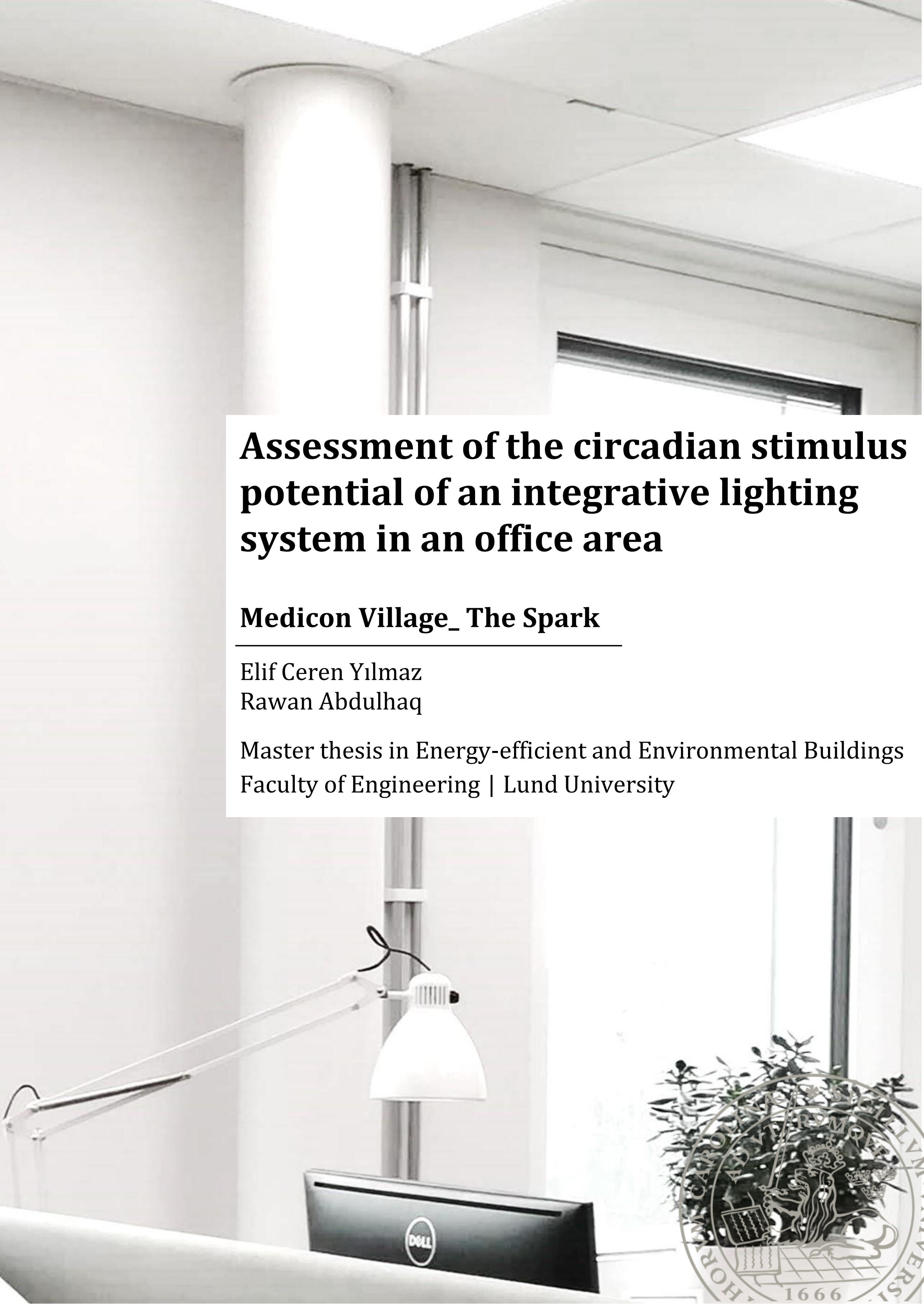

Assessment of the circadian stimulus potential of an integrative lighting system in an office area

Medicon Village_ The Spark

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Master thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University

Lund University

Lund University, with eight faculties and a number of research centers and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280-degree programs and 2 300 subject courses offered by 63 departments.

Master Programme in Energy-efficient and Environmental Building Design

This international program provides knowledge, skills, and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behavior and needs, their health and comfort as well as the overall economy.

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

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Supervisor: Niko Gentile (Energy and Building Design), Thorbjörn Laike (Environmental Psychology)

Keywords: Alertness, Circadian Rhythm, Circadian light effect, Daylighting, Energy efficiency, Entrainment, Health, Intrinsically photosensitive retinal ganglion cells, Light response, Melanopsin, Melatonin suppression, Photometric, Sleep quality, spectral sensitivity, Wavelength.

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Abstract

Nowadays, people spend 90% of their time indoors, thus creating a healthy indoor environment for occupants is of great importance. Lighting in office spaces is an important aspect when it comes to occupant health and well-being. Research in the field of lighting has mostly been focusing on the visible light spectrum and image-forming (IF) processes. However, with the discovery of melanopsin containing intrinsically photosensitive Retinal Ganglion Cells (ipRGCs), non-visual effects of light such as circadian entrainment and alertness received more attention. Non-visual effects of light have previously been subject of research under laboratory conditions, yet, there are only few field studies that were conducted in office environments to evaluate these effects.

The present study was undertaken to fill that gap by investigating an integrative lighting system in an office building, The Spark, at Medicon Village in Lund, Sweden.

The study comprises of Technical Environment Assessments (TEAs) and Observed-based Environmental Assessments (OBEAs). TEAs include a series of photometric site measurements that were carried out for collecting information about the lighting system, calibration of the daylight model. Inputs used in simulations as well as sensor recordings were obtained by Movisens light and activity devices that were wrist-worn by the participants. OBEAs cover user assessment incorporating self-reported questionnaires and semi-structured interviews. Numerical modelling with the engine Radiance was used for photometric studies, and Adaptive Lighting for Alertness (ALFA) for circadian lighting potential. Lighting energy use of the building was calculated according to the standard EN 15193 since the building was completed in late 2019 and no full-cycle electricity bills were available at the time of the study.

The results showed that the integrative lighting system can steer equivalent melanopic lux (EML), especially in areas with less daylight intake, therefore affecting the human circadian system. Based on the self-reported questionnaire and sensor recordings of wrist-worn devices, alertness of most participants increased with higher values of arbitrary unit (CCT·lux), that combines Correlated Color Temperature (CCT) and illuminance level detected by the devices. Circadian lighting simulations in ALFA showed higher EML values than the measured ones, while the closest values were obtained under only electric lighting. Semi-structured interviews indicated that most of the participants were positive towards the lighting system. The integrative lighting system complies with the energy benchmarks designated for existing and direct lighting systems; however, the system was designed with most attention to health and well-being of the occupants and to promote their circadian rhythms, rather than maximizing the energy-efficiency.

Table of content

List of Figures

List of Tables

Nomenclature

ALFA	Adaptive Lighting for Alertness
BREEAM	Building Research Establishment Environmental Assessment Method
CCT	Correlated color temperature
CEN	European Committee
CIE	Commission Internationale de l'Eclairage
COVID-19	Coronavirus disease 2019
CTS	Circadian timing system
DF	Daylight Factor [%]
EML	Equivalent Melanopic Lux
IEA-SHC	International Energy Agency-Solar Heating and Cooling Programme
IF	Image-forming
IR	Infrared
KSS	Karolinska Sleepiness Scale
LED	Light-Emitting Diode
LEED	Leadership in Energy and Environmental Design
LENI	Lighting Energy Numeric Indicator
MCTQ	Munich Chronotype Questionnaire
NIF	Non-image-forming
OBEAs	Observed-based Environmental Assessments
PSQI	Pittsburgh Sleep Quality Index
RHT	Retinohypothalamic tract
SAD	Seasonal Affective Disorder
SBS	Sick building syndrome
SCN	Supra-Chiasmatic Nuclei
SPD	Spectral Power Distribution
SVS	Subjective Vitality Scale
TEAs	Technical Environmental Assessments

Definitions

Sick building syndrome
It is the term used when building occupants have symptoms or discomforts that is related only to the time spent in a building. In case of sick building syndrome, occupants cannot describe a specific illness or a cause [1].

Melanopsin
A photopigment in mammalian retina that has the most sensitivity in the blue region of the spectrum [2].

Intrinsically photosensitive Retinal Ganglion Cells (ipRGCs)
These cells, which contain the photopigment melanopsin, are located in the mammalian eye. In addition to rods and cones, they are the third type of photoreceptors. They detect ambient light intensity and help synchronizing circadian rhythm [3].

The suprachiasmatic nucleus (SCN)
It is a structure formed by around 20 000 neurons located in the hypothalamus part of the brain. This structure, which is called the master clock, is connected to the eye and collect inputs from there [4].

The circadian rhythm
Circadian rhythms are naturally found in most living things. They represent changes that are physically, mentally, and behaviorally happening in daily cycle. These rhythms are driven by a circadian clock and closely linked to the light and dark environment of an organism [4].

Seasonal Affective Disorder
Repeated depressive symptoms that happen at the same time each year, usually in winter [5].

Integrative Lighting
The term is used to define a type of lighting system that embraces visual and non-visual effects of lighting on humans by creating beneficial physiological and psychological effects [6].

Semi-structured interviews
This type of interview is commonly used in small-scale research where the interviewer decides the general structure for main questions before interviews are conducted. Detail structure is decided during the interview according to how much interviewees has to say and how they express themselves [7].

Equivalent melanopic lux (EML)
It is a circadian metric that measures biological effects of light on humans. Measurements are taken at the eye level of the occupant on a vertical plane. While traditional lux (photopic lux) is weighted to the cones, EML is weighted to the ipRGCs [8].

Correlated Color Temperature (CCT)
It represents the color appearance of the light emitted by a near-white light source. It describes how yellow (warm) or blue (cool) the emitted light is in Kelvin (K). Light with CCT less than 3000 K is considered to have a warm appearance while CCT above 4000 K represents light with cool appearance [9].

Daylight Factor (DF)
It is the ratio of horizontal illuminance in a room to the total illuminance under an unobstructed overcast sky. It is used to characterize the daylight conditions in a room independent from time, location, and orientation because illuminance from direct sunlight is excluded [10].

Sequential
One analysis is followed by another one and the results are integrated during interpretation phase [11].

Concurrent
Different analyses are conducted separately, independently, and concurrently and results are compared simultaneously [11].

“The history of architecture is the history of the struggle for light.”

Le Corbusier – Architect

"Design is not just what it looks like and feels like. Design is how it works."

Steve Jobs – Industrial designer

“We are born of light. The seasons are felt through light. We only know the world as it is evoked by light.”

Louis Kahn – Architect

1 Introduction

In modern society, the office working population spends almost 90% of their time indoors [12]. This affects the buildings' energy use and has repercussions on the occupant's health [13]. The public interest in indoor environmental quality increased in the 1970s when sick building syndrome (SBS) was first described following changes in the building environments that followed the energy crisis in the United States [14].

Lighting is one of the many important environmental factors that can improve indoor environmental quality and comfort in the modern office settings. Indeed, light entering the human eye does not only affect the image-forming (IF) processes, but it also influences human health and well-being via non-image-forming (NIF) processes. IF processes relate to light stimuli on rods and cones, which enables vision, while NIF processes relates to all lighting effects on alertness, well-being, health, and sleep quality [15].

1.1 Buildings and occupant health and well-being

The attention towards occupant health and well-being is constantly increasing within the built environment sector. Many of the voluntary building certification schemes, such as the vastly established BREEAM and LEED schemes, putting the focus on energy mitigation measures, have recently been updated with more requirements linking to indoor health and well-being. In 2013, a voluntary certification scheme dedicated to occupants well-being, the WELL Building Standard [16] was launched. The WELL standard measures, monitors and certifies building functions and their effect on human health and well-being [17].

Since the turn of the century, research has increasingly investigated light effects on health. This comprises among other non-visual influences of light on the human body. The topic received more attention since the discovery of the melanopsin-containing intrinsically photosensitive Retinal Ganglion Cells (ipRGCs photoreceptor) where the presence of the photopigment Melanopsin helped associating between light and human circadian system stimuli [18] [19].

1.2 Light and circadian timing system (CTS)

Retinal exposure to light stimulates three types of photoreceptors: rods, cones, and the (ipRGCs). Rods and cones transduce light into neural signals that transmit IF information through ganglion cells and then send them to the thalamus and the visual cortex in the brain where images are being processed. On the other hand the ipRGCs photoreceptors are a fundamental component of the retinohypothalamic tract (RHT), which work as a pathway to carry the photic signals from rods and cones entrained by the environmental light/dark cycles from the retina to the principal circadian pacemaker in the mammalian brain; the Supra-Chiasmatic Nuclei (SCN) (Figure 1). SCN generates and regulates circadian rhythms, circannual rhythms and other endogenous rhythms of the human body through its connection to the central nervous system that makes it the central player in the circadian timing system (CTS) [15] [20] [21] [22].

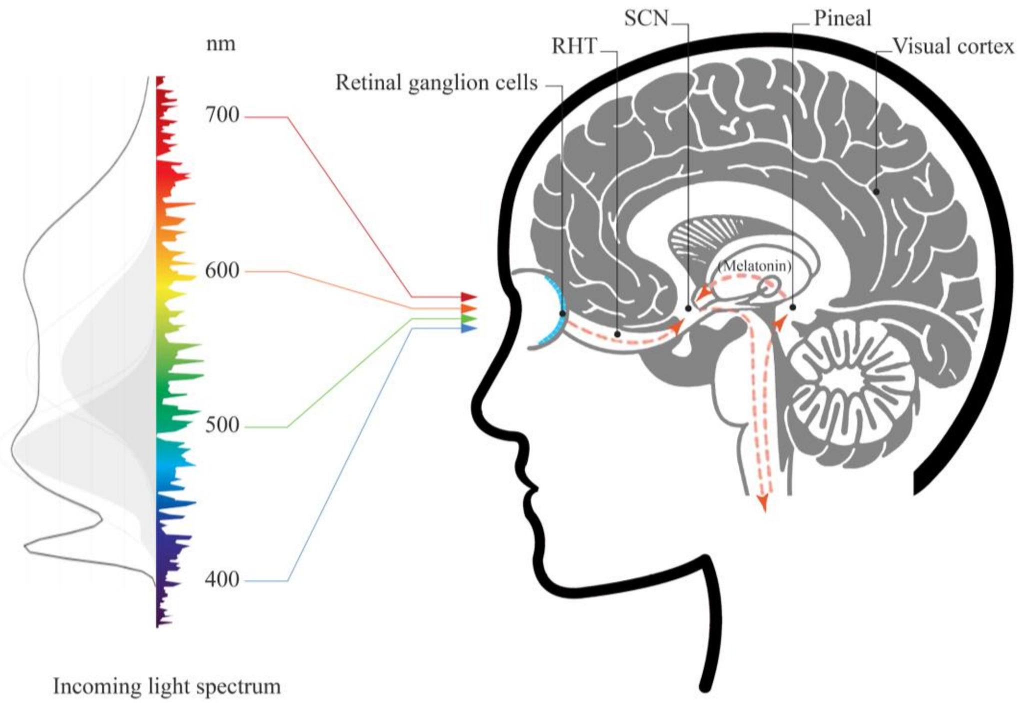


Figure 1: The ipRGCs send signals to the SCN where it sends signals to other parts of the brain

Circadian rhythms are demonstrated by many physiological and behavioral processes e.g. body temperature, hormones such as cortisol, and melatonin, mood, and cognition. The sleep/wake rhythm is one of the most important and observable circadian rhythms. The actual circadian clock is not always exactly 24 hours as sleep/wake cycles of some people can be longer when not under external signals and this is called non-24-hour sleep/wake rhythm disorder. The misalignment of the sleep/wake cycle in relation to the biological night and the misalignment of the light/dark cycle with feeding rhythms are some of the circumstances that can be described as circadian misalignment [23] [24].

The frequently extensive incidence of circadian misalignment has a significant negative impact on human body mechanisms. This effect is usually cumulative and can be seen in many body functions such as endocrine function, digestion, core body temperature, sleep-wake cycle, depression, mood, and fatigue [25] [26] [27]. Electric lighting can play a role in setting the (CTS) back [28]. Thus, it is particularly important when designing adequate daylit occupied spaces. In critical locations where a great absence of daylight is prevalent during most parts of the year, like the Nordic countries, this has an even higher significance. In fact, a type of depression known as Seasonal Affective Disorder (SAD) is a common occurrence in these areas.

The timing, duration, and prior light history are some of the important characteristics of the light that stimulate non-visual systems along with intensity and spectrum [29] and it has been shown that alertness is influenced by lighting conditions during the day [30]. Many research investigated whether or not correlated color temperature (CCT) or illuminance can be the characteristics that correlated with one’s alertness, mood, or cognitive performance [31]. In their study, Zhu et al. realized that higher illuminance resulted in more alertness of participants regardless of the time of the day. In another research by Luo [32], participants felt more alert in the higher CCT range. Even though the exact relationship is still unknown, it is conceivable to say that alertness increases with intensity and CCT. This relation had been presented qualitatively in this study by using an arbitrary variable CCT·lux. During the monitoring period in the project, both intensity and CCT were recorded through wearable sensors on the participants' wrists.

1.3 Circadian stimuli metric and circadian lighting simulation

The visual system is most sensitive to the green region of the visible light spectrum with a wavelength of 555 nm, while the ipRGCs are most sensitive to wavelengths of approximately 460 nm in the blue region of the visible light spectrum. This response has encouraged researchers to focus attention on adding short wavelength radiation on the light sources spectrum to suppress the production of melatonin thus influencing the phototransduction mechanism for the circadian system [33] [34] [35] [36].

The spectral efficiency function of the ipRGCs (C(λ)) [37] [38] and the visual system (V(λ)) are shown in Figure 2. together with the SPDs of two of CIE daylight illuminants, (D55) sunlight and (D65) overcast sky [39]. Konis points out that the circadian system (C(λ)) is closer to the maximum power of CIE daylight SPDs in comparison to the photopic one. On the other hand, peak power of CIE illuminant F11 (standard fluorescent lamp) is largely outside of the C(λ) curve. Therefore, introduction of a unit for circadian stimuli helps to differentiate circadian effects of light sources that provide similar visual effects [39].

