylight harvesting is of big importance in this study. An annual climate-based simulation was not performed, as ALFA currently does not provide this functionality. For each of the selected days, three different CCTs during occupation hours were investigated, according to the schedule provided in §3.2. A specific investigation for circadian entrainment from artificial lighting was conducted. This investigation was named Dark since it only includes lighting from artificial lights and therefore had to be simulated during night-time, it did not depend on time or date.

All the days that were determined for the simulations covered two different cases, the base and sensor case. The base case is a combination of artificial lighting running on 100% during occupation hours with daylight harvesting. The base case corresponds to the usual design of current integrative lighting systems. The sensor case is a combination of artificial and daylight harvesting too, but the lamps - in this case - are dimmed with help of a sensor, and only the artificial lighting needed to reach the 500 lux for visual requirement is added to daylight. Thereafter, each case was simulated for two different sky conditions, clear and overcast sky, see Figure 18.

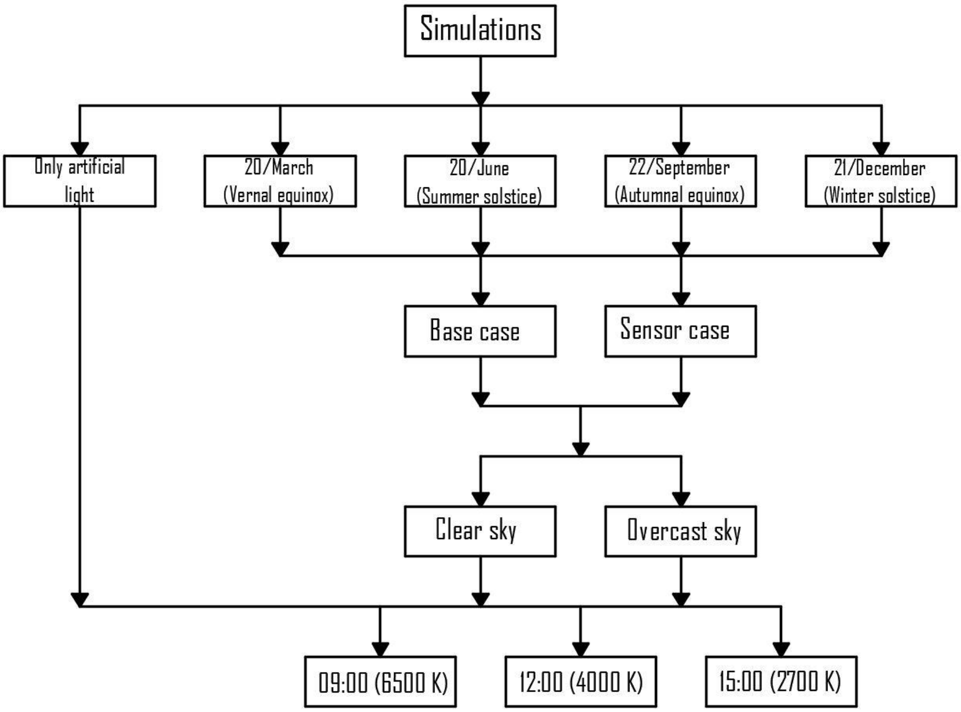


Figure 18: Simulation flow for the circadian entrainment.

The M/P ratio, EML and PL for all cases was calculated in this step, all calculations were performed in ALFA using the following inputs in Table 3,
Table 4 and Table 5.

Table 3: ALFA location settings (Helsingborg).

Latitude	56.03 ºN
Longitude	12.71 ºE
Elevation	8 m
	20/March
	20/June
	22/September
	21/December
	09:00
	12:00
	15:00
Ground spectrum	Uniform
Albedo	0.15

Table 4: ALFA grid settings.

Grid spacing	0.8
No. of directions	1
Rotation	85°
Radius	0.17
Viewplane offset	1.2
Workplane offset	0.76

Table 5: ALFA radiance settings.

Ambient bounces (-ab)	8
Limit weight (-lw)	0.01
Number of passes	50

Once the simulations above were completed, fisheye visualizations of the simulated hours were extracted from ALFA to clarify the difference between different CCTs and simulation times during occupation hours. To ensure a good quality of the visualizations, settings such as exposure, gamma and range of illuminance were adjusted.

However, because 51 different hours were simulated in this study, visualisations are only shown for specific relevant cases. Given that the study investigated two different sky conditions, clear and overcast sky, the visualisations were extracted for June 20th and September 22nd with clear sky as well as March 20th and December 21st in overcast conditions. The reason for this was because it is most probable that the sky is clear in June to September and overcast in December to March in Sweden. Besides that, visualizations were extracted from the simulations for artificial lighting during night-time as well (Figure 19). The night-time simulations were conducted to examine the effect of the artificial lighting without regard to daylight in order to understand the impact of the integrative lighting system.

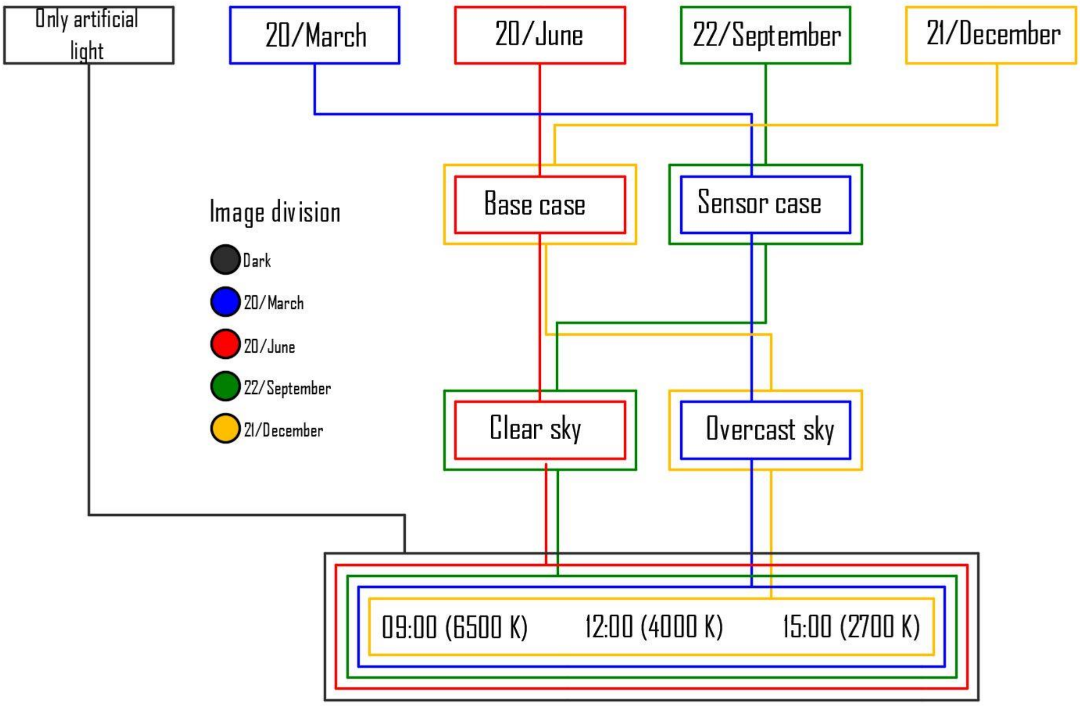


Figure 19: Scheme and layout for the extracted visualisations.

3.4.4 WELL STANDARD

The thresholds from WELL were used as a benchmark in this study with the intention of determining whether or not the lighting was healthy from a circadian perspective. Requirement A was chosen as a benchmark for all simulations except for the night-time simulation where requirement B was used as a benchmark. The reason for this is that B works when using artificial lighting only while A allows a combination of daylight and artificial lighting.

4 Results

This chapter presents the overall results of the study. Chapter 4.1 presents the results of the placement and dimming of the ceiling panels and chapter 4.2 shows the energy analysis and difference in energy use with and without daylight harvesting. Finally, chapter 4.3 presents the results for the circadian entrainment analysis.

