Optimization of Lightings in Commercial Premises

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Master's thesis

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(PROJECT, ARTWORK, ARTISTIC PERFORMANCE)

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1. **Make research on the bases of lighting and its evaluation.**
2. **Study lighting requirements in commercial buildings.**
3. **Design of lighting system in specific commercial surroundings and its experimental evaluation in Laboratory of lighting.**
4. **Make economic evaluation of the designed lighting system.**

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Bibliography:

1. **David L.D. et al. (2011): The Lighting Handbook – Reference and Application.**
2. **Suzi Pratt (2015): Natural versus Artificial Light: Which do you prefer working with?**
3. **Zbigniew Turlej Ph.D., Eng.: Elements of the Daily and Artificial Lighting in an Interior. Department of Light Technology and Optical Radiation, Electrotechnical Institute. Proceedings Of Electrotechnical Institute, Issue 251, 2011.**
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5. **Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association, Sydney, 14-16 November. Computer Tool to aid Natural and Artificial lighting integration in building design.**

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Zlín, 21 December 2018

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ABSTRAKT

Denní a umělé osvětlení v interiéru jsou klíčovými prvky, které formují vizuální prostředí a zdravotní aspekty. Velká pozornost je věnována umělému osvětlení, ale dúležitá část osvětlení je denní osvětlení. To je základem předmětné diplomové práce. Cílem je optimalizovat denní a umělé osvětlení. Diplomová práce se zabývá optimalizací denního a umělého osvětlení ve veřejných budovách nebo komerčních prostorách. Použitá metoda má na základě numerické simulace přírodního (denního) a umělého osvětlení umožňující posouzení požadované úrovně vnitřního osvětlení. Pro přirozené osvětlení byly zastínění oken, zatímco pro umělé osvětlení řízení úrovně osvětlení prováděno pomocí systémů řízení osvětlení systémem KNX. Pro účely této studie byla provedena měření na různých paracovních místech v laboratoři a použit otevřený software (Dialux Evo) k vytvoření numerických simulací osvětlení na pracovních místech s různě nastaveným zastíněním oken.

Klíčová slova: Osvětlení, Přirozené světlo, Umělé světlo, Optimalizace světla, Komerční prostory

ABSTRACT

The daily and artificial lighting in the interior are the key elements shaping the visual environment and health aspects. Much attention is given to artificial lightings, but because of the benefits of natural lights, there is the need to study their optimization. This is the basis of this study. In effect, the goal of this study is to optimize the natural and artificial lights. This Diploma Thesis presents the optimization of natural and artificial lightings in public buildings or commercial premises. The method applied was to have a detailed numerical simulation of natural (daylighting) and artificial (electric) lightings by allowing interior illumination levels assessment. For the natural light, vertical windows were considered, while for the artificial light, illumination was done using the KNX lighting control systems. For the purpose of this study, measurements were taken at various observation points in the Laboratory, and an open-source software (Dialux Evo) was used to produce numerical simulations at the observation points with the blinds set at various open positions, using the KNX lighting control systems.

Keywords: Lighting, Natural light, Artificial light, Light optimization, Commercial premises

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May God continue to bless you all, Amen.

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INTRODUCTION

General Background

The definition of light in current encyclopedias is predominantly limited to its physical explanation as the visible part of the electromagnetic spectrum. However, precisely speaking, our eyes cannot see a spectrum, it is rather the photoreceptors, i.e., rods and cones in the eyes which collect, decipher and transpose the emission or reflectance of electromagnetic waves in a specific range or photons into meaningful visual signals in our brain. However, light serves for much more than just vision in humans. Light exerts powerful non-visual effects on a wide range of biological functions and behavior [1].

Daylight (natural light) is the most sustainable source of light for building interiors [2]. Natural lighting can be thought of as available light, such as that produced by the sun or the moon. Artificial lighting is produced via another source, such as a studio strobe, Speedlight, LED light, your camera's pop-up flash, or even a streetlight or lamp [3]. The biggest benefits of using natural lighting is that it is free, abundant, and very easy to find.

The most common source of natural light on Earth is the Sun. We receive natural light throughout our sunlight hours, whether we want it or not. That is, we cannot control the amount, duration and intensity of the natural light. The light we obtain from the Sun covers the entire visible spectrum, with violet at one end and red at the other. This light is good for our health and is necessary for plants to carry out photosynthesis. Fire is another source of natural light. Natural light is full spectrum and dynamic. Full spectrum means that light contains all the colors of the rainbow. Dynamic means that the intensity and mix of colors change with the time of day. Natural light cycles from bright with a high blue content during the day to soft with a high red content in the evenings. The bright blue-rich light signals us to be awake and alert, while the soft red-rich light tells our bodies it's time to relax and prepare for sleep [4].

Artificial light is generated by artificial sources, such as incandescent lamps, compact flourescent lamps (CFLs), LEDs, etc. We can control the quality, quantity and duration of this light by controlling a number of factors. Artificial light is necessary for us to work during hours of low natural lighting (evening and/or night). The artificial light does not cover the entire light spectrum and is not too conducive to photosynthesis or health of life forms.

Problem Statement

The natural and artificial lightings in the interior are the key elements shaping the visual environment and health aspects. Much attention is given to artificial lightings, but because of the benefits of natural lights, there is the need to study their combination and optimization, most especially in commercial premises. This is the basis of this study, ***Optimization of Lightings in Commercial Premises***.

Objectives

The goal of this study is to optimize the natural and artificial lightings through the uniformity of their illuminances on the workspaces in commercial premises. The lighting system should uniformly illuminate the workspace so that an economic evaluation of the lighting system could be made.