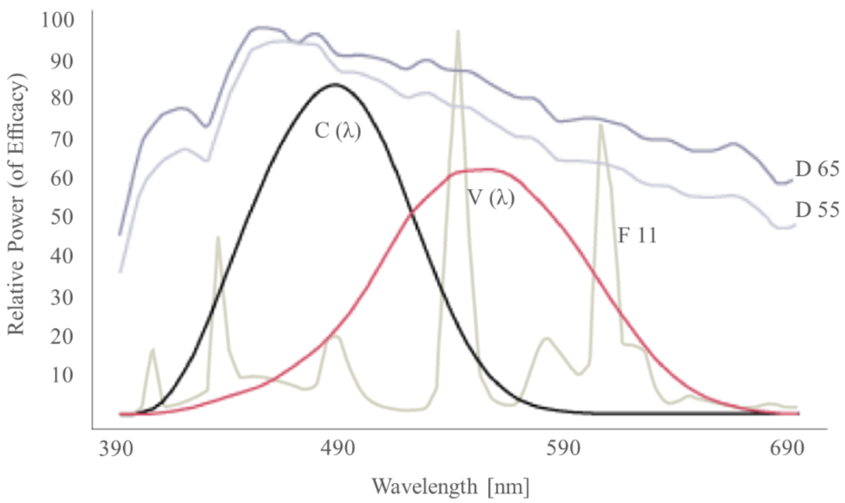


Figure 2: Normalized photopic V(λ) and circadian spectral efficiency C(λ) curves

There is not yet a consensus on metrics and benchmarks to determine circadian stimuli, but some metrics have been proposed. The WELL Standard uses the metric of adopting the Equivalent Melanopic Lux (EML) metric to assess the non-visual effects of light. The EML is based on the definition of melanopsin stimuli proposed by Lucas et al [40]. Lucas et al. differentiated melanopic lux that was firstly proposed by Enezi et al [37] and introduced the term EML as the equivalent ∝-opic illuminance by simply changing the scale of spectral efficiency function. This granted to newly proposed EML to be equal to all equivalent ∝-opic illuminances including the photopic lux, therefore, allowing EML and photopic lux to be comparable. In addition to this metric, there is a concept, M/P ratio, to describe the comparison of the melanopically weighted content of an SPD to the photopically weighted content [41]. M/P ratio is used to describe the quality of the light as it represents spectral distribution of a light source. Table 1 shows some representative source M/P ratios based on Lucas et al [42].

Table 1: Some Representative source M/P (effective mW/lm) Values based on Lucas et al (2014) values for C(λ)

	CCT [K]	M/P
Incandescent Lamp, 100W	2810	0.64
LED	3855	0.82
Sunlight	4889	1.12
CIE illuminant D65	6500	1.33

An overview of the ongoing and past research also reveals that very few computer tools are available to assess the non-visual effect of light to facilitate the process of building design [43]. ALFA (Adaptive Lighting for Alertness) is one of the two currently available spectral daylight simulation tools that utilizes spectral skies as well as spectral materials for renderings [44] and it is the only tool that can predict EML through spectral simulations [45]. It is a Radiance based simulation plug-in for Rhinoceros that performs circadian lighting simulations in 81-color-channel instead of traditional RGB-color-channel. It uses spectral raytracing method, spectral luminaires, spectral sun and sky and spectral materials. ALFA uses spectral sun and sky that are precomputed via a Radiative transfer library, libRadtran [46] and proposes four sky conditions for simulations: clear, overcast, hazy and heavy rain clouds. In the future, circadian lighting simulations can play an important role in decreasing time spent on site measurements for circadian assessments. Additionally, it can provide results before a building is built and therefore can help designers with early stage design phase.

1.4 Objectives and Research Questions

Recent smart artificial lighting systems, such as integrative lighting developed to mimic the natural daylight indoor by changing dynamically in intensity and correlated color temperature (CCT). The scope is to improve the regulation of the circadian rhythms of building occupants [6].

However, most of the current research [47] [48] [49] on circadian aspects of lighting has been conducted in heavily controlled laboratory studies. The scope of such research was generally to identify the spectral sensitivity curves of photoreceptors [50] or finding an exact dose-response relationship between specific light stimuli and circadian response. In practice, there is little knowledge about the actual claims on circadian effectiveness of artificial integrative lighting systems when installed in real uncontrolled environments, like offices, where there are many confounding factors other than light.

The aim of this paper is, therefore, to employ field study along with established calculation schemes and a simulation-based workflow in an attempt to answer the following research questions.

- Can integrative lighting steer EML in a daylit office? And does it affect one's alertness?

- Can circadian lighting computer simulations provide similar EML values as measured ones? If not, what can be the reason why the simulation tool cannot predict the measured EML?

Secondary research questions are formulated as follows:

- How do the office workers perceive, intend to behave, and control the lighting system in question?

- Does the integrative lighting system energy use comply with the European standards based on EN 15193?

2 Methods

The tested integrative lighting system is installed in a real occupied office building and runs a daily schedule consisting of four different scenes with different intensity and CCT. The investigation workflow shown below in Figure 3 included technical environmental assessments (TEAs), as well as observed-based environmental assessments (OBEAs) like self-reported alertness, appreciation of the systems, and behavioral intention of the employees. Self-reported alertness is here considered a proxy for understanding the sleep-wake cycles of the employee.

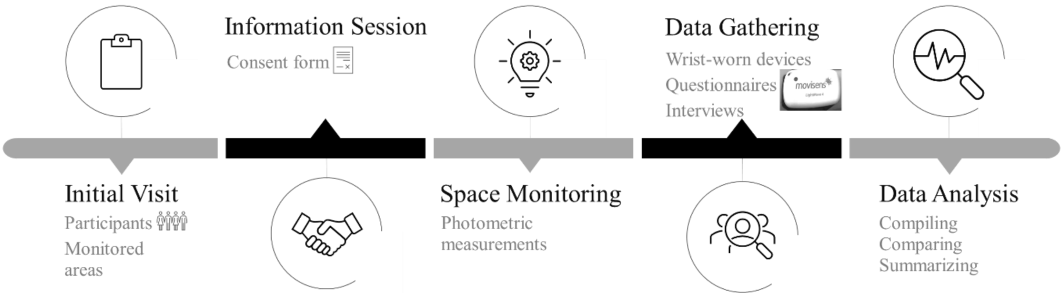


Figure 3: Thesis methodology workflow

This study examines four aspects of the daylighting and lighting system: photometry, circadian potential, user perspective, and energy (Figure 4). These four aspects are based on those proposed by a Monitoring Protocol, currently under development in IEA SHC Task 61 Subtask D.2. This study also contributes to developing the circadian and user perspective section in the aforementioned protocol by using innovative methods, like the employment of wearable light and activity logging devices and a simulation-based workflow employs the software ALFA to account for circadian aspects of lighting.

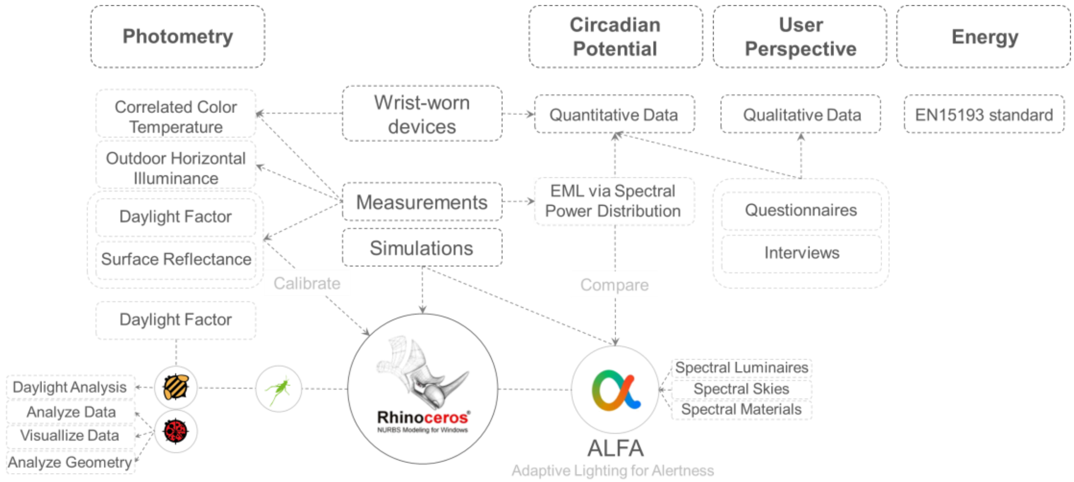


Figure 4: Thesis overview of monitoring and result analysis workflow

2.1 Case Study - Medicon Village, The Spark

The office building 'The Spark' is located on the campus and it is part of the science park Medicon Village in Lund, Sweden (N 55.71, E 13.22) (Figure 5). This building was designed by Reflex Architects in 2019, and it was selected for this study as it is equipped with modern lighting and lighting control features.

Figure 5: Medicon Village, The Spark

The building has an effective use of spaces for workplaces and meeting areas with good visibility between those staying in the building by a wide staircase which connects the courtyards with the ground floor, thus creating a physical and visual contact between floors. It provides various functional spaces into seven stories as reception, restaurant and conferences area on the ground floor, small businesses with one-room offices and shared functions in the lower floors and larger companies with up to 100 employees in the upper floors.

Most of the spaces in this building are illuminated by two daylighting strategies: the first consists of perimeter windows for outdoor view and penetration of daylight, while the second relies on two atriums with skylight in the core of the building supplying further daylight towards enclosed glazed offices in the core of the building (Figure 6).

The windows are arranged differently on the building façades, each is punctured by an individual pattern of windows with different specifications (Table 2).

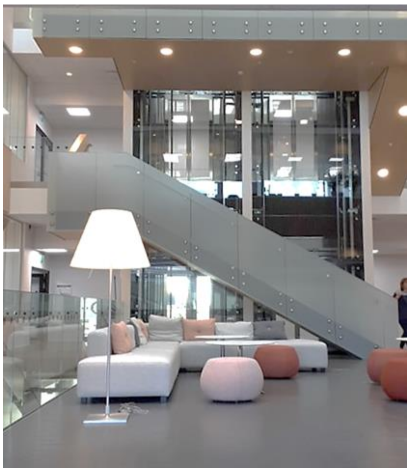


Figure 6: Atrium with skylight in The Spark

Table 2: Windows specifications in The Spark, as provided by Reflex architects. The lowest transmission and the highest reflection values in the table were utilized for simulations

	Light Transmission_LT	Light Reflection_LR
Windows_South	>55%	30 %
Windows_East	>55%	<15 %
Windows_North	>65%	<5 %

Inner glazing on the south façade (Figure 7) is located 0.3 m inside from the outer glazing. Windows on other façades are aligned as they are placed on the outer part of the frame.

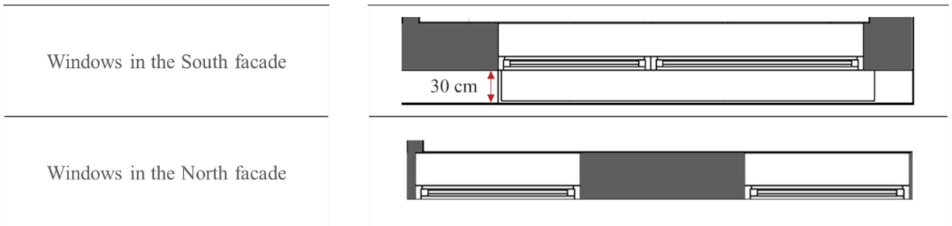


Figure 7: Windows on the South and North façade

2.1.1 Lighting and shading system at The Spark

The electric lighting system installed in the building is a state-of-the-art integrative system which dynamically mimics the outdoor daylight conditions both in intensity and color through four scenes as shown in Figure 8.

Figure 8: The light starts with a bright blue light in the morning with Scene 1 and gradually dims down towards a warmer red light in the afternoon with Scene 4

Occupants can use the system dynamically (using the auto mode that changes the scenes automatically during the day, according to a predefined schedule) or it can be overridden, by choosing manually one of the four available scenes.

Except for offices on the north façade, all office spaces are also equipped with automatic shading systems that are automated according to solar irradiance. Shading can as well be manually overridden via a switch Figure 9.

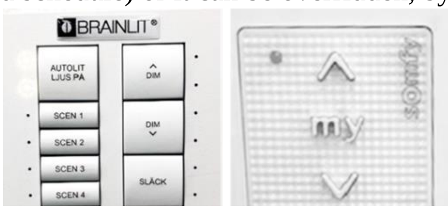


Figure 9: Lighting and shading control panels

The luminaires consist of ceiling mounted LED panels and spotlights (Figure 10).

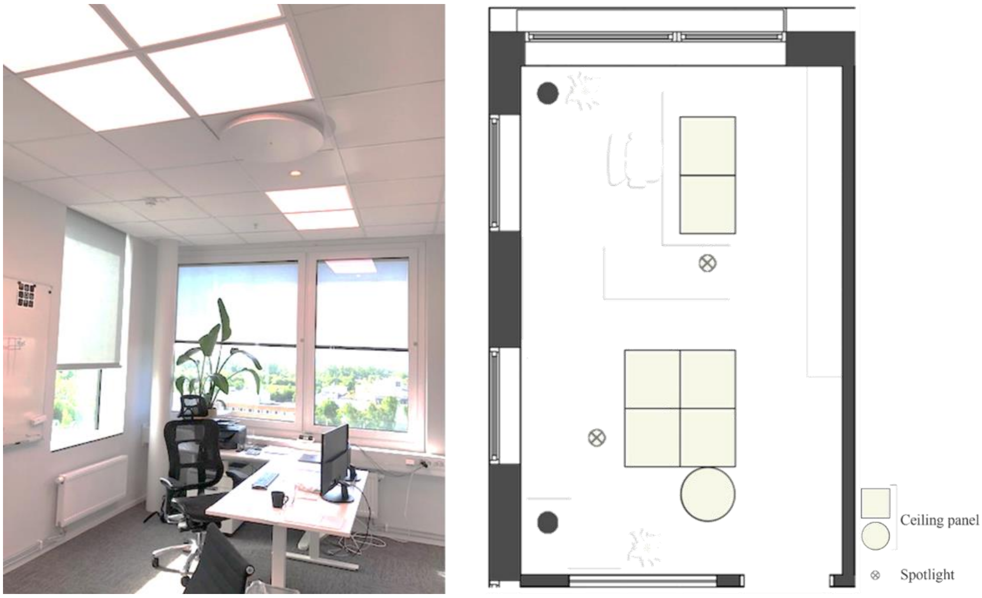


Figure 10: Luminaires distribution in one of the selected offices

2.1.2 Selection of monitored areas and participants

The monitored offices were selected based on the variety of orientations, the number of people working in them, and the dimensions of the office areas. All selected areas are either individual or two-occupant offices. This was desirable because people have more individual control over the lighting and shading system compared to people sitting in an open-plan office.

A total of five participants occupying five offices volunteered as test subjects for this study. One of the participants had an office facing an interior atrium with no view-out as shown in Figure 11. Due to the complex geometry of the office, lack of direct daylight, and the unpredictable effect of electric lighting from the atrium, this office was not modeled in the simulations. However, the user perspective of this participant was included in the respective section of this study.

Participation was voluntary and participants could discontinue their experiment at any time. All participants were thoroughly informed about the study protocol and they agreed to be part of the study by signing informed consent.

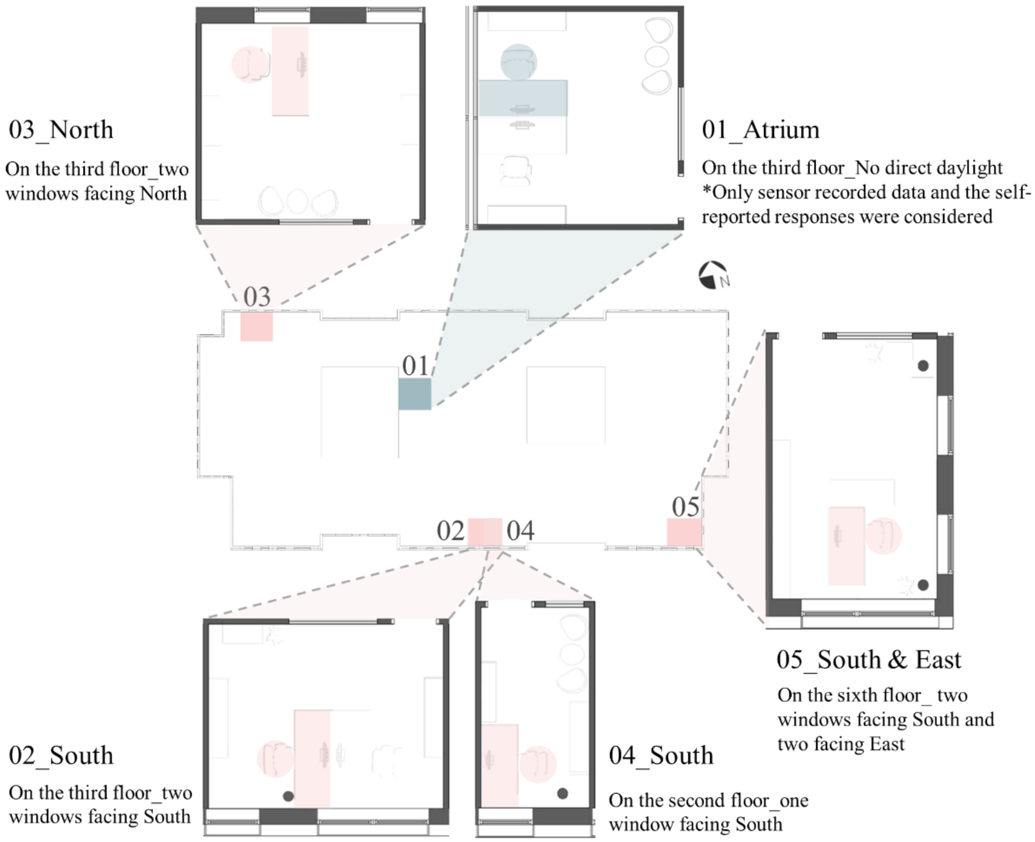


Figure 11: The five selected offices orientations

2.2 Photometry

The photometric characterization of the luminous environment consisted of the following TEAs: wrist-worn devices recording light and activity, on-site spot, and daylight simulations. Photometric measurements were carried out to characterize the space and the luminous environment with respect to the novel electric lighting system, with and without daylight.