4.1 Artificial Lighting Design

The results of the parametric analysis that was conducted in order to determine the placement of the ceiling panels showed that the placement that is presented in Figure 20 would be most suitable for the office. This placement fulfilled the requirements for 300 lux for surroundings of the workstations and 500 lux on the workstations.

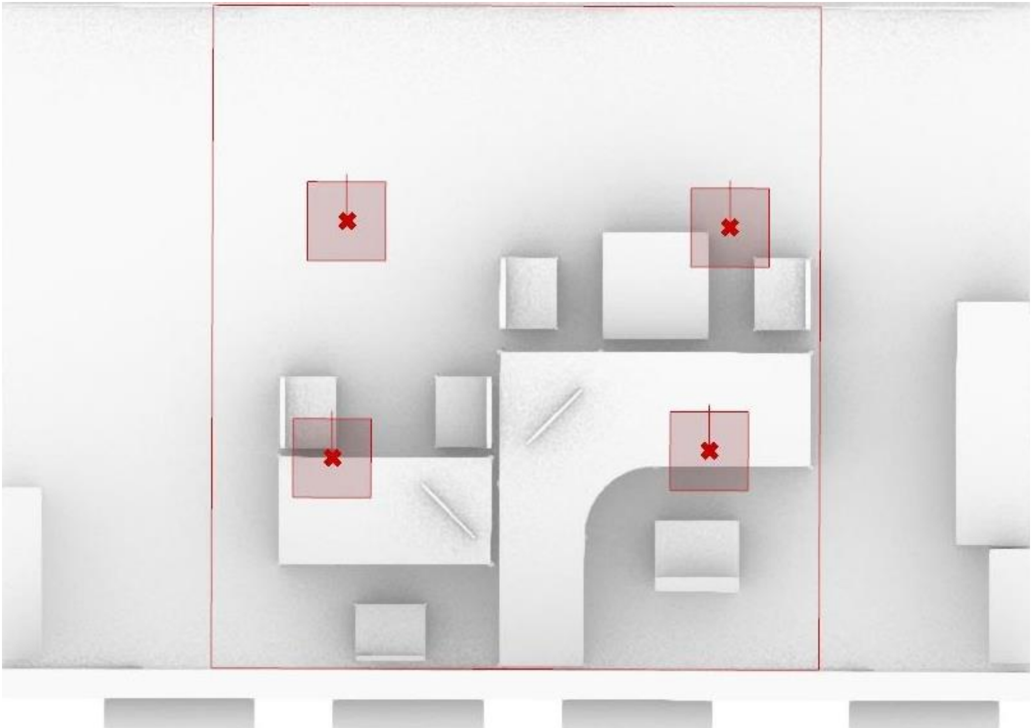


Figure 20: Placement of ceiling panels.

Since the required illumination is lower than what the lamps in this study provide when running on full capacity, the lamps were dimmed with a certain percentage to only deliver what is required to reach the thresholds. Meaning that when it is mentioned that the lamps run on 100%, it is not 100% of the ceiling panels capacity, instead 100% of the capacity that is necessary to deliver the required illumination. In the cases of this study, the CCTs 6500 K and 4000 K were used with 60% of the total capacity of the light source while the CCT of 2700 K was used with a capacity of 70%. Note that these percentages were the starting point of the simulations, the lamps were dimmed even more in the cases where a combination of artificial lighting and daylight harvesting were investigated further on in this study.

The dimming of the lamps resulted in a change in SPD curves for the ceiling panel. The power on the Y-axis was reduced with the same percentage the ceiling panel was dimmed with. On the other hand, the wavelength of the Y-axis did not change, see Figure 21, Figure 22 and Figure 23.

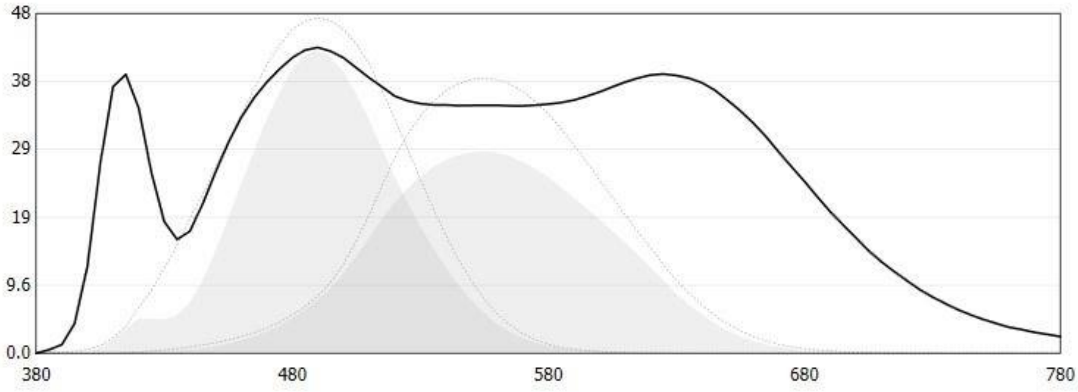


Figure 21: SPD for 6500K with 40% dimming extracted from ALFA. the Y-axis presents the power (mW/nm) while the X-axis presents the wavelength (nm). The grey shaded curve to the left shows the melanopic action while the right one shows the photopic action.

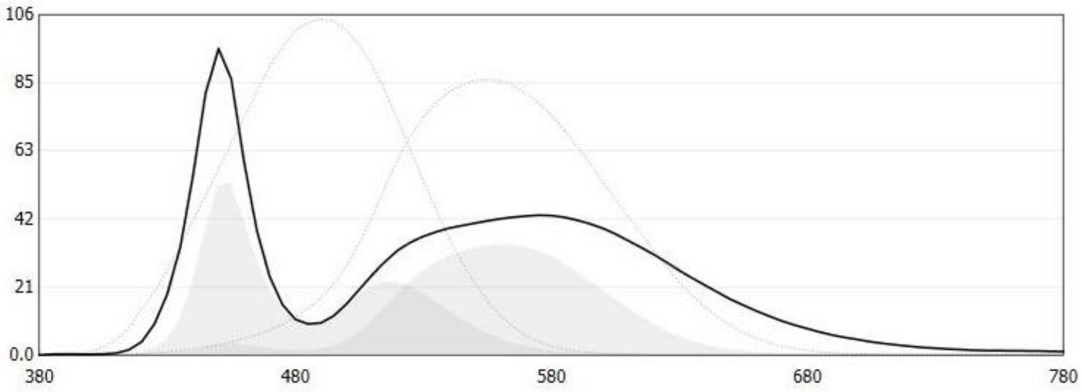


Figure 22: SPD for 4000K with 40% dimming extracted from ALFA. The Y-axis presents the power (mW/nm) while the X-axis presents the wavelength (nm)The grey shaded curve to the left shows the melanopic action while the right one shows the photopic action.

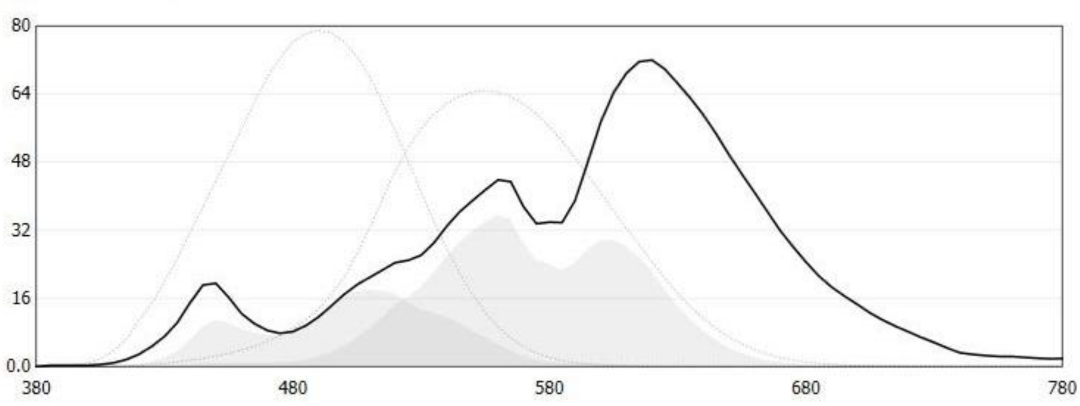


Figure 23: SPD for 2700K with 40% dimming extracted from ALFA. The Y-axis presents the power (mW/nm) while the X-axis presents the wavelength (nm)The grey shaded curve to the left shows the melanopic action while the right one shows the photopic action.