Methodology

The method applied was to have a detailed numerical simulation of natural (daylighting) and artificial (electric) lightings by allowing interior illumination levels assessment. For the natural light, vertical windows were considered, while for the artificial light, illumination was done using the KNX lighting control systems. For the purpose of this study, measurements were taken at various observation points in the Laboratory, and an open-source software (Dialux Evo) was used to produce numerical simulations at the observation points with the blinds set at various open positions, using the KNX lighting control systems.

Limitations of the study

1. There were trees behind the windows of the Laboratory which could affect the intensity of natural light into the room.
2. Unstable readings by the measuring instrument due to the unstable intensity of natural light into the room as a result of the nature of the sky.

I THEORETICAL PART

1.0 Division of lighting of premises

The natural and artificial lightings have many interconnections which are important for energy efficiency and health demands. Special attention is paid for supplementation of daylight by artificial light. Energy efficiency of daylight requirements are explained on the basis of European Standards. The health factor in lighting is important in all buildings however it is especially critical in commercial buildings where people have unrestricted mobility.

1.1 Natural light (Daylight)

Natural light is light received on Earth from the Sun, either directly or after reflection from the Moon. The prime characteristic of natural light is its variability [8], [9]. Natural light varies in magnitude, spectral content, and distribution with different meteorological conditions, at different times of day and year, and at different latitudes. Daylight has two components: sunlight, where the source is the sun, and skylight, where the source is the sky. Sunlight is light received at the Earth's surface, directly from the sun. Sunlight produces strong, sharp-edged shadows. Skylight is light from the sun received at the Earth's surface after scattering in the atmosphere. It is this scattered light that gives the sky its blue appearance, as compared to the blackness of space. Skylight produces only weak, diffuse shadows. The balance between sunlight and skylight is determined by the nature of the atmosphere and the distance which the light passes through. The greater the amount of water vapour and the longer the distance, the higher is the proportion of skylight. The illuminances on the Earth's surface produced by daylight can cover a large range, from 150,000 lx on a sunny summer's day to 1,000 lx on a heavily overcast day in winter [10]. Several models exist for predicting daylight incident on a plane, at different locations, and for different atmospheric conditions. These models can be used to predict the contribution of daylight to the lighting of interiors. Figure 1 shows a spectral distribution of daylight. It is clear that daylight contain significant amounts of ultraviolet and infrared radiation and that, over the visible wavelengths, daylight is a continuous spectrum [7].

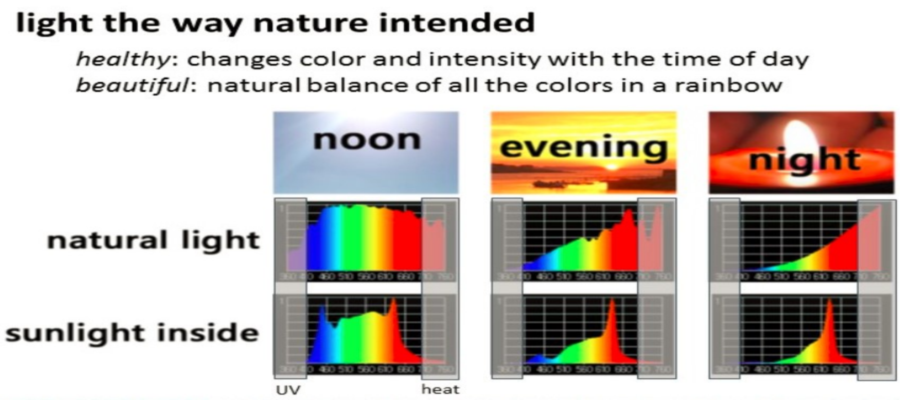
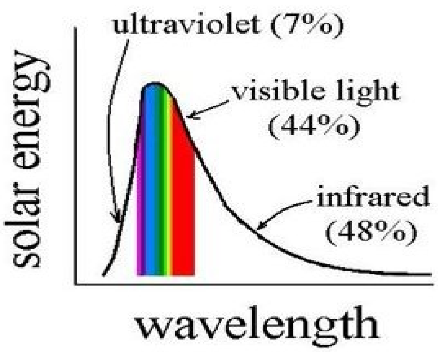


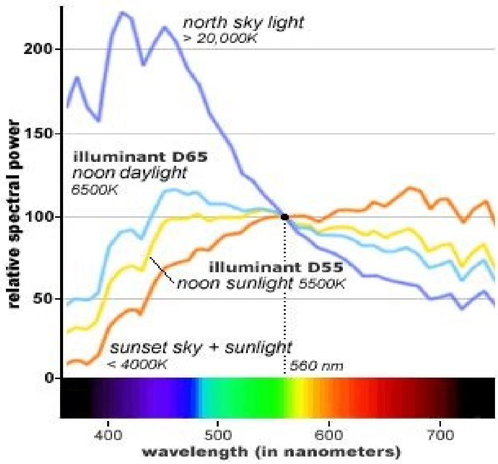
Fig. 1: *Natural light*

(*Source:* https://www.google.com/search?q=light+the+way+nature+intended&tbm=isch&source=univ&sa=X&ved=2ahUKEwja9fKG-qPiAhVQYlAKHQhRAmIQsAR6BAgHEAE&biw=1266&bih=562#imgdii= NjWgrUbAloFH2M:&imgrc=qZVk5QK1SzeF8M:)

Fig. 2: *The dynamic nature of natural light*



http://www.brighthub.com/environment/renewable-energy/articles/63714.aspx



https://www.handprint.com/HP/WCL/color1.html

Fig. 3: ***(a)*** *Full spectrum – All the colours of the rainbow UV + visible + heat (IR)* ***(b)*** *Dynamic – Intensity and colour changes with the time of the day*