In addition, measured Daylight Factor (DF) was used to verify the 3D model of the rooms. These models were later used for circadian lighting evaluation. Vertical illuminance and Spectral Power Distribution (SPD) were measured at eye position to determine the circadian potential of different lighting conditions. Outdoor horizontal illuminance measurements were conducted to evaluate sky conditions and to support the findings for circadian potential and user assessment. Reflectance and color of surfaces were measured in order to create materials for simulations. Sensor recordings were also included in this chapter as it gives information about the lighting environment of the participants.

2.2.1 Wrist-worn devices

At the earlier stages of the study, participants were given wrist-worn ‘’ambient light and physical activity sensors’’ (LightMove 3 and Lightmove 4) produced by Movisens [51]. The participants were asked to wear the devices for three consecutive weeks. During this time, the sensors recorded the physical activity of a person (based on acceleration, atmospheric air pressure), rotation rate and ambient temperature, and most importantly, ambient light.

The ambient light sensor has five channels which are red, green, blue, clear, infrared (IR) for detection of lighting conditions. An offline calculation tool, DataAnalyzer, provided by Movisens, was utilized to convert raw data to usable parameters such as the Correlated Color Temperature (CCT), measured in Kelvin, and the illuminance, measured in lux.

All five participants agreed to have the devices. Four participants agreed to wear the devices on their wrists, wearing them 24/7 during the whole period, while one participant was required to place the device on the office table all the time including weekends. However, the four participants with actual wrist-worn devices used them rarely during weekends, and it is unknown under what conditions the devices were kept. On several occasions, it was noted that the sensors were covered by participants’ coats when they were outside or even by their long sleeve clothes while they were in their offices. There were times that the sensors were not recording because the battery of the device was dead. Therefore, discontinuation was seen in recordings of each participant.

An identical device was additionally used to collect information and comparison in terms of CCT for each scene in a complete darkroom with the scope of creating luminaire files for the simulations. As mentioned before, the integrative lighting system has four different scenes with different intensity and CCT. The only available photometric information about the luminaires was for one scene, Scene 2 with approximate CCT, luminous intensity, total luminous flux, and total connected power based. This information was provided in a *.ldt file from the producer company. Information regarding the other three scenes were obtained by direct proportion between the readings from the devices and the information from the Scene2 original *.ldt file. Operatively, the files were created via the *.ldt editor by DIAL [52]. The software generated *.ldt luminaire files for the remaining three scenes. The *.ldt files were then converted into *.ies files and utilized in ALFA.

Table 3 displays the measured CCT values with Movisens sensor for all four scenes and the calculated ratio among them in percentage. Values for intensity, power, and total luminous flux are also presented in the table.

Table 3: Specifications for four scenes measured by Movisens devices

	Scene 1	Scene 2	Scene 3	Scene 4
CCT(movisens sens.) [K]	5949	4354	3115	2902
Ratio [%]	100	73	52	49
Power [W]	60	44	31	29
Total luminous flux [lm]	5241	3836	2744	2557

2.2.2 Site Measurements

A CRI Illuminance meter CL-70F from Konica Minolta was used for indoor spot measurements of illuminance, vertical illuminance, SPD, and CCT. During illuminance measurement for DF, a calibrated Hagner E4X illuminance meter was used to measure the outdoor horizontal illuminance.

Further logging of the outdoor global and diffuse horizontal illuminance were performed using two HOBO Pendant MX2202 Temperature / Light Bluetooth Loggers. Those loggers have limited accuracy (±10% of the reading) and they were used only to relate qualitatively the user perspective to the current weather conditions.

Surface reflectance for Lambertian surfaces were measured by a calibrated Hagner Screen Master luminance meter and a calibrated reference plate of known reflectance. Colors of surfaces were measured with a color reader tool (NCS colourpin II), especially to measure reflectances for non-Lambertian surfaces. In general, it was important to characterize color of surfaces in order to account for different reflectances at different wavelengths.

Site measurements for DF were carried out to validate the 3D Rhinoceros model for further simulations in Rhinoceros plug-in ALFA. It was assured that there was no shadow on the illuminance meter, the electric lighting was completely off, the roller shading was not used. The lux meter was placed at 0.85 m from the floor level at a grid which consists grid points at every 1 m. Outer grid points are located 0.5 m from the walls. The daylight factor was measured in three offices under overcast sky conditions. It was not possible to do this measurement in the fourth office due to time limitations. However, this office is similar to another office that was measured in terms of configuration, size, and furniture as they belong to the same company. Therefore, it was assumed that this model was also verified.

The SPD is very important regarding the non-visual effects and has been used as an input to obtain the EML (further explained in the circadian potential chapter), as it indicates which colors are represented within the emitted light; which influences the color appearance and the color quality of the light [53]. Table 4 presents a summary of the photometric assessments that were carried out in this study.

Table 4: The photometric on-site TEAs

	Measurement Location	Instrument	Scope	Notes
Outdoor Horizontal Illuminance [lux]	at the roof of a building of close proximity	HOBO Pendant MX2202 Temperature/Light Bluetooth Loggers	Evaluation of temperature and sky conditions	Two sensors for global horizontal illuminance and diffuse horizontal illuminance, data logging at every five minutes for three weeks
Horizontal Illuminance (DF) [lux]	on DF grids in the office and outside of the building	Hagner E4X and Konica Minolta CL-70F illuminance meters	Evaluation of DF, calibration of 3D daylight model	Measured simultaneously for indoor and outdoor illuminance levels under overcast sky
Vertical Illuminance [lux]	task sitting position, eye height (1.2 m)	Konica minolta CL-70F illuminance meter	Evaluation of circadian potential of the lighting system	Measured at eye level (1.2 m) of the participants at their workstations under four scenes
Spectral Power Distribution (SPD)	task sitting position, eye height (1.2 m)	Konica minolta CL-70F illuminance meter	Evaluation of circadian potential of the lighting system	Measured at eye level (1.2 m) of the participants at their workstations under four scenes
Correlated Color Temperature (CCT) [K]	task sitting position, eye height (1.2 m)	Konica minolta CL-70F illuminance meter	Evaluation of correlated color temperature (CCT) of the luminaires	Measured at eye level (1.2 m) of the participants at their workstations under four scenes
Correlated Color Temperature (CCT) [K]	under the ceiling panels in a dark room	Movisens light and activity sensor	Evaluation of correlated color temperature (CCT) of the luminaires, input for proportioning the scenes	Measured in a dark room under four scenes for proportioning the scenes based on a given *.ldt file
Lambertian Surface Reflectance [%]	0.3 m away from the surfaces	Hagner Luminance Meter and calibrated reference plate	Evaluation of surface characteristics, input for simulations	Measured for main surfaces in the offices, average of three consecutive measurements were taken
non-Lambertian Surface Reflectance [%]	directly located on the surfaces	NCS colourpin II	Evaluation of surface characteristics, input for simulations	Measured for main specular surfaces in the offices, RGB values obtained from the tool was converted into percentage

2.2.3 Simulations

The model of four rooms and the context was created in Rhinoceros 3D. Photometric simulations were performed using Radiance via Honeybee and Ladybug plug-ins for Grasshopper, visual scripting interface for Rhinoceros [54] [55] [56]. Daylight Factor (DF) is the only metric that was simulated in terms of photometric studies.

DF simulations were carried out for four offices in order to calibrate the model for ALFA simulations. The same test points that were measured in the offices were manually created in the 3D model and were used in the Honeybee component to run the simulations. The simulations were run under overcast sky conditions with selected Radiance parameters as shown in Table 5.

Table 5: Selected Radiance parameters for DF simulations

Ambient bounces (-ab)	Ambient division (-ad)	Ambient super-samples (-as)	Ambient accuracy (-aa)	Min. detail dimension	Limit weight (-1w)	Limit reflection (-lr)
8	512	512	0.1	0.05	0.0000001	9

2.3 Circadian Potential

The circadian potential was estimated by using measured and simulated α-opic illuminance, also called EML, measured in lux [38]. The EML is a well-known metric to describe the circadian potential. It is used in the scientific world, as well as in the professional, where it represents one of the target metrics for the WELL Standard.

EML was measured and simulated vertically at task position, eye level, for different lighting scenes, including daylight. Measured and simulated EML were later compared to the photopic illuminance, i.e. the traditional photometric illuminance, also measured in lux. This resulted in a number of M/P ratios (EML over photometric illuminance ratios), a dimensionless unit suggesting the circadian potential of the luminous stimuli. Higher M/P ratios indicate a more alerting light (higher blue component). The M/P ratio is generally lower than one, but it can be higher in some cases.

2.3.1 Site Measurements

To obtain equivalent melanopic lux (EML) for each point in time, measured SPD values (interval 380-780 nm, resolution 5 nm) gathered from the site measurements from the participant's offices for each scene under three different conditions: electric lighting (blinds down), combination of electric lighting and overcast sky, and combination of electric lighting and clear sky, were used as an input through the Irradiance Toolbox excel spreadsheet developed within the research paper by Lucas et al [38]. After putting SPD for each wavelength in the toolbox, values for effective EML (equivalent α-opic illuminance) for five human photopigments (EML is noted as ‘z’ in Figure 12) were visualized.

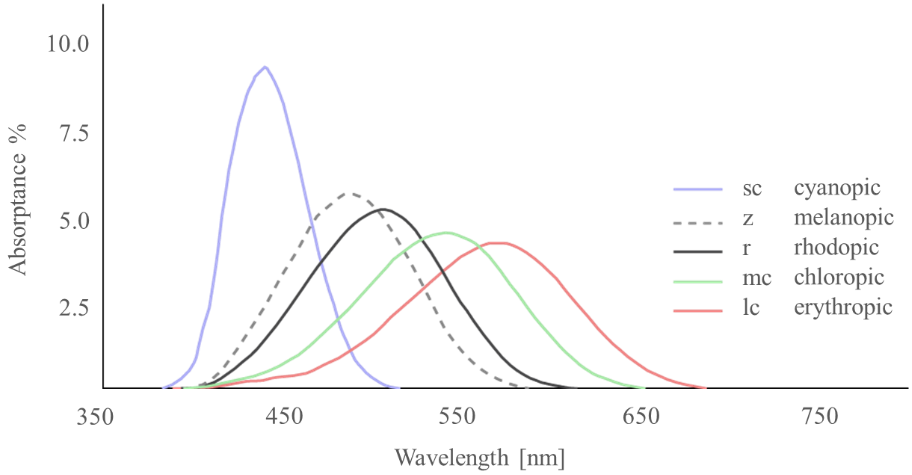


Figure 12: Spectral absorptance of human retinal photoreceptors, corrected for pre-receptoral filtering. All spectra are normalized to give an integrated area of 100%

The EML values obtained from Lucas toolbox were used to calculate the M/P (equivalent melanopic illuminance over photopic illuminance) ratio for each scene in the offices. These ratios were obtained by dividing the measured photopic illuminance to the measured EML that were calculated in the toolbox. How these ratios were later used as inputs in ALFA is explained in the chapter 2.3.2.

2.3.2 Simulations

In order to understand if circadian potential simulations could result in similar EML values as the measured ones and to make a comparison between simulated and measured values, simulations were conducted with the same 3D office model created for photometry. ALFA estimates an average EML value for each view direction at a specific zone and visualizes the potential circadian stimuli of the lighting at that view.

ALFA simulations were conducted with the settings as described in Table 6, Table 7 and Table 8. Table 6 presents the location, date and time and sky conditions that were chosen. Default settings were used for ground spectrum and albedo.

Table 6: ALFA location settings

Location	Latitude	Longitude	Elevation
Lund	55.71 °N	13.21 °E	51 m
Date and Time	20th February	3rd March	2nd and 3rd April
Sky Condition	Overcast	Overcast	Overcast and Clear
Ground Spectrum		Uniform	
Albedo		0.15	

Table 7 lists the settings that were utilized in creating simulation grids to obtain the most accurate results. A planar surface surrounding the workstation was created in Rhinoceros and was recognized by ALFA. Location and angle of the simulation grid was adjusted in a way that it mimics the sitting position of the participant looking at a computer screen (Appendix).

Table 7: ALFA grid settings

Spacing	No. Of Directions	Rotation	Radius	Viewplane Offiset	Workplane Offiset
0.7 m	4	15°	0.25 m	1.2 m	0.76 m

Table 8 shows the radiance settings that were used in simulations in ALFA. High number of passes such as 30 is especially important for image-based simulations for better resolution and accuracy.

Table 8: ALFA Radiance settings

Ambient Bounces (-ab)	Limit Weight (-lw)	Number of Passes
8	0.01	30

Materials were selected from ALFA's default library based on measured photopic reflectance and observed specularity. Therefore, material properties may not entirely match with the actual values. Similarly, luminaire settings were limited to ALFA's library of source spectrum where the M/P ratio is selected. M/P ratios recorded for each scene during measurements in one office and selected M/P ratios in ALFA with respect to the measured values are listed in Table 9.

Table 9: Measured M/P ratios by Movisens devices and selected M/P ratios available in ALFA

M/P	Scene 1	Scene 2	Scene 3	Scene 4
Simulated	1	0.87	0.57	0.45
Measured	1.07	0.85	0.56	0.46

2.4 User Perspective

User assessment is an important element in understanding the lighting environment and its effects on the occupants. It complements the data obtained from the site measurements and helps to identify positive and negative aspects that cannot be captured by measuring tools [57]. Therefore, this type of assessment is crucial in research based on field studies.

In this study, concurrent and sequential mixed methods that combine both qualitative and quantitative assessments were carried out. Due to the nature of the user assessment in field studies, qualitative data obtained from the participants was indispensable. During concurrent studies, qualitative data and quantitative data were converged and interpreted together for a better understanding of the case. For the sequential part of the research, quantitative data was followed and complemented by qualitative data for the user assessment [11] [58].

At the beginning of the study, the sensors were distributed to the participants, and a mobile application called ''Movisensxs'' was installed on their mobile phones. Surveys with different questionnaires were delivered to the participants through this application and they were notified when they had to answer each survey 2.4.1. These surveys were delivered three times a day during three consecutive weeks (from the 24th of February till 13rd March). In this research, it was hypothesized that the lighting environment has an impact on one's sleepiness and alertness. Therefore, participant responses to the questionnaires were evaluated based on the data collection of their surrounding lighting conditions.

2.4.1 Questionnaires

Each participant received and answered the surveys three times a day (arrival at work, at 12:00 and departure from work) during workdays for 3 weeks. The morning survey included three different questionnaires. These were:

1. The Pittsburgh Sleep Quality Index (PSQI), ten items [59].
2. The Karolinska Sleepiness Scale (KSS), one item [60].
3. The Subjective Vitality Scale (SVS), seven items [61].

The noon and afternoon surveys only included KSS and SVS.

PSQI is a validated and reliable sleep quality index that has been widely used in numerous studies. It is usually used to assess sleep habits and sleep quality during the past month and answers indicate the most accurate response for the majority of the time in the past month. In this study, however, the questionnaire was adapted in a way that the participants could fill it every weekday in the mornings. The data were analyzed in order to support the results rather than being a focal point.

KSS has been the most important questionnaire among all as it gives information about one's sleepiness and alertness at a particular time during the day. The scale has nine items and each item indicates a different level of sleepiness. This is a subjective scale where each participant chooses a sleepiness level that suits them the best for the last 10 minutes. Table 10 shows the KSS where higher numbers indicate higher sleepiness.

Table 10: KSS sleepiness-alertness scale

Rating	Verbal descriptions
1	Extremely alert
2	Very alert
3	Alert
4	Fairly alert
5	Neither alert nor sleepy
6	Some signs of sleepiness
7	Sleepy, but no effort to keep alert
8	Sleepy, some effort to keep alert
9	Very sleepy, great effort to keep alert, fighting sleep

SVS is a validated scale [62] that measures the level of feeling alive and alert and having enough energy for oneself. Vitality is highly related to well-being [63], and it refers to one's psychological wellness and functionality. The scale has two versions where the first one assesses the individual difference while the second is an assessment of the state of subjective vitality. In this study, only the state-level version was utilized.

Since the number of participants was limited to five, scoring for the SVS and PSQI was eliminated and the data from these questionnaires were used as supporting documents. Before conducting interviews, participants were asked to fill a short questionnaire. It was adapted from the Munich Chronotype Questionnaire (MCTQ) and was simplified by the authors of this study since no scoring was conducted due to the low number of participants. The data was used in order to support the results in case any of the participants had a very specific chronotype.

2.4.2 Interviews

Since the monitoring period was limited, it is especially important to understand the overall opinion of occupants regarding the system for a longer period of time. Therefore, participants' opinions were noted during interviews conducted with the participants at the end of the study in order to get a deeper understanding of user experience. The form of a semi-structured interview was chosen considering the small-scale project and the flexibility in questions to a certain extent [64] and they were all done remotely due to the COVID-19 epidemic that took place at the same time as this study.

As it was mentioned before under the ''User Perspective'' title, a mixed-method was adopted to evaluate quantitative and qualitative data together. This method is described by Tashakkori and Creswell [65] as analyzing and combining the collected data and interpreting the results based on both approaches for a more complete understanding of the situation. Because user assessment is an indispensable element in evaluating lighting conditions, both quantitative and qualitative data were derived from the semi-structured interviews. However, the focus for the interviews was mostly on the qualitative side due to the very small number of people. Moreover, qualitative research has a holistic approach providing a complex picture where many factors are included [11]. Quantitative study, on the other hand, was conducted to provide an insight into the general opinion on the integrative lighting system.

The interviews contained mostly open-end questions while closed-end questions were asked to provide more detail. The questions were divided into three main categories: control systems, perception, and satisfaction. After the interviews were evaluated thoroughly, some of the findings were visualized in graphs while some data were used to interpret.

2.5 Energy

The building has separate circuits for electric lighting for functional illumination and its standby and parasitic uses for control systems and detectors; however, no information regarding energy use was available from the building manager since the building was completed in late 2019 and no full-cycle electricity bills were available at the time of the study. Due to non-available meter-readings, the energy use for lighting was calculated based on the EN15193-1:2017 [66] standard, utilizing an Excel spreadsheet produced by CEN TC 169 WG9 EP for EN 15193-1:2016. The spreadsheet utilizes Method 2, the quick calculation method that normalizes outputs to square meters of useful area and gives LENI [kWh/(m²a)] as a result. Therefore, the LENI benchmark value presented in the second part of the same standard was used to assess the efficiency of the lighting system. Table 11 displays benchmark values for office spaces and the highlighted line was selected as the reference for the installed lighting system.