4.2 Energy Analysis

Table 6 presents the results of the annual energy analysis for the base and sensor case. The energy was calculated with the ceiling panels running on 100% during occupation hours for the base case, while the illumination from the ceiling panels was only used to provide the lacking illuminance from daylight when it did not fulfil the requirements of 300 and 500 lux.

Table 6: Annual energy demand for both cases.

Base case	Sensor case
254.90 kWh	88.90 kWh
7.5 (kWh/m²)	2.61 (kWh/m²)

The sensor case had 65% lower annual energy use than the base case.

4.3 Circadian Entrainment Analysis

The core of the results is divided into three different parts. Chapter 4.3.1 covers the visualisations of five different days from different cases with different sky conditions. Chapter 4.3.2 presents the results of the M/P ratios for different days, cases and sky conditions, the results between base and sensor case are compared with ALFA's thresholds for M/P ratio. At last, chapter 4.3.3 presents the results of EML for all cases in relation to what is required to fulfil the requirements in WELL standard. All results from all performed ALFA simulations are presented in the appendix.

4.3.1 Visualizations

The following figures presents the results of the visualizations from five different cases with different sky conditions. Each figure contains a visualization for EML, PL as well as the M/P ratio. The EML describes the circadian experience while the visualizations for PL and M/P ratio describes how it could be perceived. However, each figure is presented with the settings that were used if ALFA for the visualization, such as exposure, gamma and range.

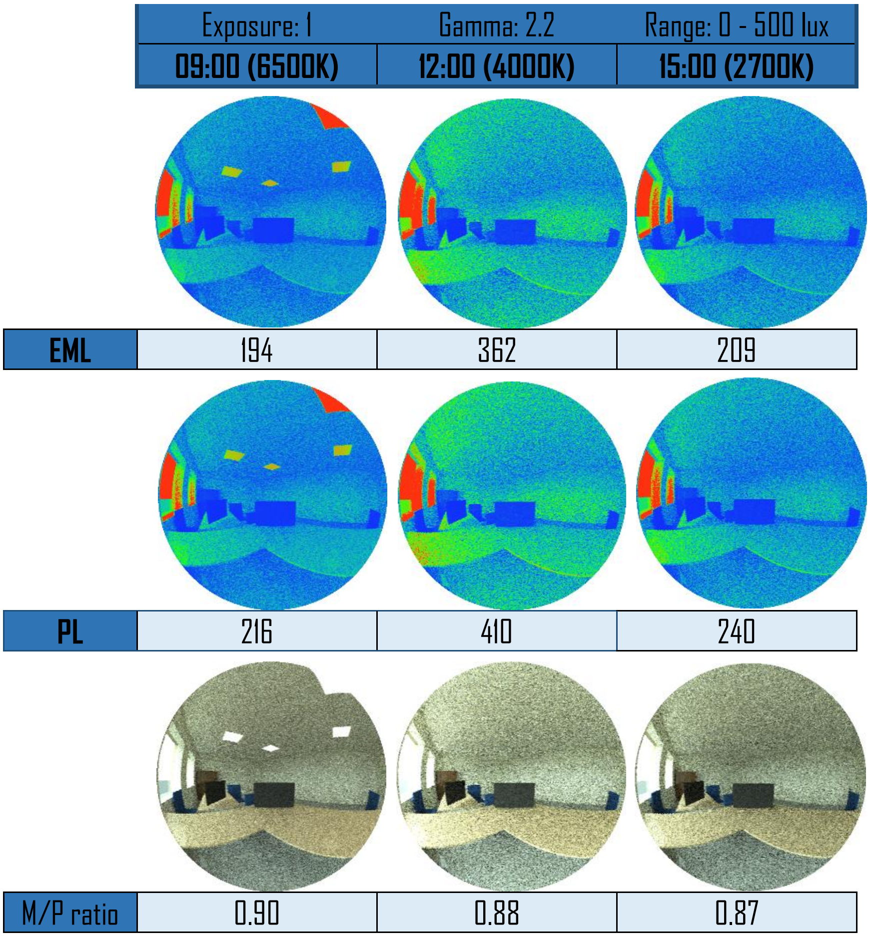


Figure 24: Visualization results for March 20th, sensor case with overcast sky.

	Exposure: 0.5	Gamma: 2.2	Range: 0 - 2000 lux
	09:00 (6500K)	**12:00 (4000K)**	**15:00 (2700K)**
EML	440	994	1706
PL	434	1087	1999
M/P ratio	1,01	0.91	0.85

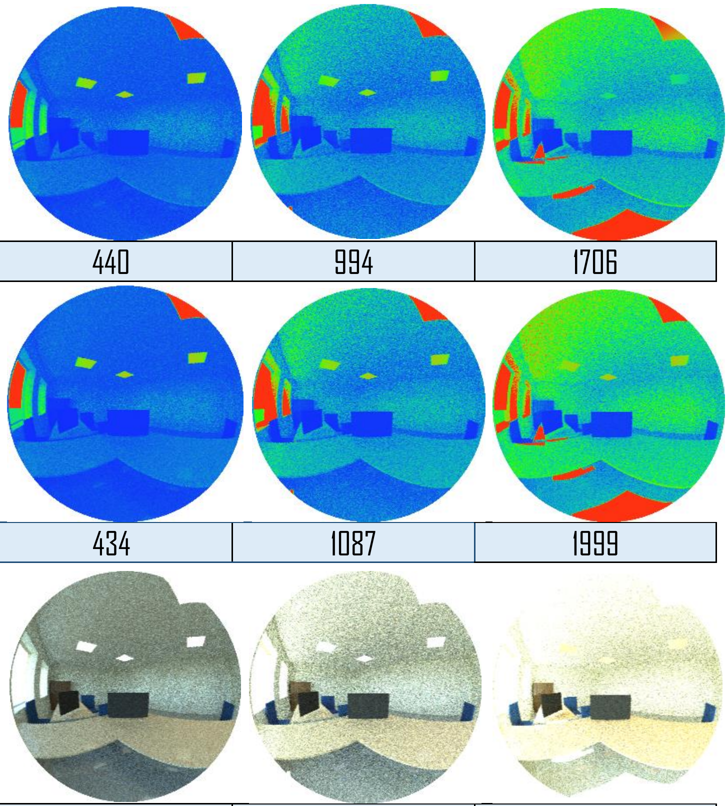


Figure 25: Visualization results for June 20th, Base case with clear sky.