The correlated color temperature of daylight can range from 4,000 K for an over cast day to 20,000K for clear blue sky, as shown below:

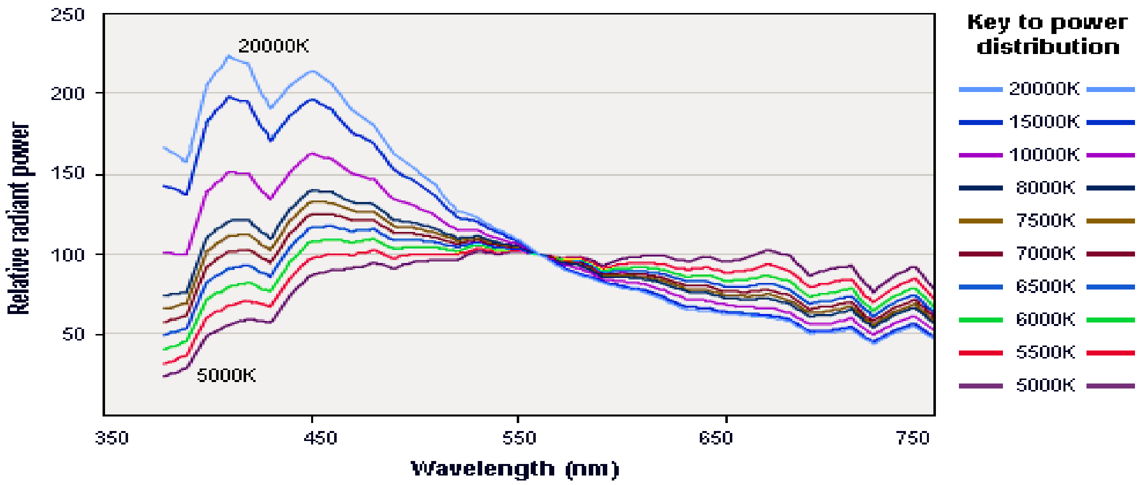


Fig. 4: *The correlated color temperature of daylight (Lighting Research Center, www.lrc.rpi.edu)*

In addition to the amount of daylight and its spectral power distribution, daylight varies in a luminance distribution over the sky. For sunlight, there are standard sky path diagrams to predict the position of a patch of skylight in a building for any specific window or skylight size, form, and orientation.

1.2 Artificial light

The first form of artificial lighting used by humans was firelight, created by the combustion of wood. Developments in basic technology lead to the creation of the oil lamp, the candle and, ultimately, the gas lamp, all of which depend on combustion of fuel. Oil lamps, candles, and gas lamps are sometimes used today, either through necessity or for the atmosphere they evoke. The lighting industry makes several thousand different types of electric lamps. The development of artificial light based on electric energy sources began at the end of the 19^{th} and early 20^{th} centuries. In developing artificial lights, the technological effort is aimed at producing light that will resemble natural daylight (sunlight). Artificial light is measured in two ways – the specific frequency range of the source and the strength of illumination, measured in lumens. Artificial light can be classified into three main sources, in accordance with its developmental generation and the technology that enabled its existence [22]:

i. **First generation** – bulbs based on heating of a wire filament (incandescent lamps) or an arc. A standard modern incandescent lamp is composed of a glass bulb containing a coil of metal wire, such as tungsten (W), in a vacuum. Incandescent lamps emit non-ionizing radiation in the visible light range and do not usually emit radiation in the ultraviolet (UV) range, except in extreme conditions of very high power. Additionally, this type of lamp also emits invisible infra-red non-ionizing radiation which is felt as heat.

Fig. 5: *Quality incandescent light bulb, after Edison*

ii. **Second Generation –** Gas discharge lamps. Fluorescent lighting is based on electric discharge of a gas (mercury) leading to emission of high-energy photons (usually UV), that impact the fluorescent coating of the bulb, producing visible light. The type of radiation emitted by fluorescent tubes and compact fluorescent lamps (CFL) includes, in addition to visible light, a small amount of UV radiation in the UVA range (315-380 nanometers), and even shorter wavelengths (higher energy) in the UVC range. Exposure to UV radiation from CFL lamps containing mercury may be reduced by distancing the lamps from the user by 30 cm or more.

Fig. 6: *Compact fluorescent lamp (CFL)*

iii. **Third generation –** Light-Emitting Diode (LED) lamps. A light-emitting diode (LED) consists of a semiconductor that has undergone doping. An electric current passing through the diode excites the atoms to high energies. When the atoms return to lower energy levels, energy in the form of photons in the visible light range is released. LED lamps emit visible light and do not emit UV radiation [7].

Display of LED and LCD screens

A variety of energy-saving LED lamps

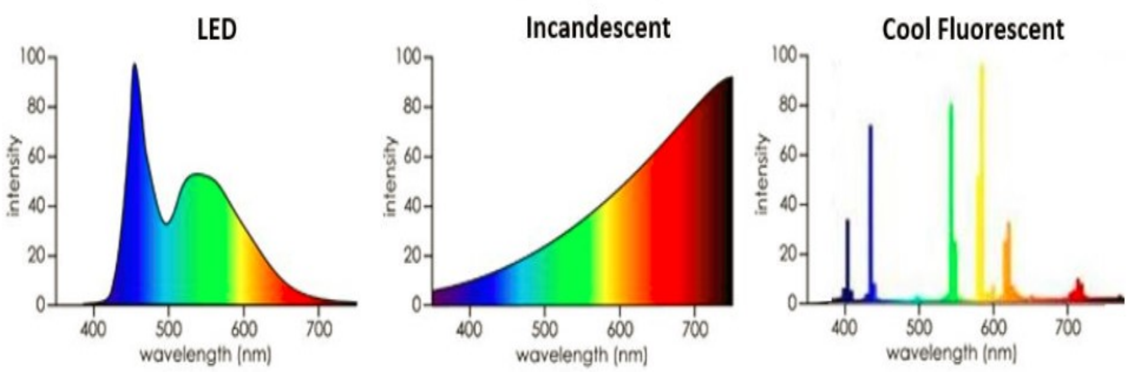
Sign illuminated by LED

Fig. 7: *Modern LED lamps*

*(Source:*https://www.tnuda.org.il/en/physics-radiation/infrared-visible-light-and-soft-ultraviolet-radiation-%E2%80%93-introduction/artificial#Light%20Emitting%20Diode% 20(LED)%20lamps)