Table 11: Examples of LENI benchmark values for spaces and lighting installations

2 Personal office	Electric lighting system [Type]	Installed power density [W/m²]	Annual operating hours		Illumination control				LENI
	[Type]	[W/m²]	[h]		Type	Dependency factor			[kWh/m²y]
			t_D	t_N		F_0	F_D	F_C	
	Efficient, direct	12.18	2250	250	Automatic	0.7	0.34	0.9	6.00
					Manual	0.8	0.49	1	10.97
	Efficient, dir / ind	14.28	2250	250	Automatic	0.7	0.34	0.9	7.04
					Manual	0.8	0.49	1	12.86
	Standard, direct	16.43	2250	250	Manual	0.8	0.49	1	14.80
	Standard, dir / ind	17.85	2250	250	Manual	0.8	0.49	1	16.08
	Existing, direct	34.95	2250	250	Manual	0.8	0.49	1	31.47
	Existing, direct / ind	43.40	2250	250	Manual	0.8	0.49	1	39.09

As mentioned before, the luminaires have four scenes with different CCT and intensity. Due to only available information relevant to Scene 2, values including total connected power for the luminaries regarding the other scenes were extracted by simple proportioning. Table 3 in 2.2.1 presents luminaire power for each scene. It was assumed that each scene has the same amount of running hours each day, therefore, the average luminaire power of four scenes was calculated and adopted to the calculation spreadsheet. Luminaire powers for ceiling panels and spotlights were listed in Table 12. Additionally, energy use for the control systems was estimated based on current requirements for luminaires sold in Europe (max 0.5 W per luminaire).

Table 12: Average luminaire power of four scenes for ceiling panel and spotlight

	Ceiling Panel	Spotlight
Averaged luminaire power [W]	41.13	9.65

Lighting energy calculations for four rooms were conducted separately by defining zones, luminaires in terms of number, power and type, and control factors in the Excel spreadsheet. Table 13 represents the inputs used in energy calculations. Office plans with ceiling luminaire locations are in Appendix.

Table 13: Energy calculation inputs

	02_South	03_North	04_South	05_South & East
Office area [m²]	20	19	9.2	18
No. Of ceiling panel [-]	9	9	5	7
No. Of Spotlight [-]	0	0	0	2
Installed power [W]	370	370	206	307
Installed power density [W/m²]	18	19	22	17
Emergency charging power [W]	0	0	0	0
Lighting control power [W]	4.5	4.5	2.5	4.5

3 Results

3.1 Photometry

Photometric studies including daylight factor, Scenes CCT, and SPD are combined and presented in this section, where site measurements are compared to and supported by simulations.
When comparing measured and simulated DF values, the course of the test points in both cases is almost the same, but measured values were lower than the simulated ones. As an example of this difference, DF comparison in an office is visualized in Figure 13.

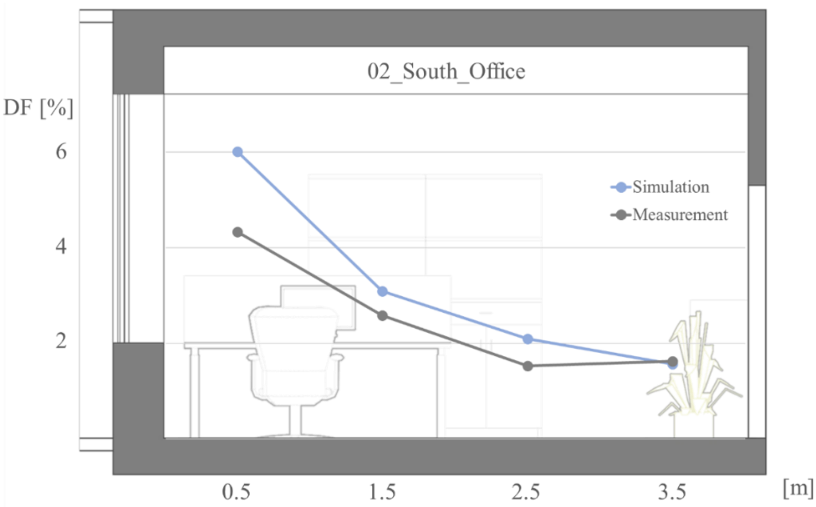


Figure 13: Section DF comparison of measurements and simulations for 02_South_Office

DF simulations results for four office rooms are shown in Figure 14. The offices presented on the left half have lower DF values while the right half shows that the offices experience more daylight. Comparing the offices on the upper part, even though the configuration is very similar, the office facing the north has greater DF values than the one on the south façade due to the thicker and complex façade on the south.

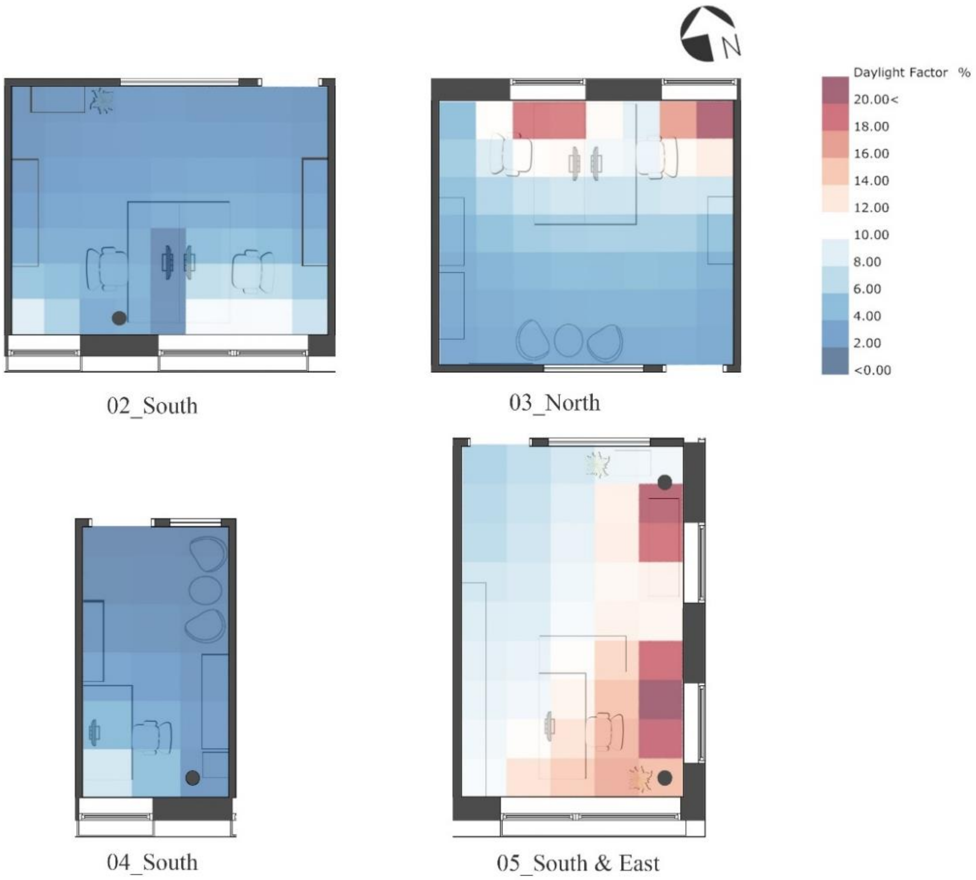


Figure 14: Simulated DF results in the selected offices

During the monitoring, it was observed that the CCT of the lighting system changes where the highest CCT appears in the morning (around 6000 K) and gradually drops to a warmer light (approximately to 3000 K) in the afternoon. This change starting with Scene 1 (bluish color) in and ending with Scene 4 (reddish color) is representatively visualized in Figure 15. The figure also shows that there is high proximity between two site measurements performed with two different instruments. The blue circle represents CCT results of darkroom measurements with a Movisens sensor that were carried out for ratio calibration between four scenes. The same measurement that was repeated under only electric lighting conditions in one participant's room with a CRI illuminance meter presented very similar CCT results meaning that Movisens sensor is rather accurate.

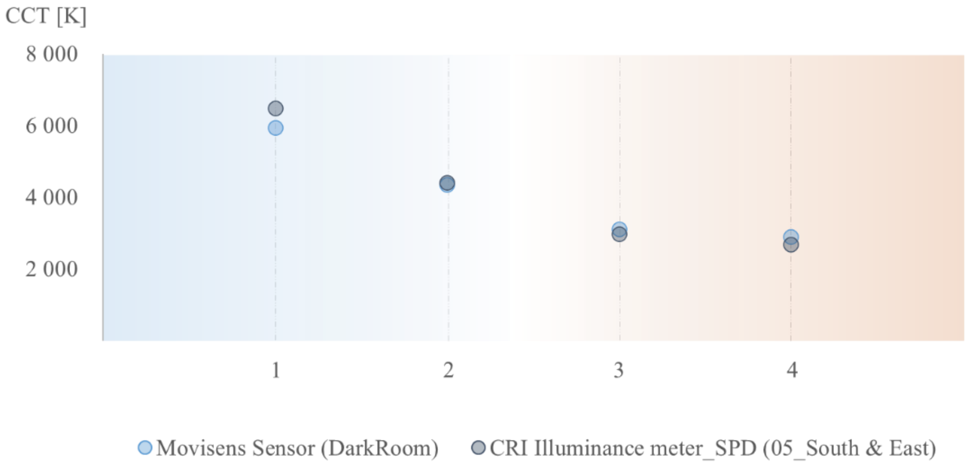


Figure 15: Measured CCT values for each scene by illuminance meter in the office with the highest daylight intake and recorded CCT values for each scene by Movisens sensor in a dark room

Figure 16 represents a comparison between measured and simulated SPD graphs in one office under electric lighting conditions that were carried out for the characterization of the electric lighting system. Measured values shown on the left side on the graph were obtained by site measurements with the Konica Minolta spectrometer at the eye level of 1.2 m where the participant is facing a computer screen. Comparing the measured values to the ALFA simulations, it can be seen that SPDs over the visible spectrum varies significantly for each scene. It is especially visible in Scene 2 where the simulated SPD had a high peak in the blue spectrum while in the measurement, the peak value is around 12 mW/(m^{2}nm) which is less than half of the simulated value (around 28 mW/(m^{2}nm)).

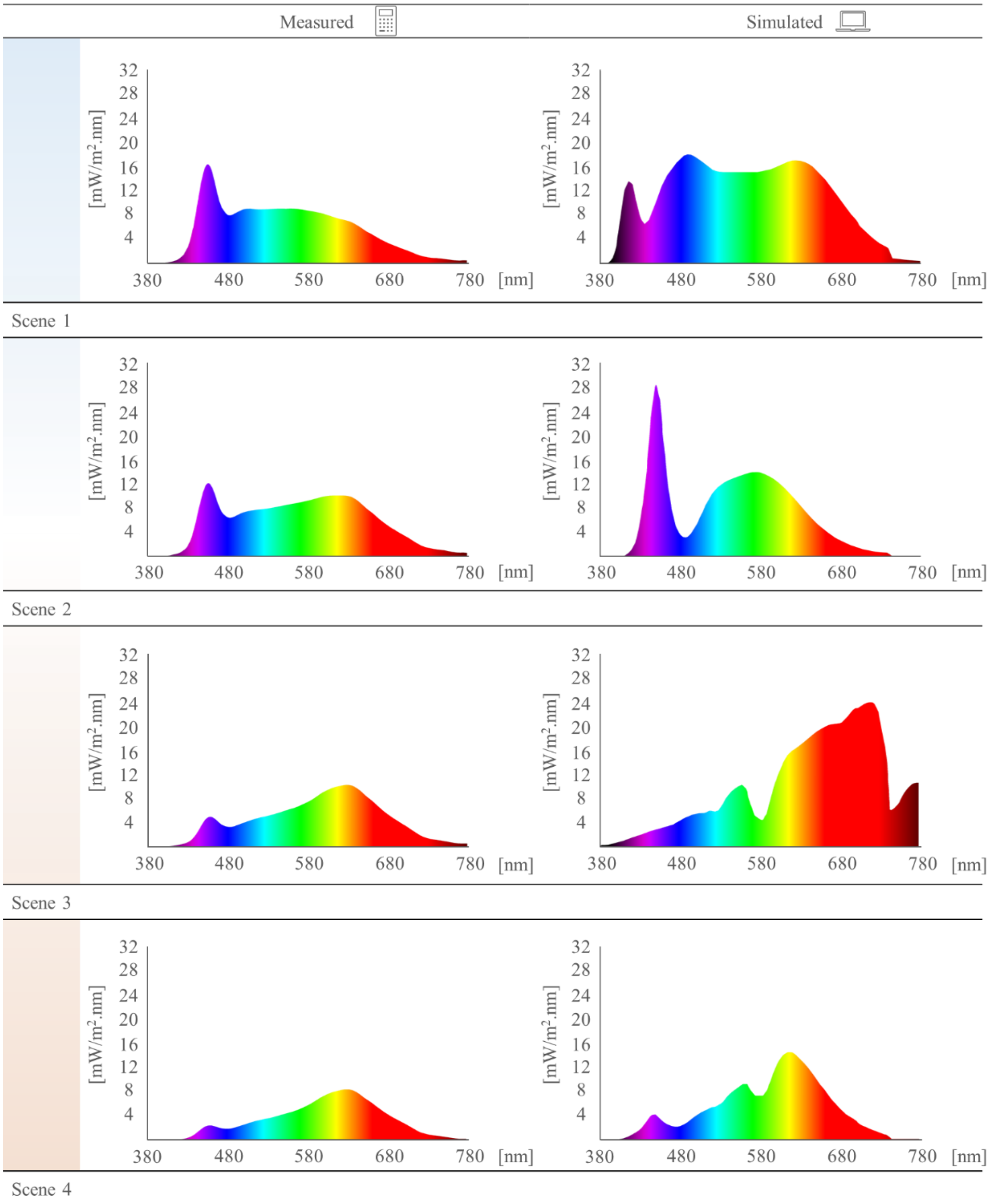


Figure 16: Measured and simulated SPD graphs in one office under electric lighting conditions

3.2 Circadian Potential

The circadian potential was evaluated through EML values and M/P ratios based on the comparison between simulation and measurement results. Figures below represent EML values under three different conditions respectively: only electric lighting, overcast sky (combination of electric lighting and overcast sky), and clear sky (combination of electric lighting and clear sky). Figure 17 shows a comparison of simulated and measured values for each scene under electric lighting for three offices, as the fourth office could not be simulated under electric lighting due to lack of roller blinds. Figure 18 and Figure 19 represent four office areas under the combination of daylight and electric lighting.

By looking at all three figures, it can be observed that the measured values are always higher than the simulated ones. Figures also indicate higher differences between simulated and measured values in Scene 1 and 2 while the values are closer to each other in Scene 3 and 4. It is worth mentioning that EML values are almost always decreasing gradually as the lighting scenes change from 1 to 4, i.e. from higher to lower CCT.

In Figure 17 (electric lighting), measured and simulated EML values are compared in three offices. The participant indicated with green color, who has four windows in the office, has always the highest EML. However, as scenes change from 1 to 4, change in EML is more dominant in that participant while the others have less prominent reduction. Similar to differences in DF between measurements and simulations, EML simulations also resulted in higher values compared to the measurements.

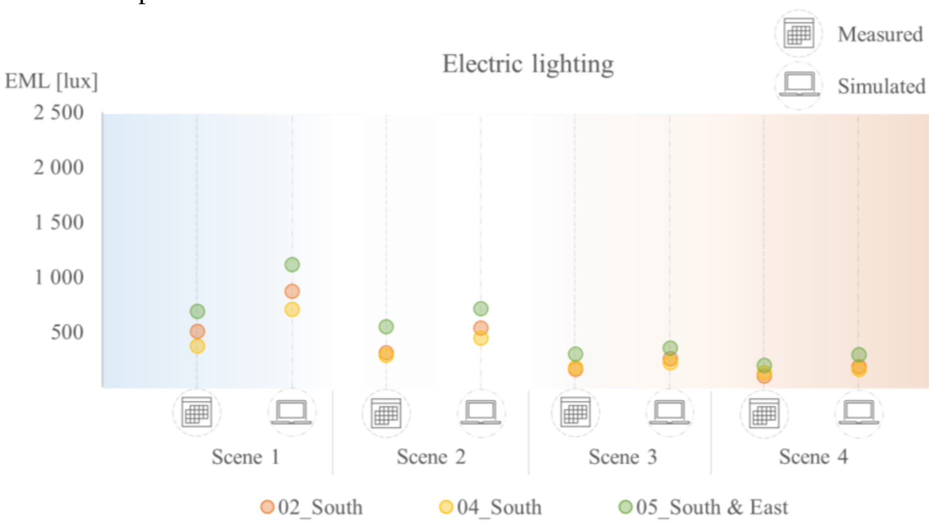


Figure 17: Measured and simulated EML for each scene under electric lighting

In comparison to the previous figure showing only electric lighting conditions, Figure 18 displays significant changes in simulated values. Additionally, the participant with the grey indicator was included in this figure. It would be expected to have similar values for 03_North (grey) and 02_South (red) since their office configurations are similar including having two windows. Moreover, in the offices with more available daylight, EML at measured views seems to be higher. This is evident in the participants 05_South & East and 03_North where the overcast sky has large effects on the increase of EML. It can also be seen from the figure that even though the red marked office has two windows, the results are similar to the yellow marked one with one window. It is also evident that the EML values decrease as scenes change from 1 to 4.