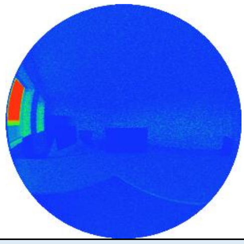
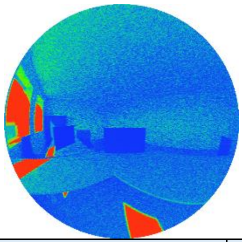
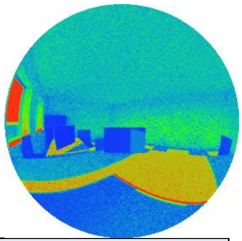
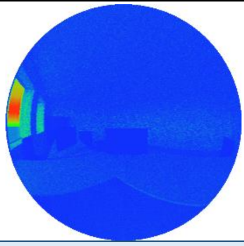
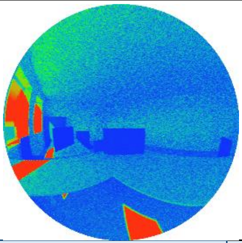
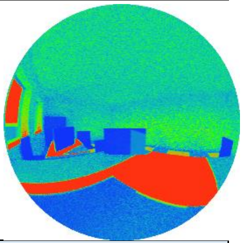
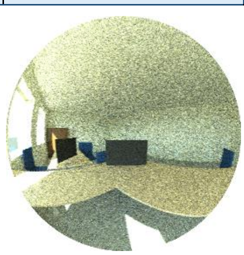
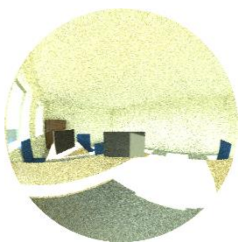
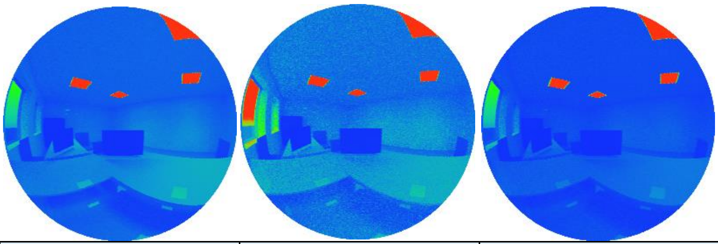
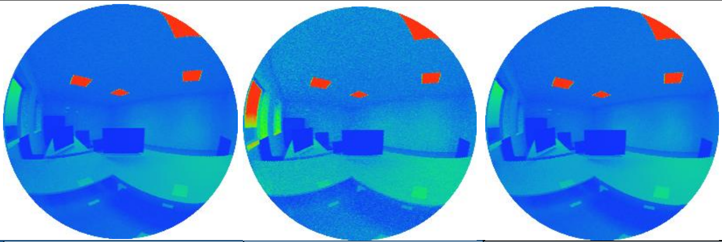
	Exposure: 0.3	Gamma: 2.2	Range: 0 - 3000 lux
	09:00 (6500K)	**12:00 (4000K)**	**15:00 (2700K)**
			
EML	269	1339	2632
			
PL	241	1543	3359
			
M/P ratio	1.12	0.87	0.78

Figure 26: Visualization results for September 22nd, sensor case with clear sky.

	Expouse: 1	Gamma: 2.2	Range: 0 - 500 lux
	09:00 (6500K)	**12:00 (4000K)**	**15:00 (2700K)**



EML	171	199	91



PL	188	245	203

M/P ratio	0.91	0.81	0.45

Figure 27: Visualization results for December 21st, base case with overcast sky.

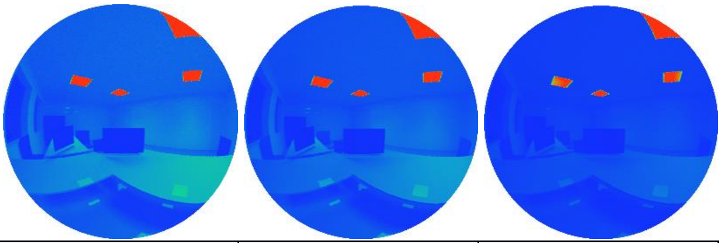
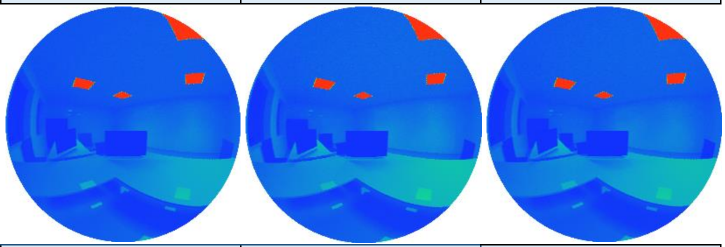
	Expouse: 1	Gamma: 2.2	Range: 0 - 500 lux
	6500 K	**4000 K**	**2700 K**
			
EML	157	135	65
			
PL	176	177	162
			
M/P ratio	0.89	0.76	0.4

Figure 28: Visualization results artificial lighting only.

4.3.2 M/P Ratio

The following figures presents all the results in terms of M/P ratio for all cases.

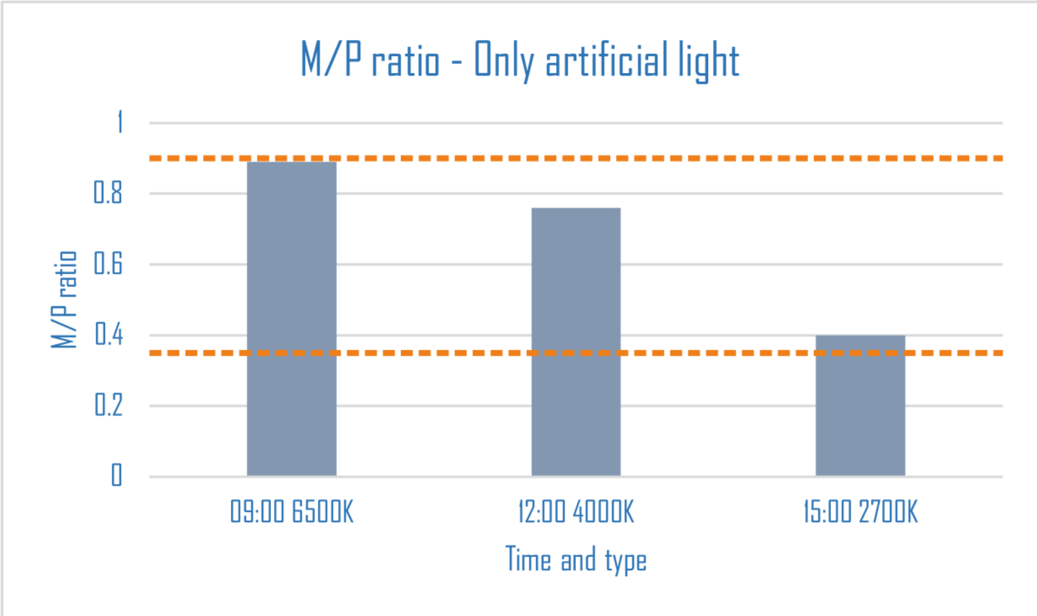


Figure 29: M/P ratio for only artificial light during night. The orange dashed lines are ALFA thresholds 0.9 and 0.35 which indicates if it is calming or alerting levels.

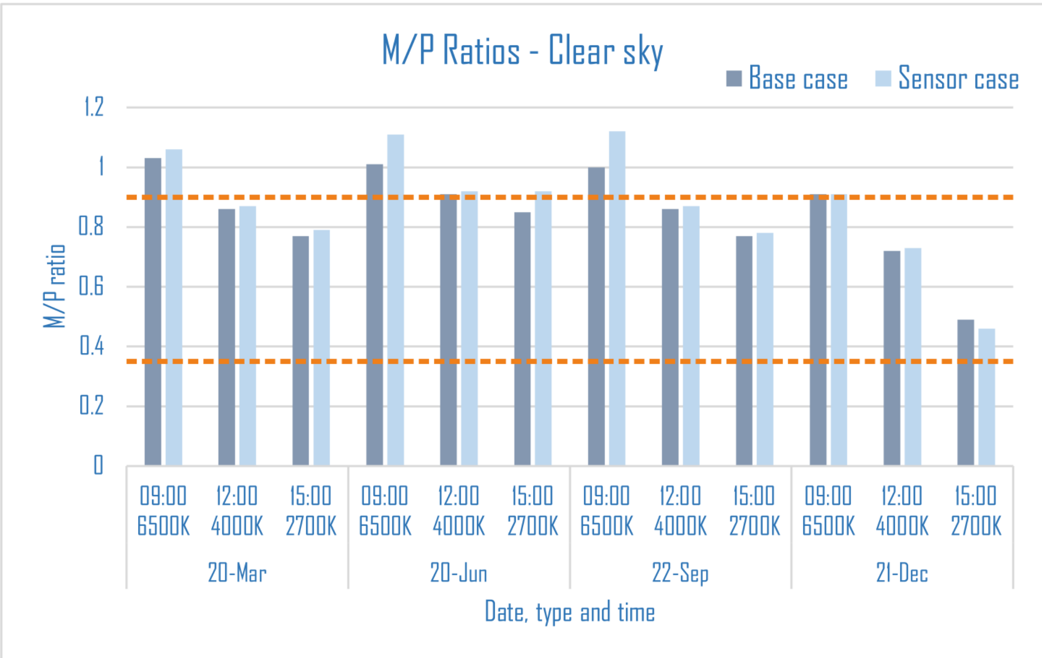


Figure 30: M/P ratio for base case and sensor case in clear sky condition. The orange dashed lines are ALFA thresholds 0.9 and 0.35 which indicates if it is calming or alerting levels.