Advantages of LED lamps

- High level of brightness and power
- High efficiency
- Use of low-voltage currents
- Low heat emission
- High reliability (physical stability)
- No UV radiation!
- Long lifetime
- Easily programmed and controlled as part of an electronic array (for example in computer and TV displays)



(a) (b) (c)

Fig. 8: *Spectral Power Distributions (SPDs) of different artificial light sources*

(Source: https://www.google.com/search?q=Spectral+Power+Distributions+(SPDs)+of+different+artificial+light+sources&tbm=isch&source=univ&sa=X&ved=2ahUKEwj77tH1-6PiAhUGU1AKHZn0DKAQsAR6BAgJEAE&biw=1266&bih=562)

Note that intensities are not the same for each source (sunset is much less intense than daylight) [4].

1.3 Combination of Natural and Artificial lights

1.3.1 General considerations

With reference to electric energy consumption, an ideal illumination system is the one designed to possibly supply the necessary light by using sunlight and skylight sources. This means that a strategy needs to be developed in such a way that artificial lights will illuminate the interior environment only at the points where the natural light is insufficient, while leaving to daylight the task of illuminating the other areas.

In order to optimize the lightings, the first step is to establish the horizontal illumination level that is a function of the planned tasks to be carried out inside the room.

After establishing the illumination level, the next step is the calculation of the artificial illumination required to supply that level, without recourse to the available natural light. This is to guarantee an artificial illumination system that is capable of performing efficiently at night time or during daytime when there is little availability of natural light.

It is noteworthy to state clearly that the illumination levels in one room lightened by a window usually present a distribution curve that has its biggest value at the surroundings of the plane of the window's opening, while the smallest value is usually near the opposing wall to the window. This is a fact that leads to a good strategy for efficient use of the natural light. It consists of dividing the interior environment in a certain number of segments that are parallel to the window (i.e. the source of natural light) and to associate each of segment to a corresponding electric circuit responsible to turn on and off the light fixtures inside it.

1.3.2 Terms and Definitions

Visual Task: Visual elements of the work being done. Note that the main visual elements are the size of the structure, its luminance, its contrast against the background and its duration.

Task Area: Partial area in the work place in which the visual task is carried out. For places where the size and/or location of the task area is unknown, the area where the task may occur shall be taken as the task area.

Immediate surrounding area: A band with a width of at least 0.5 m surrounding the task area within the field of vision.

Luminous flux *or* ***luminous power:*** This is a measure of the perceived power of light or a measure of the total quantity of visible light emitted by a source. S.I unit is lumen (lm).

Luminous intensity: This is a measure of the light power emitted by a light source in a particular direction per unit solid angle. S.I. unit is candela (cd).

Illuminance or luminous emittance: This is the total luminous flux incident on a surface per unit area. It is a measure of how much the incident light illuminates the surface. S.I. unit is lux (lx). It is equal to one lumen per square metre.

Built-in luminaires: This is the fixed luminaires installed to provide illumination in the building.

Control gear: Components required to control the operation of the lamp(s).

Luminaire power (P_i): Electrical power from the mains supply consumed by the lamp(s), control gear and control circuit in or associated with the luminaire, measured in watts which includes any parasitic power when the luminaire is turned on. Note that the rated luminaire power (P_i) for a specific luminaire may be obtained from the luminaire manufacturer.

Total installed lighting power in the room or zone (P_n): Power of all luminaires in the room or zone, measured in Watts.

$$P_n = \sum_i P_i \text{ [W]} \tag{1.1}$$

Total energy used for lighting (W_t): Energy consumed in period *t*, by the luminaires when operating, and parasitic loads when the luminaires are not operating, in a room or zone, measured in kWh.

Energy consumption used for illumination (WL,t): Energy consumed in period *t*, by the luminaires to fulfil the illumination function and purpose in the building, measured in kWh.

2.0 Basic illuminance parameters of lighting

2.1 Natural lighting

2.1.1 Description

Illumination is produced naturally, by the sun, and artificially, by oil and gas flames and electric light sources. The development and growth in use of artificial sources of light over the last century has fundamentally changed the pattern of life for millions of people on Earth [7].