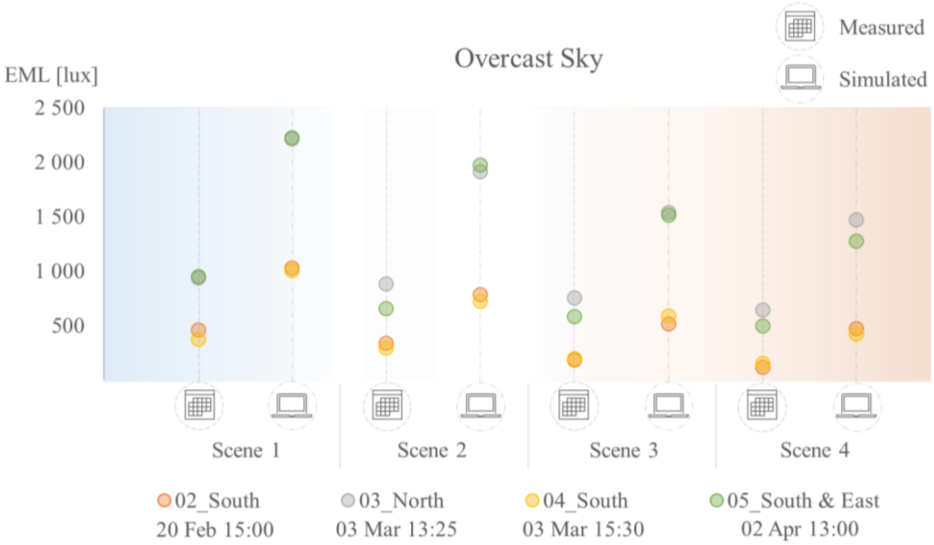


Figure 18: Measured and simulated EML for each scene under electric lighting and overcast sky

Figure 19 shows the results of simulation and measurements that were conducted under clear sky conditions. The y-axis top value in figure was changed to 8000 lux due to much higher values of EML. Except for two exceptions (green for Scene 1 and yellow for Scene 4), simulated values are greater than measured ones. This can especially be seen in values indicated with green that vary notably for Scene 3 and 4. For the simulation results presented, except the participant indicated with green color, either the values drop gradually with a decrease in CCT and intensity of the luminaires or they almost stay the same as it can be observed in yellow and grey in the transition from Scene 3 to Scene 4. Therefore, EML does not gradually decrease from Scene 1 to Scene 4 under electric light and clear sky for every office.

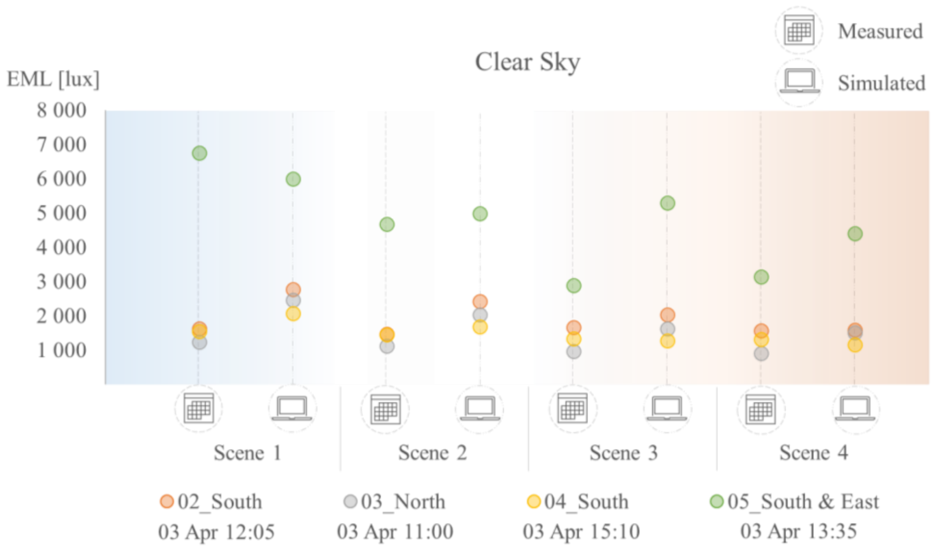


Figure 19: Measured and simulated EML for each scene under electric lighting and clear sky

In addition to the EML results presented above, ALFA provided fisheye images created for each scene showing RGB images and false-color display of EML. As displayed under each figure, in a general trend, both EML and photopic lux are decreasing as the scenes move towards Scene 4. It is important to point out that EML values are being reduced more than photopic lux values at each scene resulting in lower M/P as intensity and CCT of the lighting decline. The decrease in photopic lux can be explained with lower intensity values. EML values, on the other hand, can depend on more factors.

In Figure 20, a comparison between electric lighting and the combination of electric lighting and daylighting was presented for one office. It is clear that high EML values are greatly affected by the presence of daylighting in the office. It is also worth pointing out to the transition from Scene 3 to Scene 4 in the upper half of the figure. Even though the M/P ratio is lower in Scene 4, both photopic lux and EML are slightly increasing due to higher increase in photopic illuminance caused by the effect of daylight in simulations. This trend in image-based (fisheye) results were also observed in Figure 19, however, an increase in EML happens in measurements rather than simulations. On the other hand, the simulation results presented above indicate that higher EML was recorded in Scene 3 than 4.

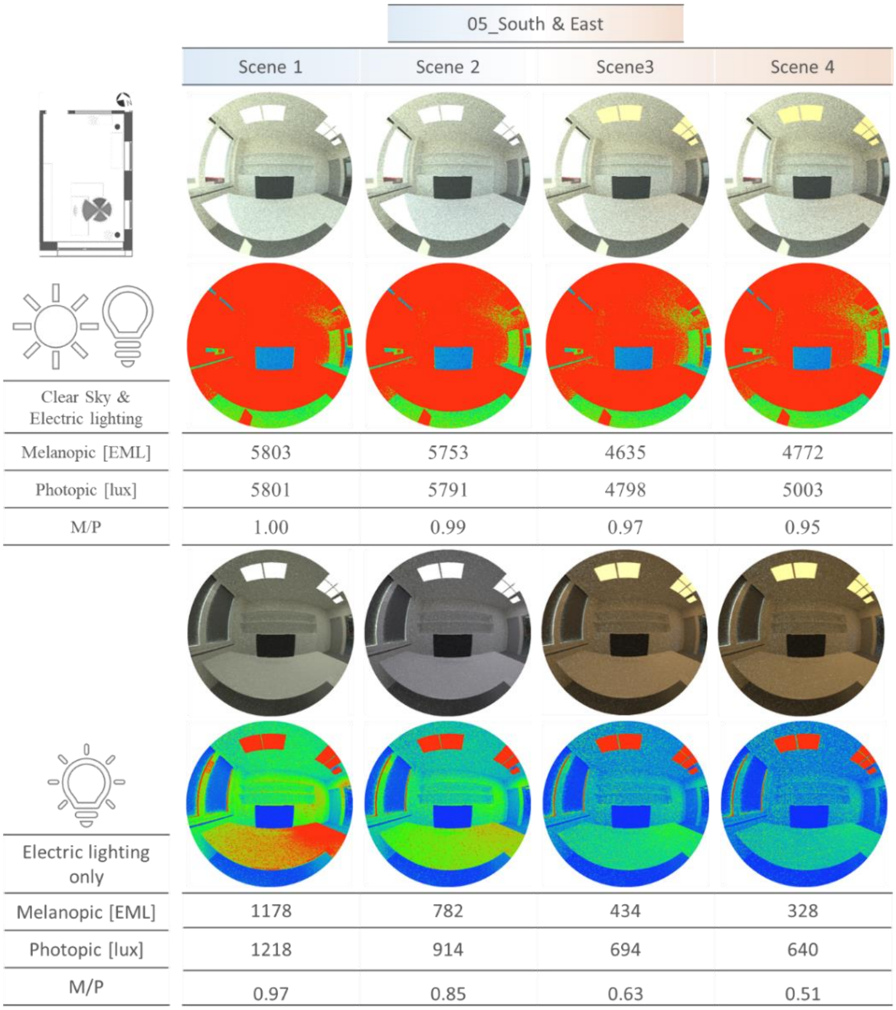
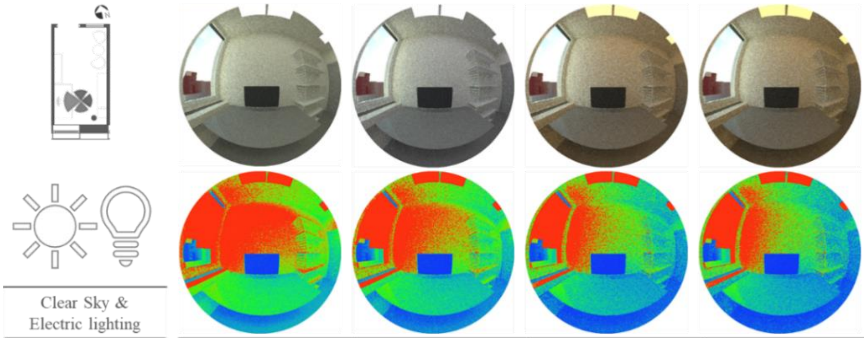


Figure 20: Image-based simulation results for a comparison between electric lighting and the combination of electric lighting and clear sky in Office 05_South & East

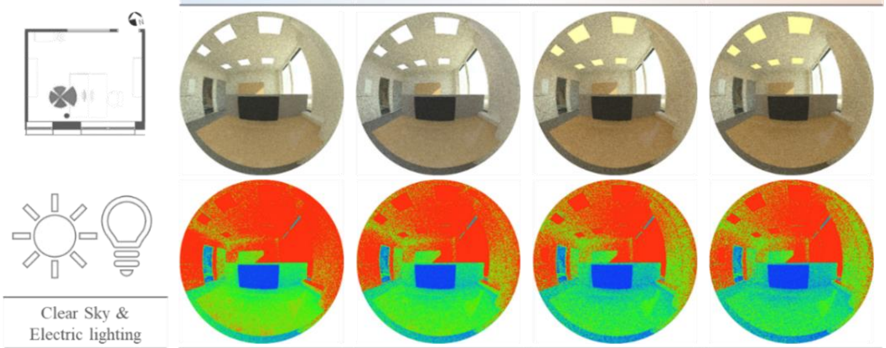
Similarly to the clear sky simulations with daylight and electric lighting presented above, Figure 21 shows an increase in EML and photopic lux from while switching from Scene 3 to Scene 4. Additionally, the M/P ratio here also increases, in this case, resulting in a higher increase in EML than photopic lux. In comparison to the previous office, both EML and photopic lux are lower while M/P ratio is still higher than 0.90 implying that the overall lighting provides an alerting environment.



Clear Sky & Electric lighting	04_South Scene 1	Scene 2	Scene3	Scene 4
Melanopic [EML]	2160	1658	1216	1508
Photopic [lux]	2177	1701	1360	1650
M/P	0.99	0.97	0.89	0.91

Figure 21: Image-based simulation results for the combination of electric lighting and clear sky in Office 04_South

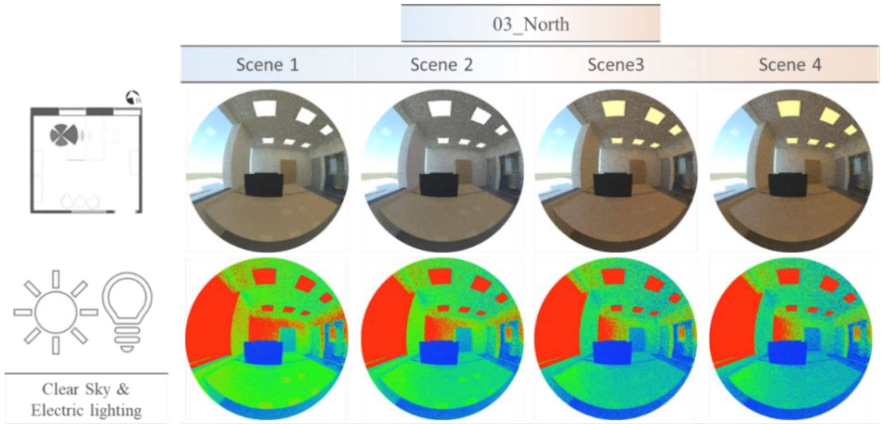
Figure 22 shows a different trend than the other figures above. Image-based simulations display that Scene 1 and Scene 2 are quite similar while Scene 3 and 4 are almost identical. For the same office under the same circumstances, grid-based simulations showed a slight decrease from Scene 1 to Scene 4.



Clear Sky & Electric lighting	02_South Scene 1	Scene 2	Scene3	Scene 4
Melanopic [EML]	2484	2486	2110	2111
Photopic [lux]	2729	2761	2543	2519
M/P	0.91	0.90	0.83	0.84

Figure 22: Image-based simulation results for the combination of electric lighting and clear sky in Office 02_South

Simulation results presented in Figure 23 are consistent and very similar to the values displayed in Figure 19. All values are declining towards Scene 4.



Clear Sky & Electric lighting	Scene 1	Scene 2	Scene3	Scene 4
Melanopic [EML]	2300	1895	1620	1514
Photopic [lux]	2124	1845	1644	1571
M/P	1.08	1.03	0.99	0.96

Figure 23: Image-based simulation results for the combination of electric lighting and clear sky daylight in Office 03_North

3.3 User Perspective

The sequential results from sensor recordings, self-reported questionnaires, and semi-structured interviews are presented in this section by combining both qualitative and quantitative data. Figure 24 and Figure 25 show the sensor recordings of wrist-worn devices for two participants during working weeks represented by the arbitrary variable CCT·lux, along with the sky condition and the participant KSS self-reported answers regarding their alertness and sleepiness on these days. Arbitrary unit CCT·lux that was created for this study is used to relate qualitative alertness to light stimuli on a bidimensional chart. Because literature shows that light stimuli increases alertness with increasing light intensity and CCT among other aspects, an increase of alertness was expected for higher values of CCT·lux

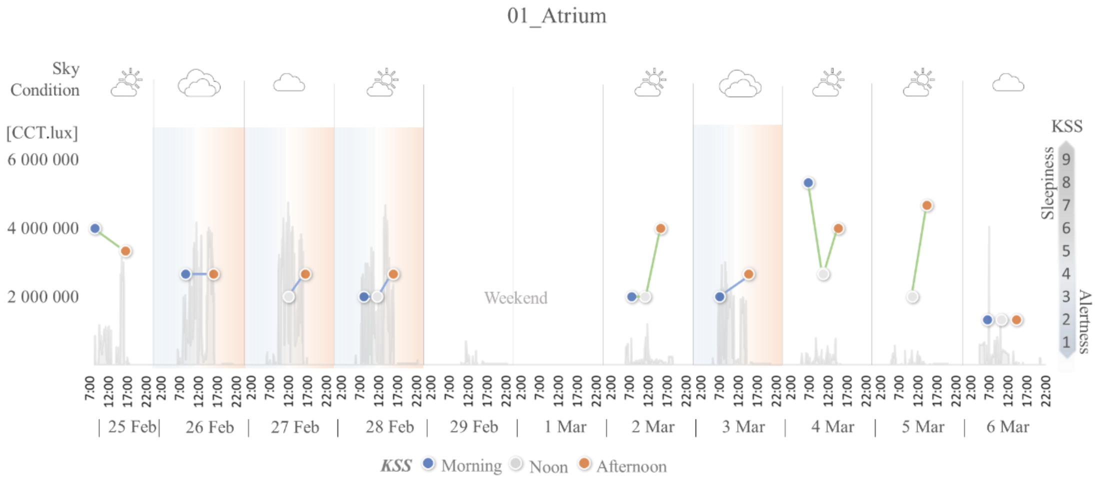


Figure 24: Qualitative and quantitative data for the participant 01_Atrium, The x-axis shows the day and time, the y-axis to the left shows the CCT·lux recorded from the sensor and to the right the sleepiness / alertness KSS scale that was self-reported by the participant three times a day in the morning, noon and afternoon

Qualitative and quantitative data for the participant 01_Atrium from the 25th of February until the 6th of March are presented in Figure 24, the pattern of the participant sleepiness and alertness self-reporting during the working days spent in the office with the integrative lighting system (26th-28th of February and 3rd of March) had a slightly different pattern compared to the days the participants worked from home or from other offices (25th of February, 2nd of March and 4th-6th of March)

Sleepiness of the participant 01_Atriums in the morning was almost always lower than it was in the afternoon when the participant was working in the office under the integrative lighting system, yet this was not the case with the participant sitting on the northern façade with two windows. Figure 25 below shows that this subject was usually less alert in the morning than in the afternoon.

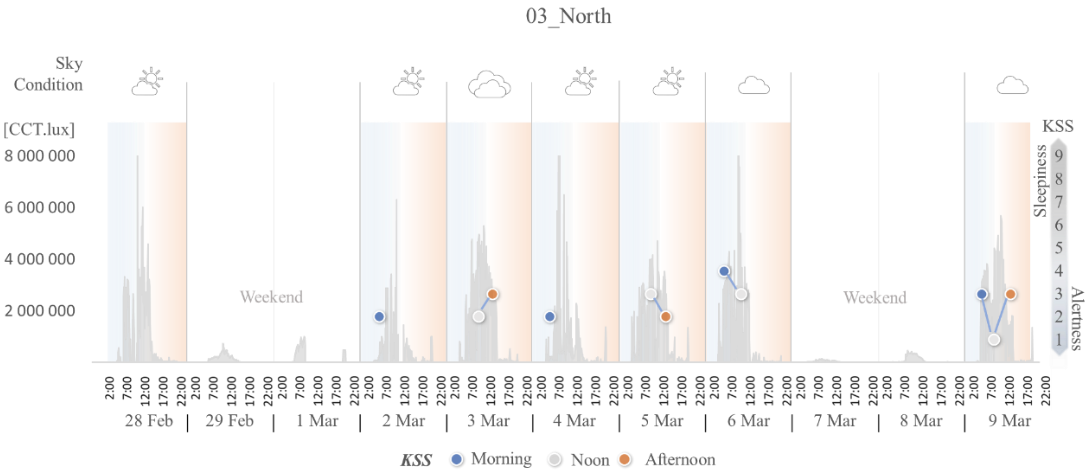


Figure 25: Qualitative and quantitative data for the participant 03_North, The x-axis shows the day and time, the y-axis to the left shows the CCT·lux recorded from the sensor and to the right the sleepiness / alertness KSS scale that was self-reported by the participant three times a day in the morning, noon and afternoon

This difference is more clearly seen in Figure 26 that shows the linear mixed-effects model for KSS and CCT·lux from all participants. While regression analysis for four participants are following a similar trend where alertness increases as CCT·lux rises. The participant indicated with grey color (03_North), on the contrary, shows the opposite tendency.