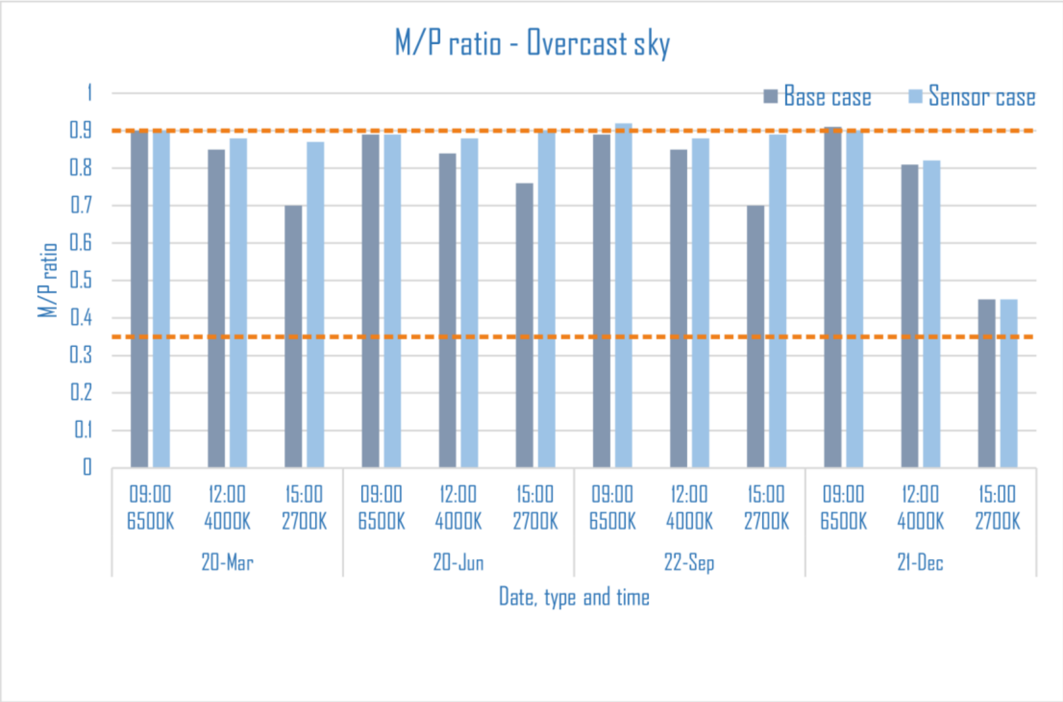


Figure 31: M/P ratio for base case and sensor case in overcast sky condition. The orange dashed lines are ALFA thresholds 0.9 and 0.35 which indicates if it is calming or alerting levels.

4.3.3 EML and WELL Standard

The following figures presents the EML results for all cases.

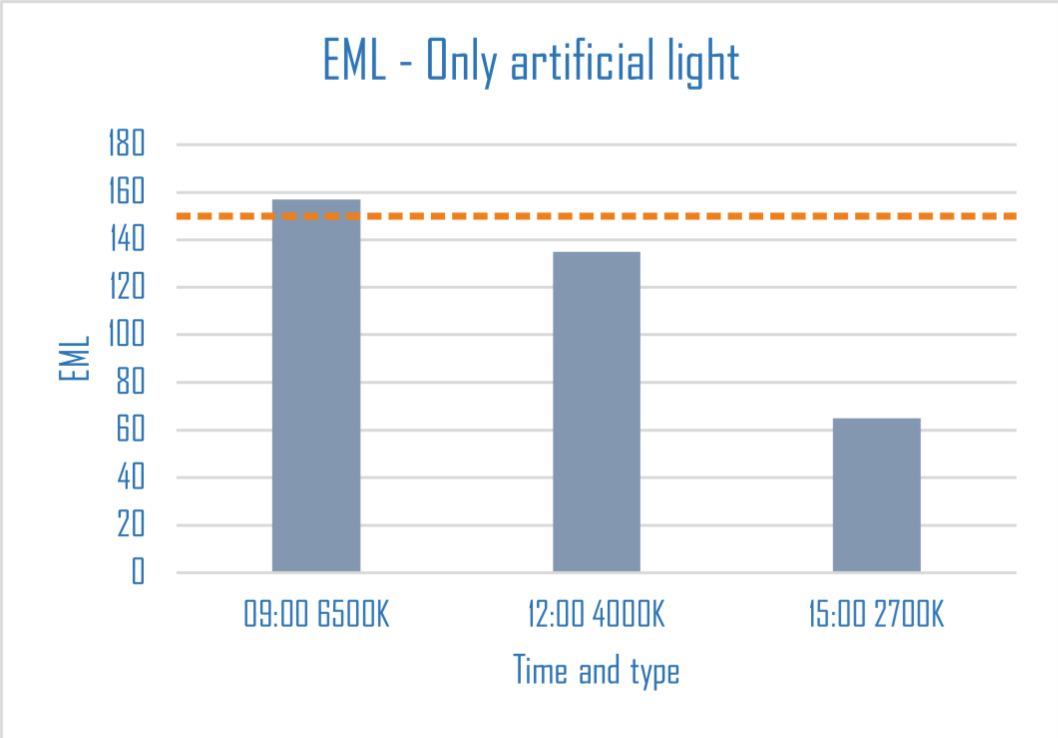


Figure 32: EML for only artificial light during night. The orange dashed line is WELL standard threshold at 150 EML.

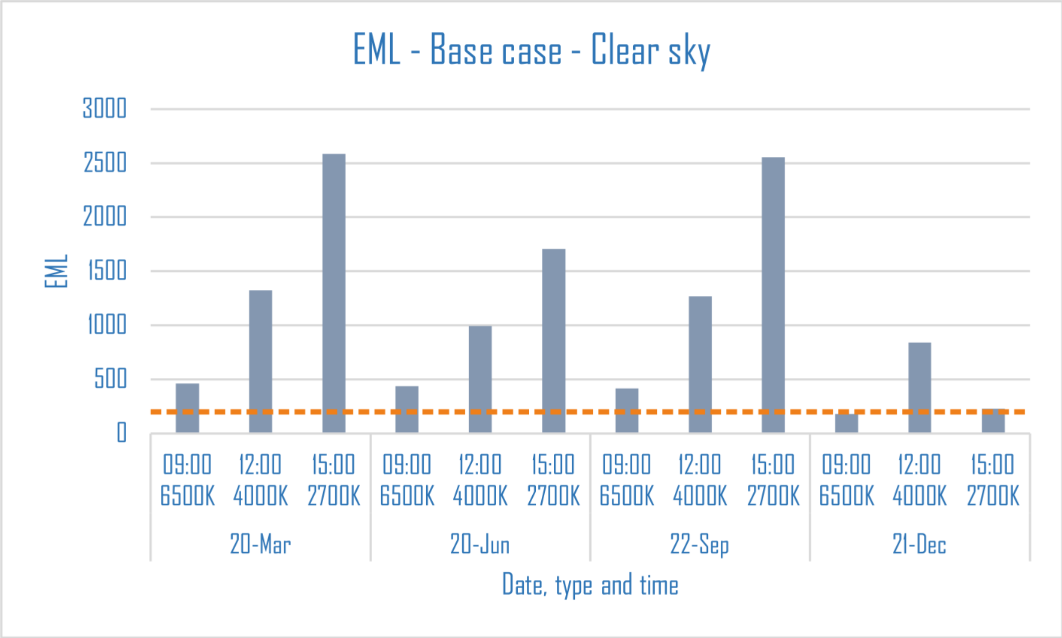


Figure 33: EML for base case with clear sky condition. The orange dashed line is WELL standard threshold at 200 EML.