2.1.2 Parameters

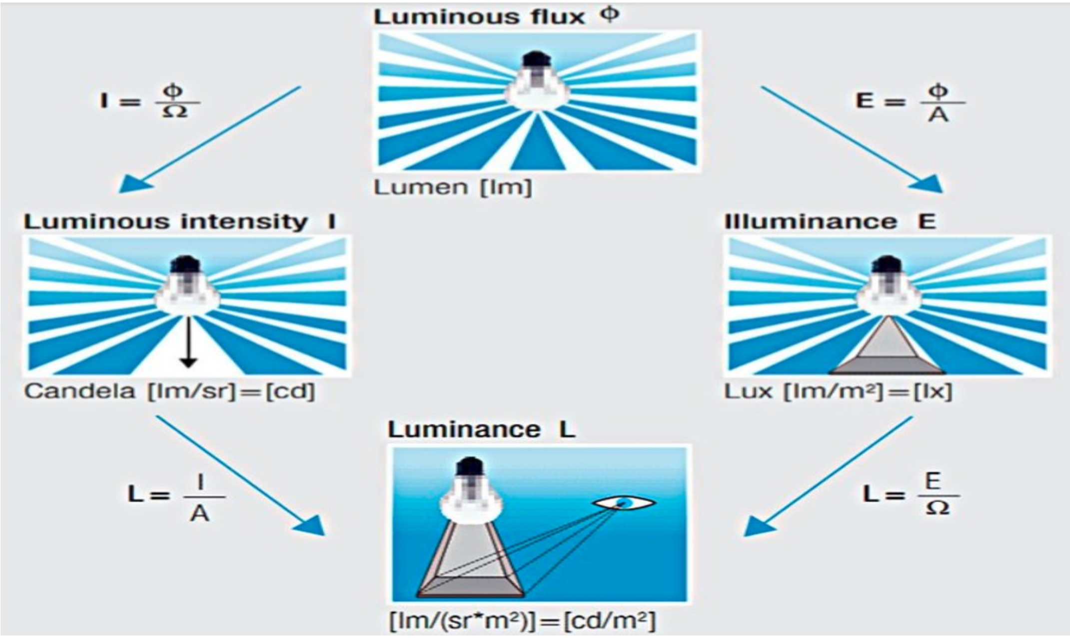


Fig. 9: *Basic parameters of light sources*

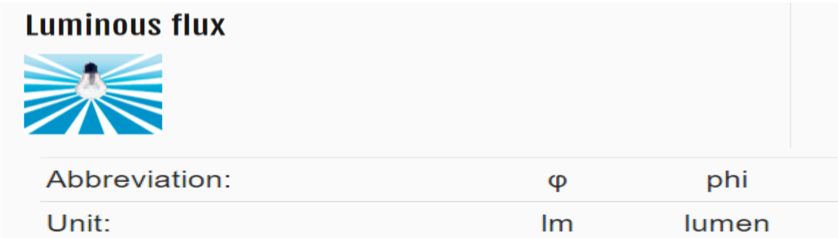


Fig. 10: *Luminous flux*

The luminous flux describes the quantity of light emitted by a light source. The luminous efficiency is the ratio of the luminous flux to the electrical power consumed (lm/W). It is a measure of a lamp's economic efficiency [13].

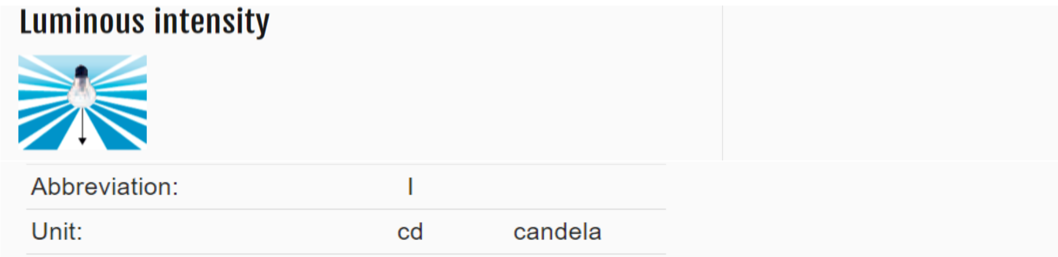
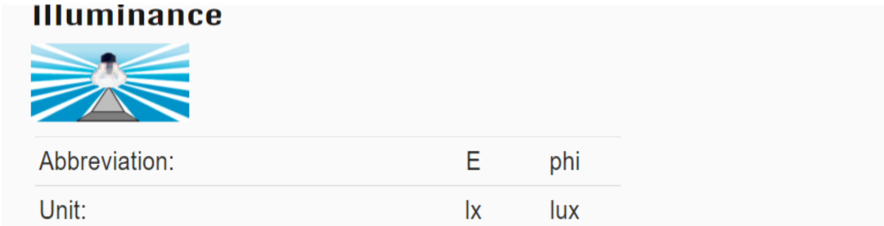


Fig. 11: *Luminous intensity*

The luminous intensity describes the quantity of light that is radiated in a particular direction. This is a useful measurement for directive lighting elements such as reflectors. It is represented by the luminous intensity distribution curve (LDC).



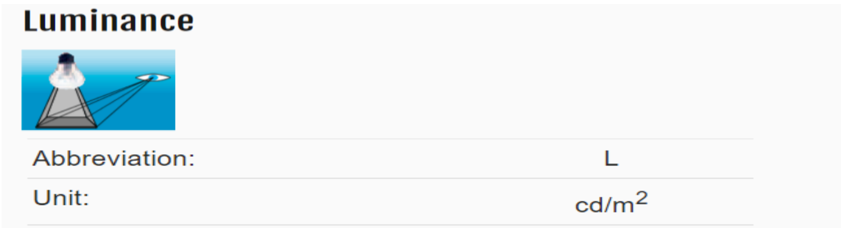
Illuminance

Abbreviation:	E	phi
Unit:	lx	lux

Fig. 12: *Illuminance*

Illuminance describes the quantity of luminous flux falling on a surface. It decreases by the square of the distance (inverse square law). Relevant standards specify the required illuminance (e.g. EN 12464 “Lighting of indoor work-places”).

Illuminance: E(lx) = luminous flux (lm) / area (m2)



Luminance

Abbreviation:	L
Unit:	cd/m^2

Fig. 13: *Luminance*

The luminance is the only basic lighting parameter that is perceived by the eye. It specifies the brightness of a surface and is essentially dependent on its reflectance (finish and colour) [13].