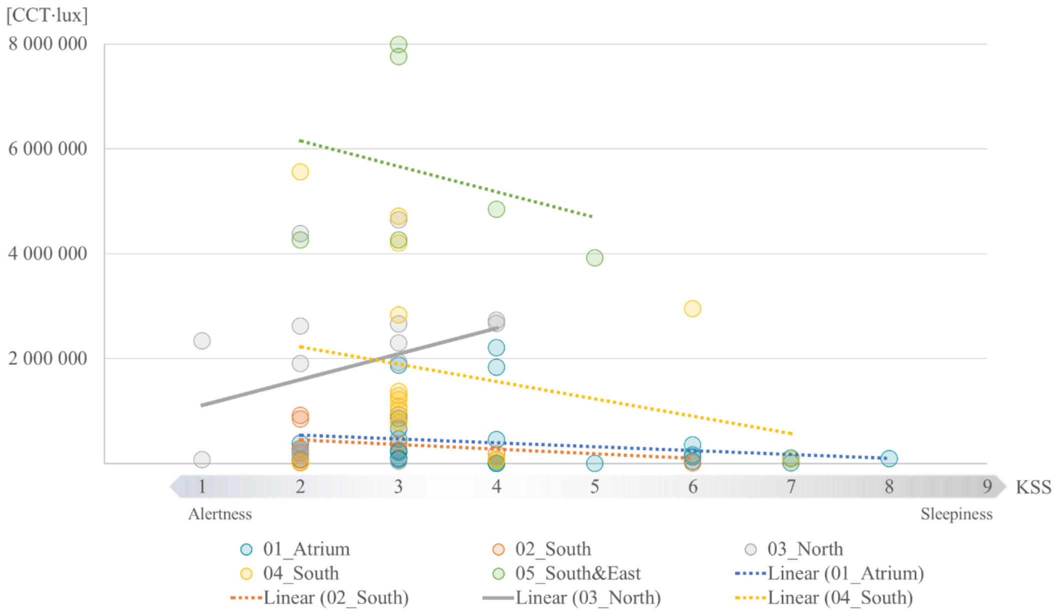


Figure 26: Linear mixed-effects model for KSS and CCT·lux for all participants

SVS results from self-reported questionnaires are presented as average values for each item in Figure 27. Each participant has a different response rate; therefore, the average values here represent some participants more than the others. It shows that participants are mostly more alert and energetic in the mornings while they are less awake and have energy in the afternoon.

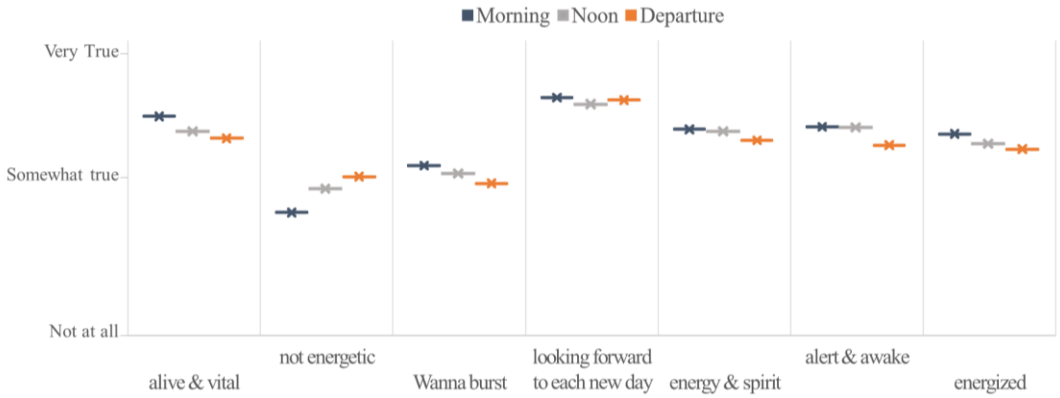


Figure 27: Average SVS responses from all participants

It was observed through the participants PSQI answers that for most nights for three weeks, the participants very seldom slept less than six hours. Having a limited number of answers to the questionnaires provided by the participants, while three participants almost did not have any problem sleeping while the other two, who have the highest answer rates among all, reported having problems sleeping for less than half of the time. Therefore, except on a few occasions, there were no irregularities in their sleep time and quality according to self-reported questionnaires. Similarly to their sleeping habits, the ages of the participants were close, between 40 and 59.

Apart from the self-reported questionnaires, interview data helped to construct a user perspective in this study. Interviews provided qualitative data that is crucial to support the findings from the self-reported questionnaires particularly at an individual level. Quantitative data contributed to creating a general image of the lighting and the control systems. Figure 28, Figure 29 and Figure 30 summarize participant opinion on the use of control systems, satisfaction and, the experience of the lighting conditions. In Figure 28, user behavior is visualized as a yes-no format. It shows that only one person among five participants intervenes with the lighting control. This person reported that lighting Scene 4 was the only scene that was utilized in the office for the whole day due to the preference of the participant. That participant expressed feelings about the lighting system when asked:

- ‘‘It was terrible. I cannot stand this light, very white blue light at the ceiling. I got migraines from the beginning [...]

- ‘‘When I came to the office each morning, it was very upsetting for me and that was due to the light.’’

This participant expressed that as the light was warmer in color, it became better even though migraine is still an issue for a couple of days a week. It was also stated that the participant gets very tired in the afternoons, more tired and earlier in comparison to previous working environments.

The participant also commented on the general lighting environment by not recommending having a working place so close to the windows, which are located on the south façade causing excessive light due to daylight and electric lighting together. Dissatisfaction with the lighting system was described by the participant, stating that the first thing in the morning is to change the lighting setting to Scene 4:

- ‘‘If I am not in the office, I feel more alert. But it takes some time. If I am in the office for 5 days, when I wake up on Saturday morning, I still have a headache. Then Sunday is an ok day’’.

Except for this participant, the other four use the automatic mode where the scene changes without any intervention. Shading control is actively used by only two participants whose offices are on the south façade. The third participant who also sits on that façade reported that there is no need to use the shading control as it works automatically when really needed. Other two do not have shading control systems due to lack of the system in their offices. Dimming control that is used to regulate illuminance levels is not utilized by any of the participants in their daily office routine. Even though all the participants claimed that there is no need to use task lamps due to enough lighting levels in the workspaces, two of them have task lamps on their desks and use them as a habit Figure 28.

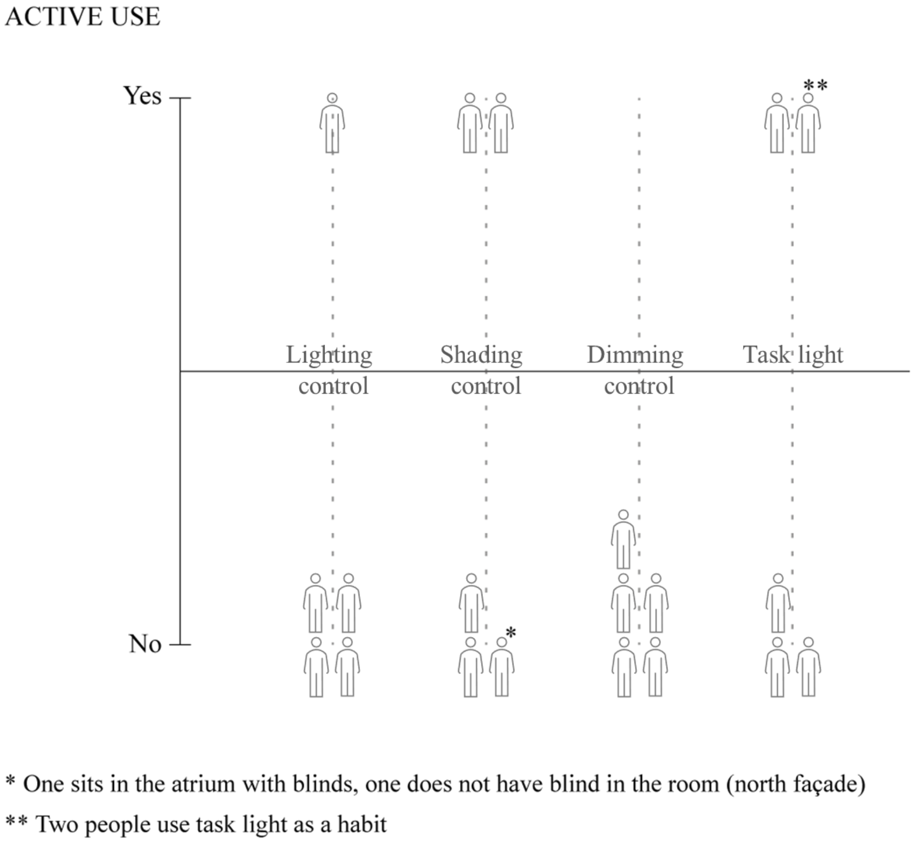


Figure 28: User behavior towards lighting and control systems

Figure 29 represents the satisfaction levels of the participants separated into the lighting system with controls and the shading system with controls. There is one person who is considered very dissatisfied as described with quotes above. However, when in control, the satisfaction level of this participant was more on the positive-neutral side. One person reported to be neutral to the lighting system while one person claimed to be satisfied. Two participants expressed themselves as very satisfied with the lighting system. On the other hand, there are two people who considered themselves satisfied with the shading system, and one neutral person who said ‘‘could have been better’’.

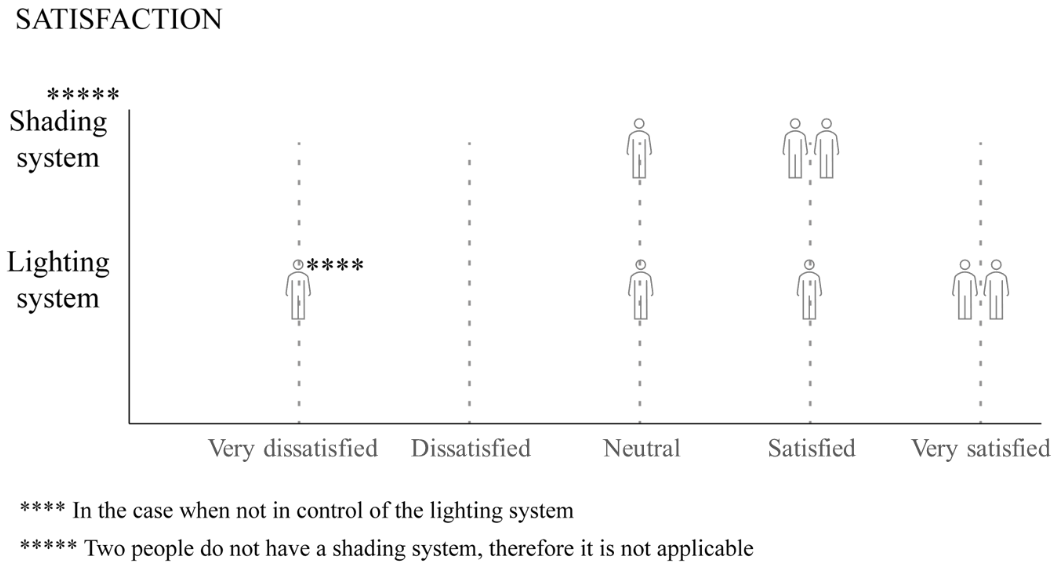


Figure 29: Satisfaction levels of the participants towards the lighting and the shading system

The person whose opinion was neutral towards the lighting system reported that there is not much difference compared to older working environments. The participants expressed:

- ‘I do not have any specific reaction to the light and the fact that it may be different from other settings I have been working in’’.
- ‘‘[…] I am not really aware of the automatic functionality. It is not something that I pay any attention to’’.

This participant also stated that the automatic mode is used in the office. However, it was also noted that, even if the system was manual only, it would have been fine as well. When the participant was asked about how the light affects alertness, the answer was:

- ‘‘It is difficult to drive only from the light. There are a lot of other factors as well. The mood you are in and what kind of tasks you are working with, if it is fun or not. I actually cannot connect it to the light only’’.

Effects of the lighting system were further expressed by the same participant:

- ‘‘Probably the light would have played a more important role if I did not have any window’’.

In the end, the participant stated that the lighting system is ok but would not consider purchasing for such an advanced system.

Figure 30 presents the participants’ experience of the lighting conditions. Positive answers about the lighting are placed at the upper half indicated with ‘yes’. It is clear that lighting experience is dominantly positive. Two people reported glare from outside due to their south-facing offices while no one reported any glare problems related to the electric lighting. All participants found lighting levels enough to work in and did not need additional light such as task light. The person who reported being very dissatisfied is the same person who noticed a change of light between the scenes as well as having health problems, namely migraine.

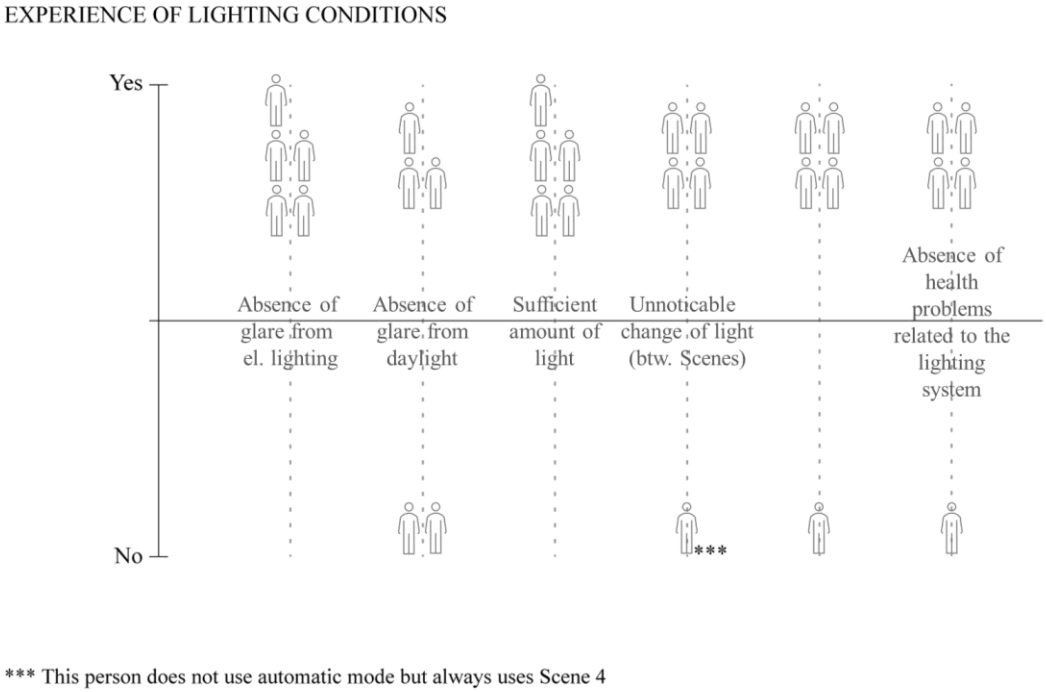


Figure 30: Participant experience of the lighting conditions

The person who acknowledged as satisfied expressed opinions about the lighting system:

- ‘‘The lighting is very good, and I like it [...] especially the changes over the day gives more comfortable light’’.

In the beginning, the first time coming in the office, the light was perceived as very bright and was manually dimmed. Later the participant got adapted to the very bright light of Scene 1 and to the whole system in general. Experience in adapting to the system:

- ‘‘It just happened naturally; it did not take long’’.

However, when the participant was asked about how the light change in scenes affect alertness, the answer was:

- ‘‘[...] but actually I got a little bit more tired when it started to dim down. I could feel that it affected me. Probably relaxed more but also, I get a bit sleepier. That also has to do with that I often work late hours’’.

It is interesting to point out that the person sitting in the atrium office with no view out is very satisfied with the lighting system claiming that:

- ‘‘I’m happier with it than I thought I would be’’.

When asked to make a comparison with other work environments, the answer was:

- ‘‘The difference is that I am not sitting close to an ordinary window. So, I cannot see out really. […] But I am not really bothered due to the lighting system. It helps. [...] Other offices I had been in were darker. Here, it is like sitting outdoors and I do not need extra lighting like task light. In other places, I felt the need [...]’’

In addition to not being able to recognize that the days are getting longer with the spring coming, it was stated that:

- ‘‘I am like in a bubble. No change at all. I think that is due to that I cannot see out. [...] I have no idea if it rains or is dark or clear sky. […] It is good because I can concentrate but it is maybe a little bit artificial […]’’

The participants’ answers to the short questionnaire based on MCTQ and modified by the authors revealed that the working schedule of the person is very flexible and requires traveling and working in other places. During the interview, it was also noted that if the participant stays in that office all the time, the experience would likely be different. The participant also commented on the effects of the lighting system on the sleepiness:

- ‘‘I know that it should. I have no idea if it is affecting my sleep just because. Almost at the same time when we moved here, I started to do some meditation. That could also be helpful with my sleep. But what I notice is that I am more alert, and I forget to go home at the end of the day’’.

The other participant who claimed to be very satisfied with the system and who also sits in the office with the most daylight intake expressed:

- ‘‘I will never ever go and sit in any other environment. I have a problem when I am at home’’.

The participant further explained the differences to previous experiences in other office spaces and home lighting:

- ‘‘You do not feel tired in the middle of the day or after lunch. And you are always a bit more focused. [...] I do not get tired when I sit under this light even if I work a lot and that is very amazing. I also sleep very well which is also a good effect of this lighting’’.

- ‘‘Headache was the difference when we first moved in. But we had very bad lighting where we sat before. It was extremely bad. So, the change is very visible’’.

- ‘‘If I sit at home or in a place with a different lighting system, I would definitely feel the difference. But when I am in the office, it is much better there because it is very well lit, it does not make me tired the way I get tired at home’’.

It was also acclaimed by the participant that people who visited the office were satisfied with the lighting system as well. On the other hand, this participant who appeared to be neutral towards the shading system said that it could be better and further explaining that the automatic system does not work very well. However, being able to manually control was perceived as a positive aspect.

3.4 Energy

Calculated LENI results are listed for each office in Figure 31.