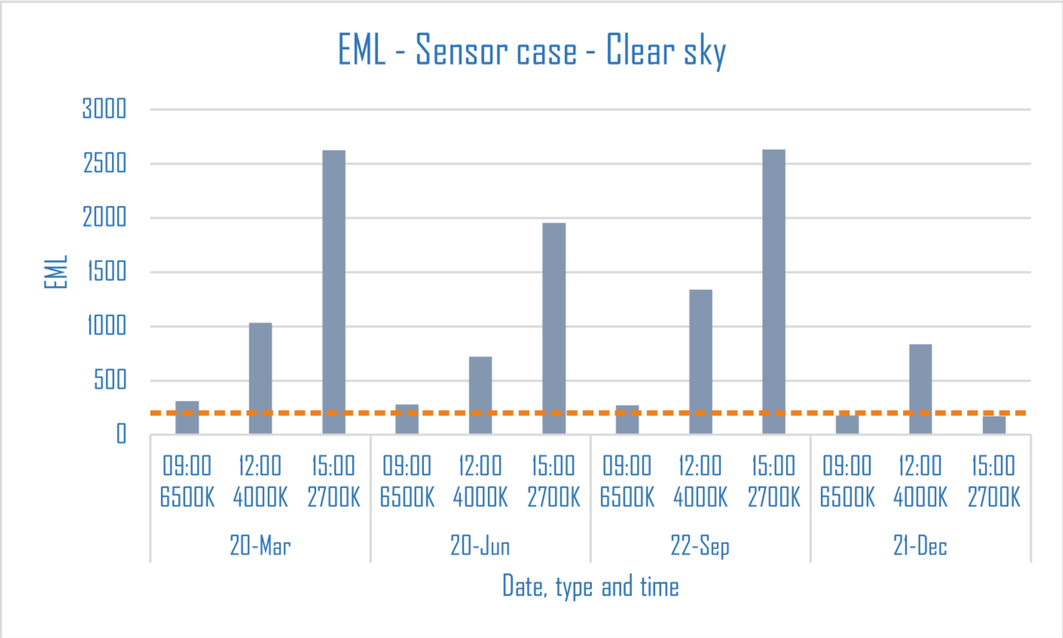


Figure 34: EML for sensor case with clear sky condition. The orange dashed line is WELL standard threshold at 200 EML.

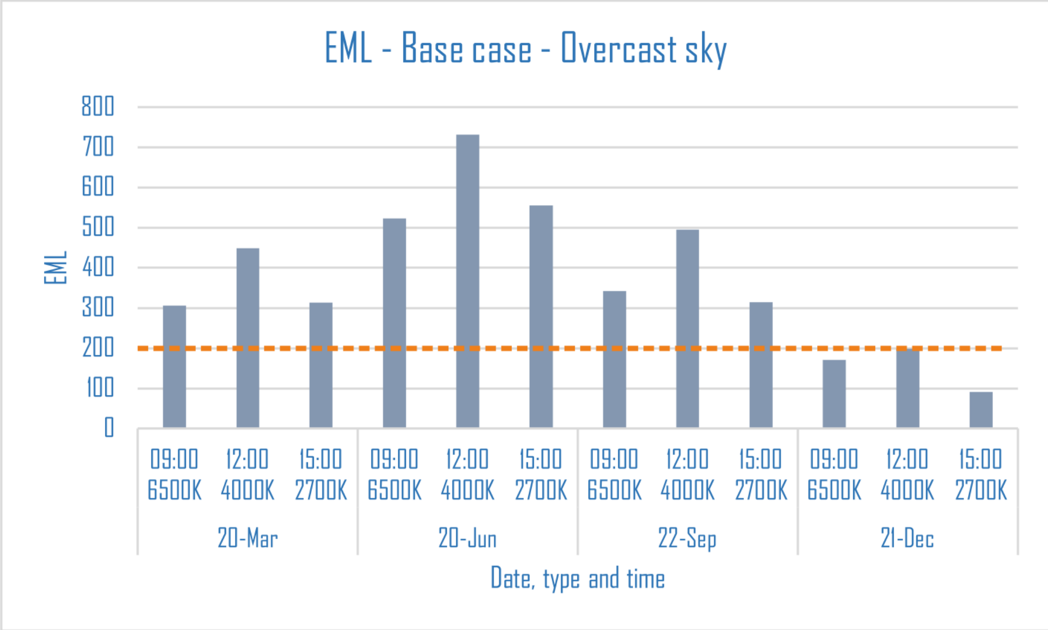


Figure 35: EML for base case with overcast sky condition. The orange dashed line is WELL standard threshold at 200 EML.

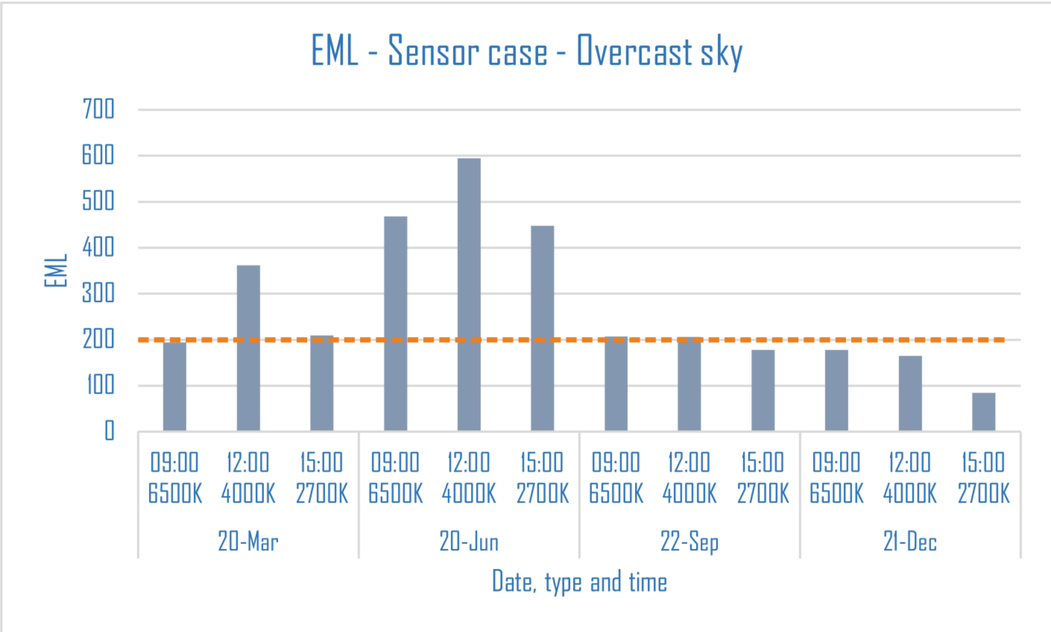


Figure 36: EML for sensor case with overcast sky condition. The orange dashed line is WELL standard threshold at 200 EML.

5 Discussion

The overall discussion of the study is covered in this chapter. Chapter 5.1 covers the electric lighting design, chapter 5.2 covers the energy analysis and chapter 5.3 covers the circadian entrainment analysis. Lastly, chapter 5.4 discusses the method that has been used in this study.

5.1 Electric Lighting Design

A challenge that was faced early in this study was to determine the placement of the ceiling panels, considering that chosen placement would be used throughout the entire study. This required a well thought out and accurate placement that could supply the required illuminance or order to fulfil the thresholds of 300 and 500 lux. After all, it is possible to state that there were three main factors behind the placement decision, those are the energy, illumination and light distribution.

All these factors depend on each other in a way that affects the result. The first factor is the energy use, the placement of the lamps affected the required amount of ceiling panels which influenced the energy demand. For instance, misplacing the panels could result in uneven distribution of light, which then required more ceiling panels to make sure that the entire office had enough illumination. The next factor was that the illumination from the panels were too high, they provided higher illuminance than what was required. The last factor was the distribution of light, considering that the illuminance was as highest vertically downwards from the ceiling panels and lower between them. The reason for this is the lighting distribution curve of the ceiling panel and there was nothing that could be done to make this better.