2.1.3 Calculation of lighting energy in buildings

Calculation methods

i. Quick method

When using the quick method of estimation of the annual lighting energy estimation for typical building types, the equation:

$$W = W\mathrm{L} + W\mathrm{P} \text{ [kWh/year]} \qquad (1.2)$$

shall be used.

Note: 1. The energy requirement estimation by the Quick method will yield higher *LENI* values than that obtained by the more accurate Comprehensive method.

2. The default values for t_D, t_N, F_c, F_D, F_O and W_p are given in Annexes E, F and G in EN15193-1 standard.

ii. Comprehensive method

The comprehensive method allows for a more accurate determination of the lighting energy estimations for different periods e.g. annual or monthly. When using the comprehensive method of lighting energy estimations, the equation:

$$W_t = W_{L,t} + W_{P,t} \text{ [kWh]} \quad (1.3)$$

shall be used for the required period *t*.

Note: 1. Determination of the daylight dependency factor (F_D) for a room or zone is described in Annex C of EN15193-1 standard.

2. Determination of the occupancy dependency factor (F_O) for a room or zone is described in Annex D of EN15193-1 standard.
3. This method may be used for any periods and for any locations provided that the full estimation of occupancy and daylight availability is predicted.

2.1.4 Determination of the daylight dependency factor FD,n

The determination of the daylight dependency factor $F_{D,n}$ for the nth room or zone should be made for annual and monthly time period. The daylight dependency factor $F_{D,n}$ for room or zone in the building is determined as a function of the daylight supply factor $F_{D,S,n}$ and the daylight dependent electric lighting control factor $F_{D,C,n}$ and given by

$$F_{D,n} = 1 - (F_{D,S,n} \bullet F_{D,C,n}) \quad (1.4)$$

where:

- $F_{D,S,n}$ is the daylight supply factor that takes into account the general daylight supply in the zone n. It represents, for the considered time interval, the contribution of daylight to the total required illuminance in the considered zone n.
- $F_{D,C,n}$ is the daylight control factor that accounts for the daylight depending electric lighting control system's ability to exploit the daylight supply in the considered zone n.

Note: 1. $F_{D,n}$ can be determined for any time period (annual, monthly or hourly). The factor has to be adjusted according to the period of the operation time at daytime t_D.

2. Other daylight supply systems that rely on enhancements to increase or make possible daylight penetration beyond the perimeter zones are available and may be calculated by using daylight factors or other methods for the calculation of F_D.
3. In zones without daylight availability, $F_D = 1$.

Lower electricity consumption and operating expenses would be achieved with the installation of modern LED lamps that have long useful lives.

2.2 Artifical lighting

2.2.1 Description

Artificial light, as opposed to natural light, refers to any light source that is produced by electrical means. Artificial lighting has many different applications and is used both in home and commercially. Artificial lights are available in a wide variety of shapes, sizes, colors of light emitted, and levels of brightness. The use of artificial lighting is crucial in agriculture and gardening, particularly in indoor cultivation.

2.2.2 Parameters

Maintained Illuminance (E_m): Value below which the average illuminance on the specified surface is not allowed to fall. *Note that it is the average illuminance at the time maintenance should be carried out.*

$$E_m = Avg(E_t) = \frac{\Sigma(E_t)}{n} \tag{1.5}$$

Illuminance Uniformity (U_o): Ratio of minimum illuminance to average illuminance on a surface.

$$U_o = \frac{E_{min}}{E_{avg}} \tag{1.6}$$

Unified Glare Rating (UGR-)

UGR (Unified Glare Rating) is a method of calculating glare from luminaires, light through windows and bright light sources.

The UGR rating helps to determine how likely a luminaire is to cause discomfort to those around it. For example, the discomfort that a LED Panel will cause the workforce within an office. This classification ranges from 5 to 40, with low numbers indicating low glare. UGR is calculated by using an equation which takes into account a number of factors that may contribute to glare caused by a luminaire, such as the angle of the luminaire, the likelihood of glare and the luminance value (lumen output), as shown below:

$$UGR = 8\log_{10}\left(\frac{0{,}25}{L_b}\sum\frac{L^2\omega}{p^2}\right) \quad (1.7)$$

where:

- L_b is the background luminance in cd x m^{-2}, calculated as E_{ind} x π^{-1}, in which E_{ind} is the vertical indirect illuminance at the observer's eye,
- L is the luminance of the luminous parts of each luminaire in the direction of the observer's eye in cd x m^{-2},
- ω is the solid angle (steradian) of the luminous parts of each luminaire at the observer's eye,
- p is the Guth position index for each individual luminaire which relates to its displacement from the line of sight.

***Note*:**

1. The variations of UGR within the room may be determined using the formula (or the comprehensive table) for different observer positions. Limits for this condition are under consideration.
2. If the maximum UGR value in the room is higher than the UGR limit, information on appropriate positions for work stations within the room may be needed.
3. Discomfort glare from windows is still a topic of research. There is currently no suitable glare rating method available.

Colour rendering index (R_a)

An important parameter of the light source is a general color rendering index R_a and termed also CRI (Color Rendering Index). The color rendering index numerically expresses the degree of conformity of color perception of objects illuminated, contemplated illumination and color perception of objects illuminated contracting illumination source under specified conditions. Human vision and his ability to recognize colors during human evolution to adapt to daylight and so light. Temperature light sources such as. Bulb. Therefore, these sources color rendering index of 100, which means that there is no distortion.