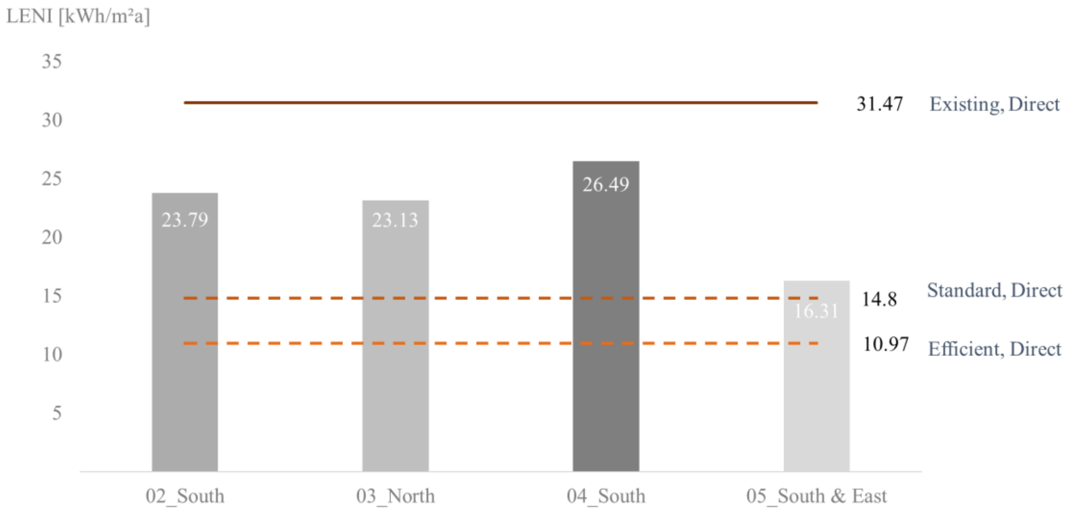


Figure 31: Energy calculation results

All offices perform better than the benchmark (EN15193-2 2017) set for existing office buildings with direct lighting systems, 31.47 kWh/(m²a). Even though the building was constructed recently, and the installed integrative lighting system is a new technology, it cannot satisfy the benchmark for efficient lighting systems or standard lighting systems. It is important to emphasize that the installed power density for each room is between 17 W/m² and 23 W/m² as presented in the methods. According to the Table 13 presented in section 2.5, these values refer to the standard lighting system rather than the existing one. However, LENI results demonstrated that, even though the installed power is lower compared to the existing lighting system standards, the output values can only comply with the existing lighting system.

4 Discussions

Figure 32: Workstation in 02_South office

Results for DF of simulations and measurements showed that the values can vary notably, depending on grid locations, simulated results were slightly higher than the measured ones. The differences were especially closer to the workstations area, it can be attributed to the fact that the 3D daylight model only included the main furniture in the office e.g. desks, computer screens, and bookshelves. As shown in Figure 32, additional objects like chairs, books, and other items that can create shadows in reality, were ignored in the model in the interest of simplicity. This could have influenced the measurements and hence, could be the reason for these lower values. Moreover, the test points located at the end of the room near the glazed part of the wall were affected in the measuring process by the light coming from the corridor, which influenced a rise in the DF results for these points compared to their simulated values. Furthermore, limitation of time and accessibility to the monitored spaces increased considering the COVID-19 epidemic that took place at the same time as this study, which made it difficult to have a comprehensive monitoring level for all selected spaces e.g. DF measurements were not carried out in the office of the participant sitting on the northern façade.

However, all offices aside from the one located toward the atrium with no view out were simulated. It should be noted that windows configuration on the south façade is more complex than the ones in the north façade as they have an extra glass layer on the outer skin which may be caused the reduction in the amount of daylight seen in the simulated results coming into the offices in the south façade compared to the one on the North façade.

Sensor recordings were indispensable elements of TEAs that provided a large amount of data about the ambient light and physical activity. They also contributed to calibration of the luminaire files that were used in ALFA by proportioning method. The proportioning method was only applied because the specifications of the lighting scenes were limited, as only Scene 2 *.ies file was provided from the producer company. Therefore, it was necessary to rely on the ratios between the CCT of the four scenes conducted from site measurements, CCT, total luminous flux, and total connected power for the other scenes were approximated. However, it was acknowledged from the beginning that it is not a very accurate way for both simulations and energy calculations. It should be noted that both intensity and CCT were recorded through these wearable sensors on the participants' wrists, which yielded a loss of data as some participants forgot to charge their sensors for several hours/days. Moreover, CCT data showed inconsistencies during the whole monitoring period, whereas illuminance data were more coherent possibly as a result of the participant's wrist movements or position in which the sensor might be covered by an external object i.e. (clothes, etc.). These limitations and inconsistency in data also influenced the initiation of the arbitrary variable CCT·lux

Moreover, considering the measured and simulated SPDs of the luminaries, it can be clearly stated that the measured values are reflecting the real conditions and providing correct SPDs while simulated SPD graphs show higher values at all wavelengths, but especially indicate larger spikes at peak wavelengths. These differences can be because of the omitted objects to a certain extent, however, it is more likely to be affected by how ALFA works with spectral skies and fixed luminaire power distributions. Because ALFA provides fixed SPD graphs for each M/P value in source spectrum options under luminaire settings, simulation results are highly dependent on these graphs that cannot be edited manually. In addition to this, the limited material library in ALFA has effects on the differences with the measurements. Even though the default library offers a wide range of material options, it is still more limited than creating new materials based on measurements. Despite the fact that it is possible to create materials in ALFA, the software requires SCI (specular component included) and SCE (specular component excluded) values in percentage for wavelengths between 360 nm and 740 with 10 nm intervals, therefore it is very time-consuming.

Both photometric (DF) and circadian potential simulations (EML) showed that, especially under overcast sky, the participant sitting in the north facing office benefited more from the daylight compared to the other participant with almost the same office configuration sitting in the south facing office. This considerable difference is mostly based on the complexity of the window where south facing windows have an extra glazing layer with less light transmission and more reflectance values. Because overcast sky is dominant in countries like Sweden, people whose offices are on the north façade rather than the south façade in this building can have more access to higher circadian stimuli provided by the sky.

Similarly to the differences occurred in DF simulations, ALFA simulations for circadian potential studies under electric lighting and overcast sky showed greater values in EML compared to the measured ones. However, the differences climbed up even greater in the offices with the highest DF values. On the other hand, the offices with lower DF values provided closer values especially when the scenes changed through Scene 4. An interesting exception was observed with EML values under clear sky and Scene 1 where measurements provided higher results than simulations for the office with the most daylight (05_South & East). It is clear that when the daylight was abundant in offices, simulation results started to be less consistent (especially under clear sky) while less daylit spaces provided nearer values between simulation and measurements. The reason might be the unrealistic spectral sky models used in the software. In addition, the same behavior of ALFA can be seen in different scenes under the same sky conditions. Results showed that simulation and measurement values were closer in Scene 4 and the gap increased towards Scene 1. This can be connected to how ALFA processes spectral skies and spectral luminaires in simulations. In this study, it was evident that ALFA provides greater EML values at higher CCT and intensity as seen in simulations with sunny sky and Scene 1. Therefore, higher CCT·lux inputs in ALFA results in higher EML, thus alertness. However, ALFA’s predictions of EML are more consistent when CCT·lux are lower as observed in Scene 3 and 4.

It can also be hypothesized that ALFA simulations are very sensitive. This is probably because of the dependence of EML in various aspects such as number and types of luminaires, sitting and eye location of the person, proximity and directionality of windows, office configuration, glazing types, and window configurations. However, simulations that were carried out consecutively without any change resulted in various values (in photopic lux, EML and M/P) where some were quite different. In these cases where the results looked inconsistent, simulations were run several times for confirmation. This behavior of ALFA could not be predicted, and no justification could be provided in this study. Results in ALFA differed also between grid-based simulations and image-based ones. However, this behavior can be expected by aforementioned sensitivity of ALFA and the nature of how grid-based and image-based simulation take place.

The participants in this study moved to this building around October and November in 2019, therefore, the experiences that the participants shared were limited by time, starting from autumn 2019 until the beginning of spring 2020. Additionally, and even though the questionnaires were short and simple, the fact that they were handed three times a day every working day led to survey fatigue where the response rate from most of the participants was not constant. However even with these limitations, it was observed that how participants feel about the lighting system varies greatly from one to another. Even though the perception and reaction were more on the positive side, one person expressed great dissatisfaction with the system, especially towards the automatic mode and the scenes with higher CCT·lux. While one person does not think that lighting only can affect one's sleepiness and alertness, and saying that there are many other factors, other people reported that it affected alertness during work and sleep quality at night positively either solely depending on the lighting or the combination of physical activity and the lighting. These responses and reactions were aligned through the self-reported answers of the participants and their comments during the interviews, e.g. the participant who reported ''It is difficult to drive only from the light. […]'' was the only participant that showed the opposite tendency when it comes to the regression analysis between KSS scores and CCT·lux and this trend was also seen in the participant's results in figure x. On the other hand, the participant who mentioned in the interview ''I know that it should" when talking about how the light might affect this participant's sleepiness, the same tendency was followed in the KSS and CCT·lux results of this participant in being more alert with higher CCT·lux values, which correlate with the hypothesis that was set in the beginning. With this behavior, it is becoming unclear if the participant's beliefs are influencing their experience in perceiving the effects of the lighting on their alertness or sleep quality.

The electric lighting circuit for the system was not provided with a separate electricity meter. Due to limited access, the energy consumption was calculated according to the European Standard EN 15193. However, these calculations can be inaccurate since many assumptions were made regarding e.g. losses during standby, control systems, total connected power for each scene and dimming through scene change. Therefore, it can be stated that the lighting system serves another purpose rather than being energy-efficient. As the producer's aim was to create a lighting system that mimics natural daylight in order to promote human circadian rhythm for improving sleep and well-being, it can be stated that energy-efficiency of this system is not the primary desire. Moreover, in comparison to traditional lighting in office spaces designed with efficient systems, lighting levels that are provided is significantly higher.

5 Conclusions

This study investigates the circadian potential of an integrative electric lighting system in an office environment by means of quantitative and qualitative methods. Quantitative methods, TEAs, include on-site measurements, simulations, and recordings, while quantitative methods, OBEAs, consist of questionnaires and interviews conducted with the participants. This section emphasizes the main points of this study and answers the research questions.

- It was observed that the integrative electric lighting system can steer EML of the occupants as the values changed from Scene 1 to Scene 4. However, this effect of the lighting system is more prominent in the offices with less daylight intake. In the offices where daylight is prevalent, e.g. under clear sky and electric lighting studies in this research, EML values were not profoundly changing with the change of the scenes as the effect of daylight dominates the effect of the electric lighting. Therefore, the system can be more effective in areas only lit by electric lighting and areas with insufficient daylight.
- As monitoring spaces were limited and do not cover all office types in the building, along with their differences in area, orientation, and daylight exposure, thus, the documented responses and measurements in this study cannot conclude the whole experience and effect of the lighting system in the occupants' sleepiness and alertness in the whole building. The small number of participants did not provide statistical data that can contribute to a more generalized idea about the lighting system.
- Based on the self-reported questionnaires from the participants, four participants showed a positive correlation between alertness and arbitrary unit CCT·lux while one participant reported higher alertness at lower CCT·lux. Therefore, even though it was seen that the lighting system can steer EML, the findings does not acknowledge that the system also affects the alertness of the participants as the data was not enough to draw such a robust conclusion.
- The simulated EML values were almost always higher than the measured ones under all lighting conditions (electric lighting and combination of daylight and electric lighting under overcast and clear sky). However, the closest values between simulation and measurement happened under electric lighting conditions. When daylight was prevalent in offices, the differences climbed even higher. Therefore, it can be hypothesized that ALFA can predict EML driven by the integrative lighting system with overestimation, even though this overestimation might be due to the 3D daylight model to a certain extent. However, in the simulations where combinations of electric light and daylight were used, this prediction behavior became less valid. This is also evident in the offices with different daylight intake. It was observed that when an office has higher daylight available, the difference between simulations and measurement becomes prominent. In this sense, it can be assumed that spectral skies used in ALFA, especially the clear sky model, are not close to real conditions and this has large influence on the difference of the measured and simulated EML values. Moreover, even though the simulated values mostly follow the same pattern as in the measurements, some values were explicitly different from one lighting scene to another. One reason can be the default and limited SPD options in luminaire settings in ALFA based on M/P ratio. SPD that does not match with the one for an actual luminaire can cause misconception of the lighting system and the luminous environment as it might be the case for this study. Additionally, it was observed that

ALFA is very sensitive. Simulations that were run consecutively without any changes provided various values causing fluctuation from one simulation to another. Therefore, this could also be the one of the reasons for the fluctuations that were not expected based on the measurements.

- Majority of the participants claimed to be satisfied with the system and acknowledged that the lighting helps them to be alert and stay focused on their work task. One person reported great dissatisfaction with the system in the case when the participant is not using the control panel. This participant reported that the Scene 4 which provides the least EML is constantly used in the office and concerns were mentioned about not feeling alert at work. The participant who claimed to be neutral said that the alertness and sleepiness is not affected only by the light but also many other factors.
- Except one participant who prefers Scene 4, none of them intervenes with the automatic mode that dynamically changes the scenes. All participants acknowledged that they do not utilize the dim control and rather use the maximum illuminance level. Participants who have shading and control systems in their offices intervened with the system only on very few occasions. However, considering that people moved to the building in the autumn and have not experienced summer yet, this behavior towards the shading control might change.
- The integrative lighting system complies with the standard for the existing and direct lighting system. However, considering that this building is newly built, and the lighting system is a new technology, it can be stated that this is not an energy-efficient lighting system. Furthermore, because this integrative lighting system is designed to contribute to the health and well-being of people and to promote their circadian rhythms, it can be hypothesized that energy-efficiency was not the primary object of the producer company.

6 Future research

As the case study investigation was limited, the future possible research that can be carried out to clarify or analyze this study results are listed below:

a. As mentioned before, the integrative lighting system steered the EML in the investigated areas with limited daylight access, yet the minimum threshold for daylight intake that affects the efficiency of the system is not known. Future research can be carried out to investigate more areas with different daylight intake to have a deeper understanding of this relation.
b. Simulation results were always higher than the measured ones. The highest influence in this can be related to the spectral sky models in ALFA. It is true that there are efforts to create spectrally accurate sky models [45]. However, there is a need for further development, measurements and testing in this area in order to integrate spectra for simulation tools [67]. Development in this area can enable circadian lighting simulations to be widely used and designers can benefit from this at early design stages.
c. The number of participants in this study was very limited. However, their working schedules and the age groups that they belong to are similar. Further studies that include larger number of participants with more variations in their conditions can be conducted to get more accurate results in user perspective regarding the integrative lighting system.
d. The study was conducted during late winter and early spring in Sweden due to time limitations. Results of this study can differ when conducted during darker periods (winter). Therefore, research that analyze the integrative lighting system in different seasons, especially in winter, is necessary to understand the integrative lighting system more.
e. It was found that the energy use of the integrative lighting system investigated in this study was not satisfying the benchmarks for the efficient or the standard lighting systems according to the European Standard EN 15193. Further studies are needed to design a similar system that can have a positive effect on occupant well-being but with lower energy use.

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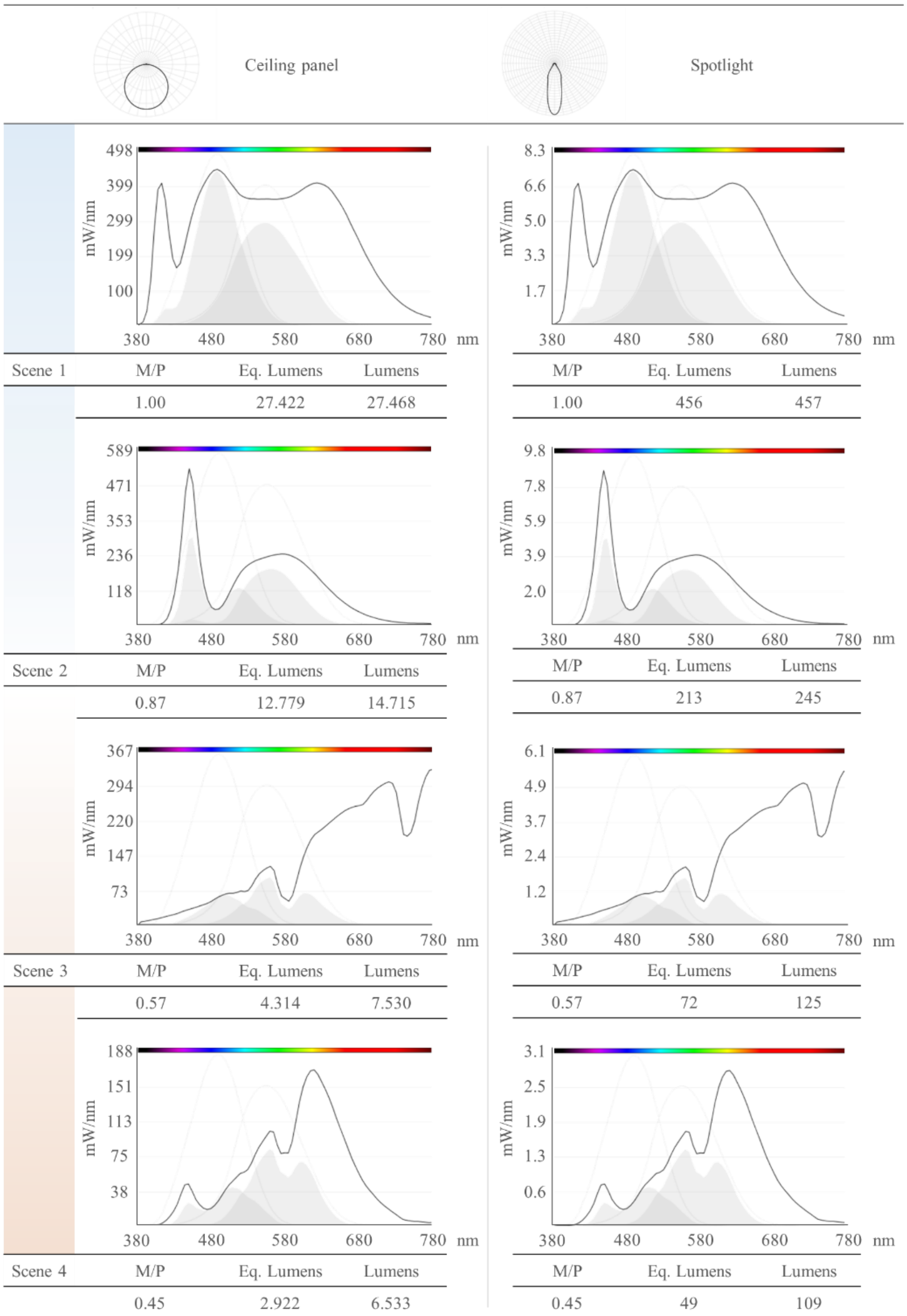
8 Appendix

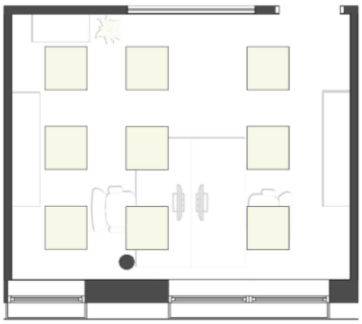
Photometry

Spectral power distribution of luminaires for each scene for ceiling panel and spotlight. From source spectrum library in ALFA.