In an effort to find a balance between illuminance and distribution, a parametric study was conducted. Simulations were run with the ceiling panels placed both centrally and more towards the walls in the office. However, the panels were moved for each simulation and this process kept going until sufficient distribution of light was achieved with a result of four ceiling panels. However, the illumination was still far more than what was necessary, it could have been fixed by removing one or two ceiling panels but that would affect the light distribution and were therefore excluded. Instead, it was decided that the ceiling panels could be dimmed with a certain percentage in order to reduce the illumination to the lowest possible while still fulfilling the requirements.

It was challenging to find a balance between the placement, dimming and amount of ceiling panels while still fulfilling the required thresholds. Considering that the study only covers only one type of ceiling panels together with several factors that depended on each other, it was inevitable to not dim the lamps a little more than what was necessary compared to what it would look like in a normal case. A normal case is when dimming is necessary to the ones with higher illumination only. For instance, 2700K at 100%, 4000K at 80% and 6500K at 70% perhaps. Another factor that could be of importance is that the workstations in the office are placed on the same side of the office. If there would be workstations on the other side of the office as well, that would have made it easier to find a balance as it would be symmetrical.

5.2 Energy Analysis

The most important part of the study was to investigate if the combination of integrative lighting and daylight harvesting could result in similar M/P profiles to daylight while reducing the energy demand. Having said that, reducing the energy demand as much as possible in the sensor case was decisive in order to strengthen the point of the study. The simulation of the base case showed a result of 7.5 kWh/m^2year which approximately is three times higher energy demand compared to the sensor case that showed a result of only 2.61 kWh/m^2year.

The results regarding the energy demand were simulated several times to make sure that the results were correct. One thing that is worth contemplating is that the artificial lighting was not even necessary for several hours during occupation time. Sometimes people tend to turn on the lights even though it is not necessary, an explanation could be that people tend to turn on the lights because it is a habit and not because they feel that there is not enough illumination in the room. It means that a lot of energy has gone to waste if the results that show low energy use for the sensor case also maintain the same M/P ratio level as the base case.

It is proven that much of the energy used for lighting systems is wasted because it is in many cases not adapted to the need. This does not only apply for this study, but it also applies for all areas where the illuminance is not adapted to the actual need and is instead adapted to a requirement for a certain area. It is easy to use more than what is necessary when something other than energy is in focus, for instance the circadian entrainments of occupants. The pursuit of better health and circadian entrainment results in lost or less focus on the energy.

In one way or another, it is hard to guarantee that such a system would work well in reality. The results that have been presented and discussed in this study are from simulations only and have not been measured in reality, therefore it is hard to say with certainty that such a system would work as well in reality. Moreover, the energy results were calculated with a EPW file for Helsingborg city, which makes the results less reliable for the sensor case considering that all the years do not have the same ratio between clear and overcast sky. Several factors were hard to measure, adjust and anticipate. For that reason, the results from this study should be considered as an example of what it could look like for a year.

5.3 Circadian Entrainment Analysis

The visualizations from “only artificial lighting” clearly showed the difference in the CCTs of the chosen ceiling panel. These visualizations clearly gave support to the concept of integrative lighting, which is the changes in intensity and CCT during a day with respect to the circadian entrainment of the occupants. It was also clear that M/P ratios relate to thresholds that were suggested in ALFA where 0.9 is alerting, 0.35-0.9 is neither and below 0.35 is calming.

The results from March 20th looked slightly different in comparison to the ones from artificial lighting only. The results from the sensor case with overcast sky showed that the EML and PL had a similar range between 0 lux - 500 lux. The M/P ratios were a lot higher on the other hand. which goes against the concept of integrative lighting where the CCT changes to stimulate the circadian entrainment. The RGB pictures clearly showed that all 3 pictures had the similar nuance and brightness, which can be experienced as alerting.

Further on, the results from June 20th showed that illumination from daylight was dominating even though the ceiling panels were running on 100%. The panels were barely visible in the visualization for 15:00, which supports the fact that illumination from the panels barely contributes and is not necessary. However, the difference in EML and PL is much higher when comparing this day to the day with artificial lighting only, which mainly depends on the daylight that resulted in a more even M/P ratio curve during the day in comparison to when only artificial lighting was used.

The visualisations from September 22nd, sensor case with clear sky looked similar to the base case with clear sky from June 20th. What was remarkable here was the changes in EML and PL which were much lower at 09:00 and much higher 15:00. One could argue that it is because the day is longer in early summer (June) compared to September where day and night are approximately of equal length. However, this would not have mattered if it would be simulated with overcast sky. Since the sunrise is earlier in June, it has time to rise higher and give more illuminance compared to September where it is not as high as it would be in June at the same time in the morning. However, the sun is higher in September at 15.00 compared to June at the same time in afternoon, which results in higher illuminance in September at that time.

The base case with over sky for December 21st turned out to be the one with results most similar to the ones from artificial lighting only. It was expected that it would turn out this way considering that December is a month with short days and overcast sky, which makes the need for artificial light necessary. The results were quite similar in terms of EML, PL and M/P ratio, except for that the numbers for December month were a little higher due to the illuminance from daylight compared to the illumination from artificial light during the night.

The idea from the beginning was to extract visualizations for all the 51 cases that were simulated, which would be best for the study as it would give a picture of what each case could look like. However, instead it was decided to only do it for a few due to the simulation time for each visualization. In the same manner, the idea was to have the same settings in terms of gamma and exposure for all visualizations to clarify the differences. This had also to be excluded and the settings were instead adjusted to each visualization, the reason for this is that some visualizations turned out to be too bright or too dark, which made it very hard to see the differences.

It is easier to identify the differences and/or similarities in M/P ratio between the base case and sensor case with the same when having the same sky condition. The concept of integrative lighting is clearly shown in the case for "Only artificial light" (Figure 29) and that is how the trend should look like.

When comparing the results for M/P ratio with clear sky (Figure 30), it is clear that the trend is followed reasonably but with a higher ratio that desired. The reason for that is that daylight contributes to an increment in EML, which resulted in a higher M/P ratio. This was proved in several parts of the result where the M/P ratio was equal to 1 or above at 09:00 which was both good and expected since the M/P ratio should be at alerting levels above 0.9 in the morning. The problem here was that even though a clear trend was shown, the M/P ratio never dropped below a M/P ratio of 0.35 around 15:00. Instead, the results looked like the following:

- Altering levels at 09:00
- Neither calming nor altering at 12:00
- Neither calming nor altering at 15:00.

This trend was dominating for almost all days with clear sky, both base case and sensor case except for June 20th where the sensor case showed values above 0.9 for the M/P ratio which was not expected nor desired. Even the base case showed an M/P ratio above 0.9 at 09:00 and 12:00, the reason for this behaviour was as mentioned before, June 20th is the longest day of the year and the sun illuminance levels were very high during these hours. That being said, it resulted in a higher EML for a big share of the occupation hours, which increases the M/P ratio. On the other side of the coin, December 21st which is the shortest day of the year, the results looked quite different where the M/P ratio barely reached 0.9 in the morning. Nevertheless, the M/P ratio dropped to 0.7 around 12:00 and kept decreasing until it reached 0.45 at 15:00. The reason why the results looked different was that December 21st is a very short day with an early sunset which contributed to a lower EML. Besides that, the sensor sensed when the illuminance had dropped and therefore, the illumination from the ceiling panel became higher at 2700 K which was calming.