Specific power (Luminous Efficiency)

Specific power, or else luminous efficiency resources, is one of the most important indicators of the quality of the light source. It expresses the efficiency of conversion of electrical energy into light. The unit is lumens per watt [lm.W-1]. Specific performance in different types of light sources are constantly being improved. Especially in LED lighting was at this parameter in recent years seen a lot of progress. The picture below shows the historical development of specific performance for basic lighting groups [34].

Tab. 1: *Specific power basic lighting groups [34]*

Light source	Luminous efficiency [lm.W-1]
ordinary light bulbs	10-18
halogen bulbs	20-30
mixed lamps	20-28
High-pressure mercury lamp	40-60
compact bulbs	40-87
induction lamps	60-97
linear fluorescent lamps	50-104
Metal halide lamps	50-130
High-pressure sodium lamps	70-150
Light emitting diodes (LEDs)	60-160
Low pressure sodium lamps	100-200

2.3 Combined lighting

2.3.1 Description

The natural and artificial lighting have many interconnections which are important for energy efficiency and health demands. The amount of artificial necessary to give an ideal balance of brightness between those areas lit by daylight and those served by artificial light is in proportion to amount of exterior daylight. It is also dependent on distribution of daylight in the room and on the amount of unobstructed sky that can be seen. Another factor which is important is the spectral quality of the light used to supplement daylight, although it is not essential for the supplementary light to match exactly the color of natural daylight. The natural light itself varies very much in its spectral content quality through the day. One advantage of supplementary artificial light is that it allows more freedom in the design of windows and relieves the designer of the necessity to provide high daylight factors at the back of the room [7].

Nevertheless, the design of the windows requires careful consideration to reduce the area of the sky visible to the eye from inside the room, to limit the brightness of surfaces and provide good distribution of daylight without necessarily providing maximum penetration to the back of the room. A minor, but not negligible factor is the effect of the supplementary lighting on dull days. Again limited experience suggests that when the average brightness of the sky falls below 1000 cd/m2 the need is likely to be felt to switch on the normal night-time lighting. This leads to the problem of reconciling the requirements for supplementing the daylight and requirements for artificial lighting at night-time. There are two possibilities [7]:

- an independent system, which may give lighting of an entirely different character, or
- some modification of the supplementary system.

Which of the two methods is most appropriate in given circumstances will depend to some extent on the distribution direction, and color of the light from the supplementary system.

2.3.2 Parameters

Luminous environment

For good lighting practice it is essential that in addition to the required illuminance, qualitative and quantitative needs are satisfied. Lighting requirements are determined by the satisfaction of three basic human needs:

- Visual comfort, where the workers have a feeling of well-being; in an indirect way also contributing to a high productivity level,
- Visual performance, where the workers are able to perform their visual tasks, even under difficult circumstances and during longer periods,
- Safety.

Main parameters determining the luminous environment are:

- Luminance distribution,
- Illuminance,
- Glare,
- Directionality of light,
- Colour rendering and colour appearance of the light,
- Flicker,
- Daylight.

Luminance distribution

The luminance distribution in the field of view controls the adaptation level of the eyes which affects task visibility. A well balanced adaptation luminance is needed to increase:

- Visual acuity (sharpness of vision),
- Contrast sensitivity (discrimination of small relative luminance differences)
- Efficiency of the ocular functions (such as accommodation, convergence, pupillary contraction, eye movements etc.).

The luminance distribution in the field of view also affects visual comfort. The following should be avoided for the reasons given:

- Too high luminances which may give rise to glare,
- Too high luminance contrasts which will cause fatigue because of constant re-adaptation of the eyes,
- Too low luminances and too low luminance contrasts which result in a dull and non-stimulating working environment.

The luminances of all surfaces are important and will be determined by the reflectance and the illuminance on the surfaces. Ranges of useful reflectances for the major interior surfaces are:

- Ceiling: 0,6 to 0,9
- Walls: 0,3 to 0,8
- Working planes: 0,2 to 0,6
- Floor: 0,1 to 0,5

Illuminance

The illuminance and its distribution on the task area and the surrounding area have a great impact on how quickly, safely and comfortably a person perceives and carries out the visual task. All values of illuminances are maintained illuminances and will provide for visual comfort and performance needs.

i. Recommended illuminances at the task area

The value of illuminance may be adjusted by at least one step in the scale of illuminances (see below), if the visual conditions differ from the normal assumptions. A factor of approximately 1.5 represents the smallest significant difference in subjective effect of illuminance. In normal lighting conditions approximately 20 lx is required to just discern features of the human face and is the lowest value taken for the scale of illuminances. The recommended scale of illuminance (in lx) is:

20 - 30 - 50 - 75 - 100 - 150 - 200 - 300 - 500 - 750 - 1000 - 1500 - 2000 - 3000 - 5000

The required maintained illuminance should be increased, when:

- Visual work is critical,
- Errors are costly to rectify,
- Accuracy or higher productivity is of great importance,
- The visual capacity of the worker is below normal,
- Task details are of unusually small size or low contrast,
- The task is undertaken for an unusually long time.

The required maintained illuminance may be decreased when:

- Task details are of an unusually large size or high contrast,
- The task is undertaken for an unusually short time.