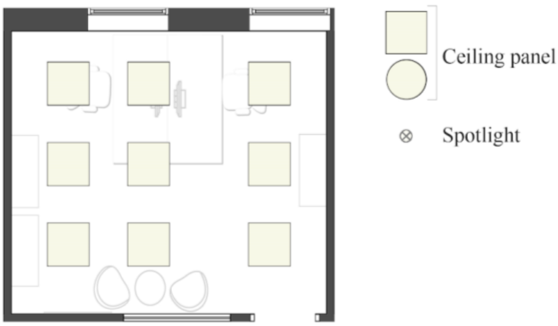


LightMove 4 sensor from Movisens

Luminaires distribution in the offices

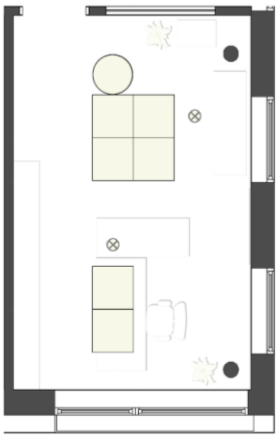


Participant_South_2 Windows



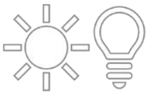
Participant_North_2 Windows

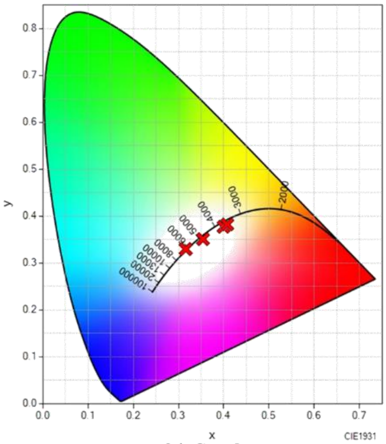
Participant_South_One Window

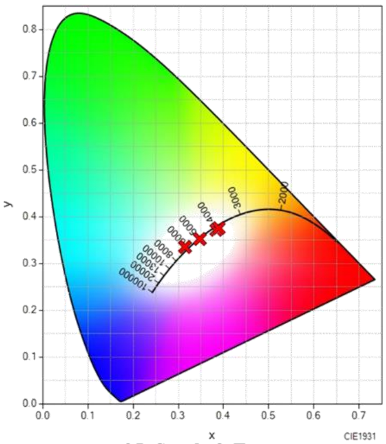


Participant_South&East_4 Windows

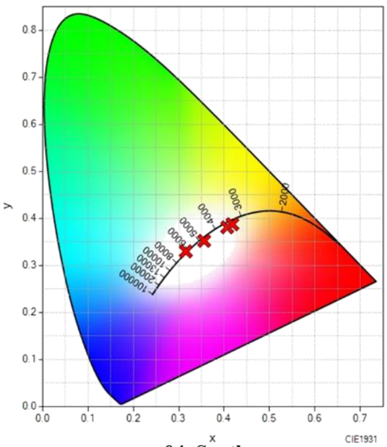
CCT values for each scene in the highest and lowest daylight intake offices:

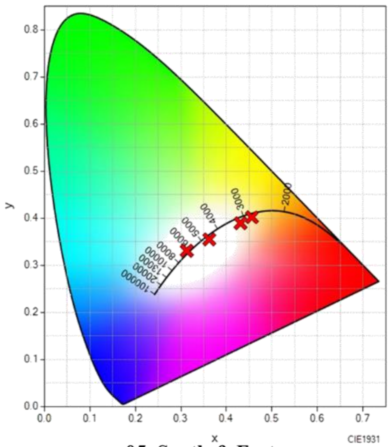






CCT / K	04_South (lowest daylight intake)	05_South & East (highest daylight intake)
Scene 1	6330	6362
Scene 2	4667	4914
Scene 3	3522	3868
Scene 4	3376	3760

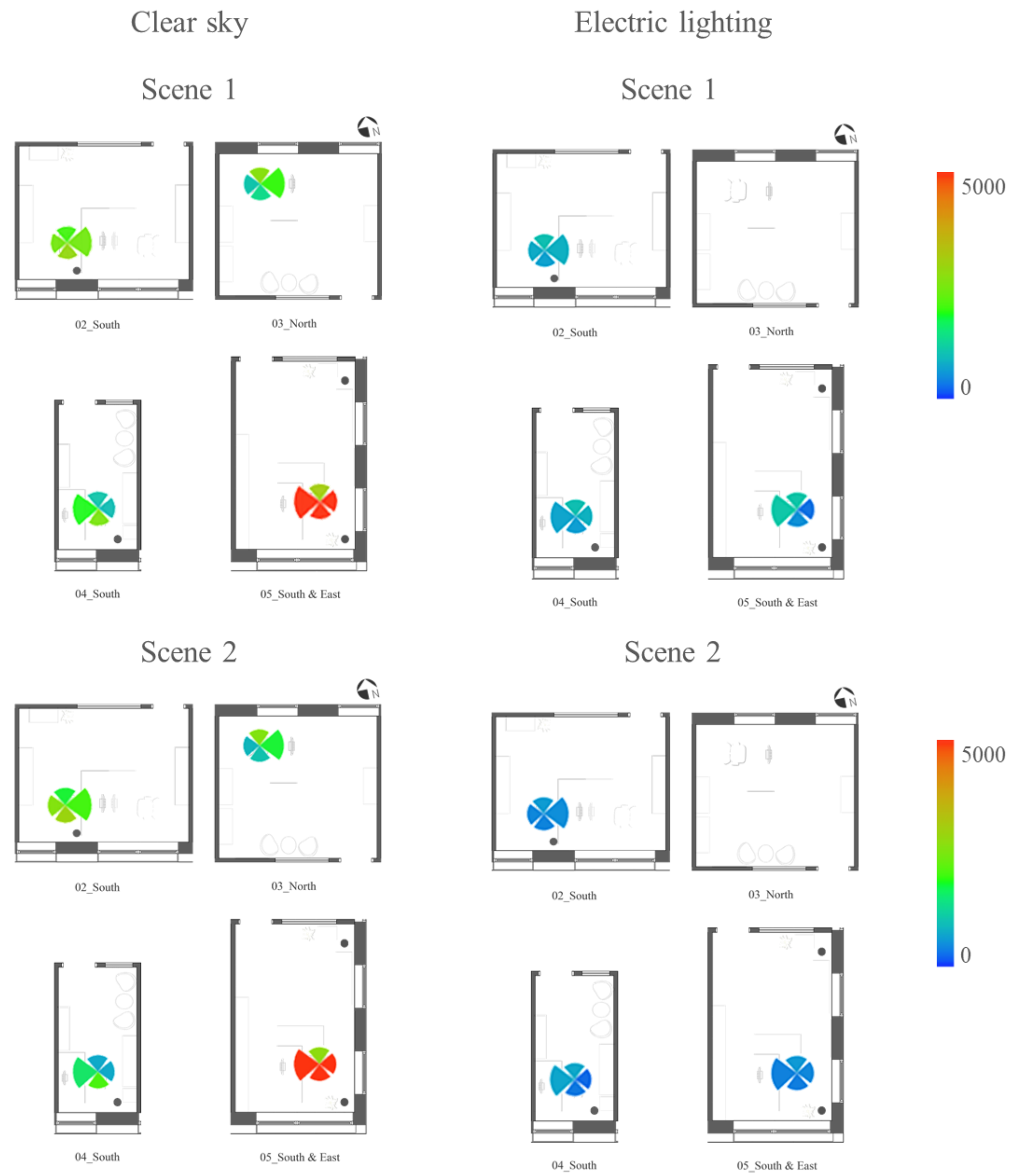


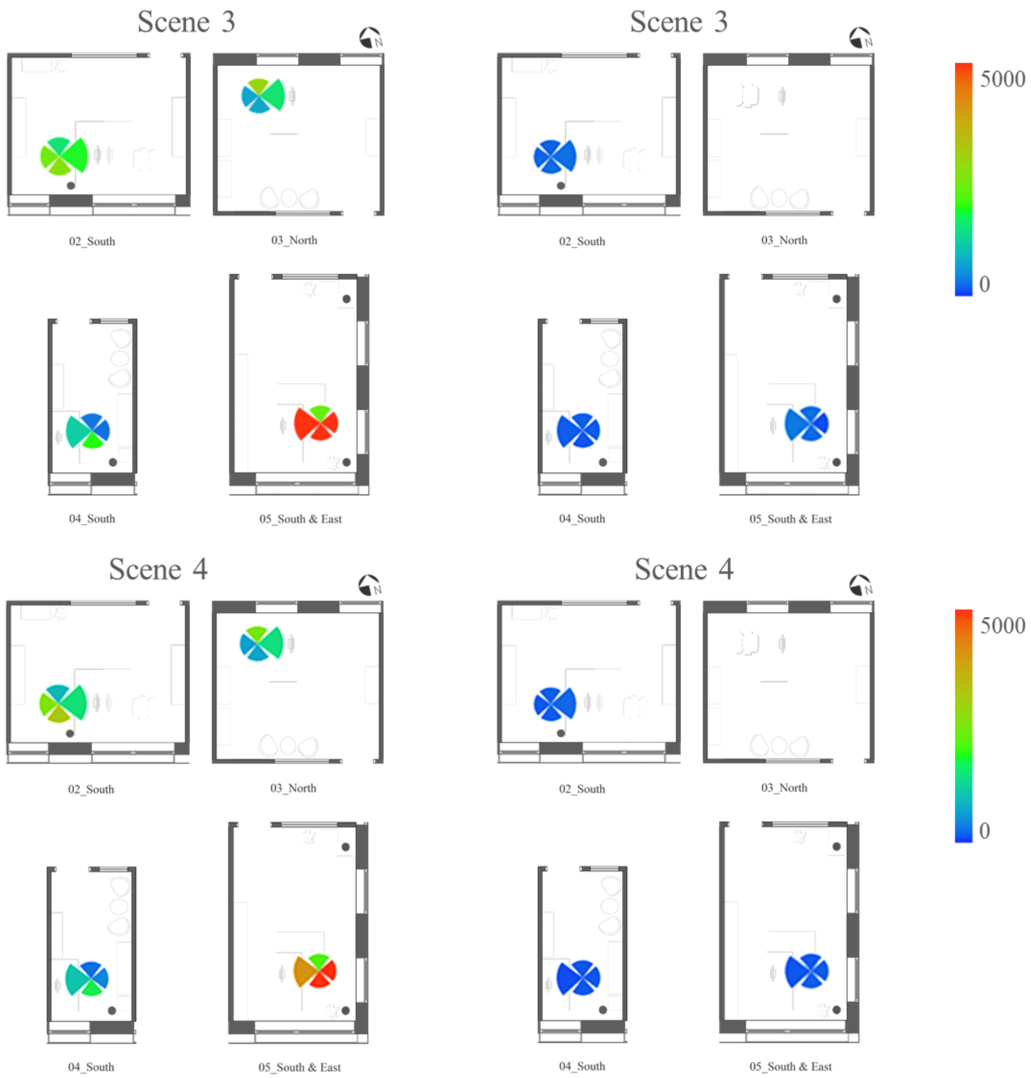


CCT / K	04_South (lowest daylight intake)	05_South & East (highest daylight intake)
Scene 1	6347	6482
Scene 2	4603	4401
Scene 3	3394	2983
Scene 4	3209	2691

Circadian Potential

Circadian lighting simulations in ALFA. Each lighting scene for four offices are presented under combination of electric lighting and clear sky and only electric lighting. Eye location and direction for simulations at each workstation is shown as enlarged. The unit for the results is EML and the scale is between 0 and 5 000.




Scene 3
02_South
03_North
04_South
05_South & East
Scene 3
02_South
03_North
04_South
05_South & East
5000
0
Scene 4
02_South
03_North
04_South
05_South & East
Scene 4
02_South
03_North
04_South
05_South & East
5000
0

User Perspective

Daily Questionnaires

Pittsburgh Sleep Quality Index (PSQI) , Karolinska Sleepiness Scale (KSS) and Subjective Vitality Scale (SVS) Questions.

* Required

1. PSQI 1. When did you go to bed last night? *

2. 2.How long (in minutes) has it taken you to fall asleep last night? *

3. 3.When did you get up this morning? *

4. 4.How many hours of actual sleep did you get last night? (This may be different than the number of hours you spend in bed) *

5. 5.You had trouble sleeping last night, because you... *

   Check all that apply.

   - [ ] Could not get to sleep within 30 minutes
   - [ ] Woke up in the middle of the night or early morning
   - [ ] Had to get up to use the bathroom
   - [ ] Could not breathe comfortably
   - [ ] Coughed or snored loudly
   - [ ] Felt too cold
   - [ ] Felt too hot
   - [ ] Had bad dreams
   - [ ] Had pain
   - [ ] Other reason(s)
   - [ ] I didn't have any trouble sleeping last night

6. 6.If you chose Other reason(s), please write down the reason.

7. 7.Did you have to take medicine to help you sleep last night? *

Mark only one oval.

- Yes
- No

8. 8.Did you have trouble staying awake while driving, eating meals or engaging in social activity yesterday? *

Mark only one oval.

- Yes
- No

9. 9.During yesterday, has it been a problem for you to keep up the enthusiasm to get things done? *

Mark only one oval.

- Yes
- No

10. 10. How would you rate your overall sleep quality last night? *

Mark only one oval.

- Very good
- Fairly good
- Fairly bad
- Very bad

11. KSS. 1. Please choose what describes the best your sleepiness for the last 10 minutes. *

Mark only one oval.

- Extremely alert
- Very alert
- Alert
- Rather alert
- Neither alert nor sleepy
- Some signs of sleepiness
- Sleepy, but no effort to keep awake
- Sleepy, some effort to keep awake
- Very sleepy, great effort to keep awake, fighting sleep

12. SVS 1. At this moment, I feel alive and vital. *

Mark only one oval.

	1	2	3	4	5	6	7	
not at all true								very true

13. 2. I don't feel very energetic right now. *

Mark only one oval.

	1	2	3	4	5	6	7	
not at all true								very true

14. 3. Currently, I feel so alive I just want to burst. *

Mark only one oval.

	1	2	3	4	5	6	7	
not at all true								very true

15. 4. At this time, I have energy and spirit. *

Mark only one oval.

	1	2	3	4	5	6	7	
not at all true	⬭	⬭	⬭	⬭	⬭	⬭	⬭	very true

16. 5. I am looking forward to each new day. *

Mark only one oval.

	1	2	3	4	5	6	7	
not at all true	⬭	⬭	⬭	⬭	⬭	⬭	⬭	very true

17. 6. At this moment, I feel alert and awake. *

Mark only one oval.

	1	2	3	4	5	6	7	
not at all true	⬭	⬭	⬭	⬭	⬭	⬭	⬭	very true

18. 7. I feel energized right now. *

Mark only one oval.

	1	2	3	4	5	6	7	
not at all true	⬭	⬭	⬭	⬭	⬭	⬭	⬭	very true

Short questionnaire adapted from MCTQ

Name: ____________________________

PERSONAL DATA

Age Interval: ☐ 20-29 ☐ 30-39 ☐ 40-49 ☐ 50-59 ☐ 60+

Sex: ☐ Female ☐ Male ☐ Prefer not to disclose ☐ _________ (fill in the blank)

SLEEP HABITS (WORKDAYS)

I usually go to bed around ☐ 20:00-22:00 ☐ 22:00-00:00 ☐ After 00:00 on workdays.

After going to bed, I fall asleep ☐ directly ☐ in short time ☐ in long time.

I usually wake up at ______ o'clock on workdays.

I set alarm clock on workdays: ☐ Yes ☐ No

If yes, I usually wake up before the alarm rings: ☐ Yes ☐ No

It is ☐ easy ☐ difficult to wake up.

SLEEP HABITS (WEEKENDS-FREE DAYS)

I usually go to bed around ☐ 20:00-22:00 ☐ 22:00-00:00 ☐ After 00:00 on weekends/free days.

After going to bed, I fall asleep ☐ directly ☐ in short time ☐ in long time.

I usually wake up at ______ o'clock on weekends/free days.

I set alarm clock on workdays: ☐ Yes ☐ No

If yes, I usually wake up before the alarm rings: ☐ Yes ☐ No

It is ☐ easy ☐ difficult to wake up.

There are certain reasons why I cannot freely choose my sleep times on free days: ☐ Yes ☐ No

If yes, the reason is (for example: kid(s), pet(s), hobbies, etc.):

____

WORK DETAILS

My usual work schedule starts at ______ o'clock, ends at ______ o'clock.

My work schedules are ☐ very flexible ☐ a little flexible ☐ rather inflexible ☐ very inflexible

Are there times that you work from home? ☐ Yes ☐ No

If yes, how often? _______

PHYSICAL ACTIVITY

Do you do any exercise? ☐ Yes ☐ No

If yes, how often? ☐ 2-3 times/week ☐ 1 time/week ☐ 2-3 times/month ☐ Less than 2-3 times/month

STIMULANTS

I regularly drink ☐ coffee ☐ tea ☐ caffeinated soft drinks ☐ none

General structure for the semi-structured interview

THEME	GENERAL GOAL	SPECIFIC GOALS
Behaviours	Characterization of the participants daily rhythm and routine	- Sleep - Activity - Use of space
Perception	Characterization of the general lighting system experience	- Satisfaction - Brightness - Glare - Side effect
Control System	Characterization of the manual control system and users' attitudes	- Users' preferences in automatic/manual controls - Use task lamp - Use of blinds

LUND UNIVERSITY

Dept of Architecture and Built Environment: Division of Energy and Building Design
Dept of Building and Environmental Technology: Divisions of Building Physics and Building Services