The results for the simulations with overcast sky looked quite different for both the base case and sensor case. The base case lost a little part of the trend with small reductions in M/P ratio while the sensor case totally lost the trend. Basically, there was no trend, the M/P ratio was constantly at 0.9 or even higher. However, December 21st was the only day with different results and the reason here was the same as before, the day is too short and the illuminance levels indoors reduces, which results in higher illumination from the ceiling panel. The strange behaviour of the sensor case in terms of M/P ratio is complex and took a pretty long time to figure out. One explanation could be that ALFA uses a particular SPD sky definition which may imply a constant high blue component in the daylight. This means that when the sky condition was changed from clear sky to overcast sky, the position of the sun was of less importance while the melanopic action was the dominant part of the SPD during working hours. Nonetheless, this did not apply to the afternoon of December 21st when the illuminance was low to a level that resulted in the ceiling lamp controlling itself more than daylight. Whereas the sun position was of greater importance for the cases with clear sky where the results were more comprehensive throughout the year except for June 20th where the sun was too high during a big share of the occupation hours. The sun position affects the intensity of the light which was the problem in the case since overcast sky does not consider this part. The intensity varies when simulating with clear sky due to the sun position, while the intensity does not vary in the same way when simulating with overcast sky which led to higher M/P ratios as shown in the results for the sensor case with overcast sky (Figure 31).

The results for EML could be compared to the requirements that WELL Standard has set in order to gain points according to their certification system. Starting with "Only artificial light" WELL states that "150 EML or greater for all workstations where electric lighting provides the maintained illuminance on a vertical place facing forward in order to simulate the view of the occupant", which is one of two alternatives that can be fulfilled. The requirement was fulfilled at 09:00 with a CCT of 2700K. The other two simulation hours showed a result under the threshold, it could depend on that the focus was on the energy in the early design stage and the artificial lighting was therefore dimmed until exactly 500 PL was achieved. In this phase, EML had not been measured and the design phase continued with results only for PL and energy demand that were reasonable at that point.

WELL Standard also states that another requirement that can be fulfilled is "200 EML should be present at 75% or more of the workstations in work areas, this light level may include daylight and is at least present between the hours 09.00 AM - 1.00 PM for all the days of a year" which was fulfilled in all results for this study. Let's assume that all the EML results for both base case and sensor case with clear sky and overcast sky would apply for the whole year along with the accurate selection of simulation days, it is possible to claim that all four figures, Figure 33, Figure 34, Figure 35 and Figure 36 showed the requirement was fulfilled in all cases.

The trend that was observed in the EML results for clear sky was due to the sun position as it was mentioned before. However, it could sound misleading after mentioning that the M/P ratio should be high in the morning and decrease later during the day. On the other hand, the figures for overcast sky Figure 35 and Figure 36 showed that there was no specific trend, instead it was fluctuations during the course of a day. All the EML results would have had a similar trend if they would be compared to the results for PL during the same date and time. Simply put, daylight is a crucial factor, and this could be proved by comparing these results to the ones from "only artificial light".

5.4 Methodology Discussion

This study was carried out during the COVID-19 pandemic which has limited the study in terms of access and communication as well as the choice of office and physical visits. The method that was used throughout the study could have been adjusted and applied in several different ways in order to increase the accuracy of the results, the study became therefore more limited and focused more on calculations and simulations. The following points is what could have contributed to more optimum results and higher reliability:

- More options for integrative lighting in order choose a type that would suit this office better.
- A sensor that is more developed and advanced for sharper results. The placement of the sensor was difficult considering that it would be placed vertically higher in

reality, it had to be placed on the table in this study in order to fulfil the requirement for 500 lux on the workstations.

- A more advanced modelling in Rhinoceros 3D that includes more of the smaller details such as wall paintings and books on the bookshelves instead of a simplified model.
- Investigation of the circadian metrics earlier in the study instead of putting all focus on the artificial lighting and energy use.
- Less limitations in ALFA regarding the choice of M/P ratio for the artificial lighting, lower rendering time for the visualizations and more than one SPD for daylight.

6 Conclusion

This study raises the question on whether the energy use for lighting can be reduced by combining integrative lighting with daylight harvesting, while still eliciting a circadian response for workers in offices. The results and discussions have led to the following conclusions:

- The artificial lighting design is a complex process that must be handled carefully in order to find a balance between intensity, distribution and dimming to reduce the energy use.
- The sensor case was by far better than the base case in terms of energy. The reason for this is that the illumination from daylight was enough to fulfil the requirement for illuminance in the office during occupation hours.
- The sensor solution was very useful and efficient in terms of energy use, but it did not work as well for the circadian study, specially not during overcast sky which is the dominating sky condition in Sweden. It did not perform good during summertime with clear sky either, which most likely is the time where Sweden has clear sky. It could be due to the reasons that ALFA only uses one SPD for daylight as well as that a shading system was not considered in this study.
- ALFA uses only one definition for SPD which most likely has affected the results in a negative way considering the variation of intensity during the day as it differs between overcast sky and clear sky. The sun position is of greater importance in clear sky conditions because the higher the sun is, the higher intensity. Whereas the sun position is unclear during overcast sky which results in even intensity during the day, which then results in less variation in the results.
- Time decisive for the results. A clear difference is shown in M/P ratios when comparing the results for summertime with clear sky to wintertime with overcast sky due to the difference in intensity of light. Nevertheless, during winter when the sunset is earlier and it is generally darker, the M/P ratio decreases because the artificial lighting controls more than the daylight for that specific time.
- An investigation of the circadian metrics such as EML is necessary in early stages of a study like this. This part was postponed in this study which for instance led to the EML requirements in WELL never was fulfilled for artificial lighting only. This could have been prevented if it would be investigated in the beginning of the study. But despite that, the threshold of 200 EML at 75% or more of the workstations in work areas was fulfilled anyway.

To summarize, the performance of the sensor case was generally better than the base case considering that it uses as much of the daylight as possible. However, it is hard to say that it is completely in line with the concept of integrative lighting, which is to stimulate the circadian entrainment. An office with decreased energy use for integrative lighting was achieved in this study, adjustments on the incoming daylight should be done in order to achieve the desired values for the sake of circadian entrainment.

7 Future Research

Circadian lighting design is a complex subject and integrative lighting is still considered a relatively new technology. Besides that, limitations in this study have left some questions unanswered, the future possible research could therefore analyse the following:

- If the undesired alerting M/P ratios could be controlled with help of shadings or adjustment of working position.
- How people experience the dynamic changes in CCT and intensity.
- How measured PL and EML are compared to the simulations.
- Other methods/tools than a sensor in order to help reducing the energy use.
- A comparison between ALFA and other circadian lighting design software, for instance LARK.

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Appendix

All results from ALFA are shown below.

Base case - Overcast sky					
Time and Type		20-Mar	20-Jun	22-Sep	21-Dec
	M/P	0.9	0.89	0.89	0.91
	EML	306	523	343	171
	PL	340	589	385	188
	M/P	0.85	0.84	0.85	0.81
	EML	449	731	495	199
	PL	530	870	580	245
	M/P	0.7	0.76	0.7	0.45
	EML	313	555	315	91
	PL	451	728	450	203

Sensor case - Overcast sky					
Time and Type		20-Mar	20-Jun	22-Sep	21-Dec
	M/P	0.9	0.89	0.92	0.9
	EML	194	468	207	178
	PL	216	524	226	197
	M/P	0.88	0.88	0.88	0.82
	EML	362	594	206	165
	PL	410	677	234	202
	M/P	0.87	0.9	0.89	0.45
	EML	209	448	178	84
	PL	240	499	201	185

Base case - Clear sky					
Time and Type		20-Mar	20-Jun	22-Sep	21-Dec
	M/P	1.03	1.01	1	0.91
	EML	463	440	415	180
	PL	450	434	414	198
	M/P	0.86	0.91	0.86	0.72
	EML	1323	994	1270	840
	PL	1542	1087	1475	1163
	M/P	0.77	0.85	0.77	0.49
	EML	2586	1706	2558	229
	PL	3341	1999	3328	463

Sensor case - Clear sky					
Time and Type		20-Mar	20-Jun	22-Sep	21-Dec
	M/P	1.06	1.11	1.12	0.91
	EML	310	281	269	180
	PL	291	254	241	198
	M/P	0.87	0.92	0.87	0.73
	EML	1033	723	1339	836
	PL	1191	783	1543	1144
	M/P	0.79	0.92	0.78	0.46
	EML	2628	1955	2632	173
	PL	3346	2126	3359	379

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