In continuously occupied areas, the maintained illuminance shall not be less than 200 lx.

ii. Illuminances of immediate surroundings

The illuminance of immediate surrounding areas shall be related to the illuminance of the task area and should provide a well-balanced luminance distribution in the field of view. Large spatial variations in illuminances around the task area may lead to visual stress and discomfort. The illuminance of the immediate surrounding areas may be lower than the task illuminance but shall not be less than the values given in Table 2 below:

Table 2 — Uniformities and relationship of illuminances of immediate surrounding areas to task area

Task illuminance lx	Illuminance of immediate surrounding areas lx
≥ 750 500 300 ≤ 200	500 300 200 E_{task}
Uniformity: ≥ 0,7	Uniformity: ≥ 0,5

In addition to the task illuminance the lighting shall provide adequate adaptation luminance in accordance with the standard recommendations.

iii. Uniformity

The task area shall be illuminated as uniformly as possible. The uniformity (U_o) of the task area and the immediate surrounding areas shall not be less than the values given in the Table above.

iv. Glare

Glare is the sensation produced by bright areas within the field of view and may be experienced either as discomfort glare or disability glare. Glare caused by reflections in specular surfaces is usually known as veiling reflections or reflected glare. It is important to limit the glare to avoid errors, fatigue and accidents. In interior work places, discomfort glare may arise directly from bright luminaires or windows. If discomfort glare limits are met, disability glare is not usually a major problem.

Note: Special care is needed to avoid glare when the direction of view is above horizontal.

a. Discomfort glare

The rating of discomfort glare directly from the luminaires of an indoor lighting installation shall be determined using the CIE **Unified Glare Rating (UGR-)** tabular method, based on the formula:

$$UGR = 8\log_{10}\left(\frac{0{,}25}{L_b}\sum\frac{L^2\omega}{p^2}\right) \qquad (1.8)$$

There are a number of different UGR limits that should not be exceeded in certain environments, these include:

UGR Rating	Environment
UGR ≤ 16	Technical drawing
UGR ≤ 19	Reading, writing, training, meetings, computer-based work
UGR ≤ 22	Craft and light industries
UGR ≤ 25	Heavy industry

UGR Rating	Environment
UGR ≤ 28	Railway platforms, foyers

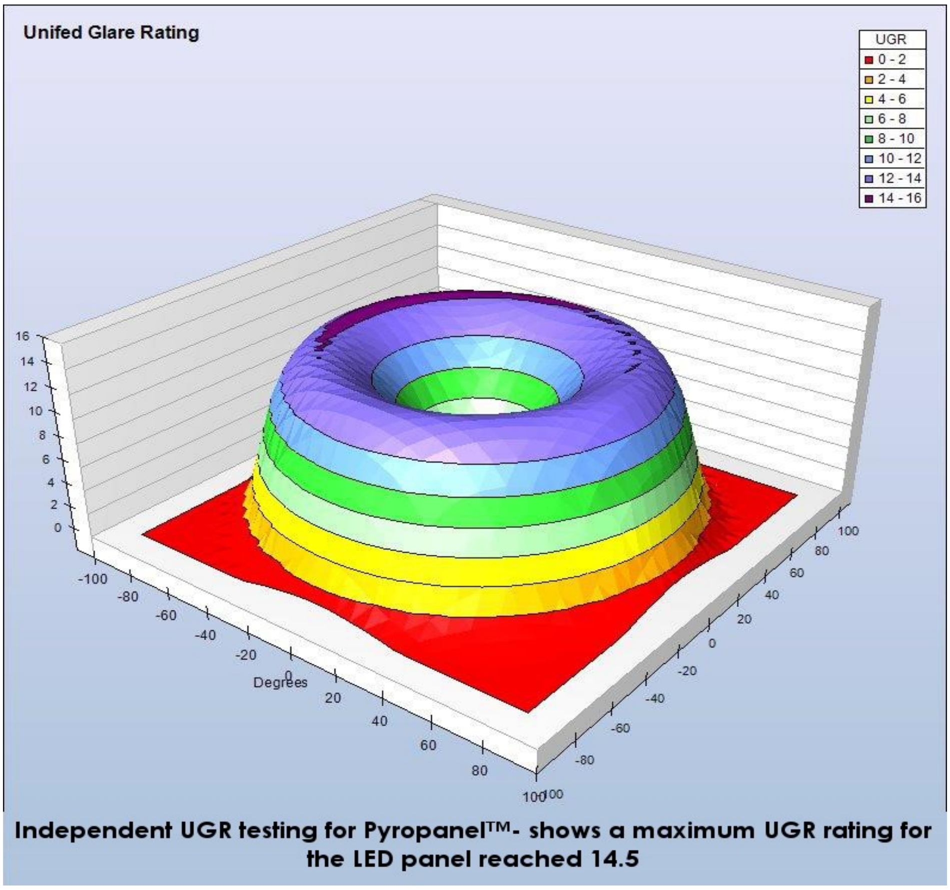


Fig. 14: Unified Glare Rating (http://www.northgatelighting.co.uk/what-is-ugr/)

b. Shielding against glare

Bright light sources can cause glare and can impair the vision of objects. It shall be avoided for example by suitable shielding of lamps or shading of windows by blinds. The minimum shielding angles given in Table 3 below shall be applied for the specified lamp luminance.

Note: The values given in Table 3 do not apply to uplighters or to luminaires mounted below normal eye level.

Table 3 — Minimum shielding angles at specified lamp luminance

Lamp luminance $kcd \times m^{-2}$	Minimum shielding angle
20 to < 50	15°
50 to < 500	20°
≥ 500	30°

c. Veiling reflections and reflected glare

High brightness reflections in the visual task may alter task visibility, usually detrimentally. Veiling reflections and reflected glare may be prevented or reduced by the following measures:

- Arrangement of luminaires and work places,
- Surface finish (matt surfaces),
- Luminance restriction of luminaires,
- Increased luminous area of the luminaire,
- Bright ceiling and bright walls.

v. Directional lighting

Directional lighting may be used to highlight objects, reveal texture and improve the appearance of people within the space. This is described by the term "modelling". Directional lighting of a visual task may also affect its visibility.

a. Modelling

Modelling is the balance between diffuse and directional light. It is a valid criterion of lighting quality in virtually all types of interiors. The general appearance of an interior is enhanced when its structural features, the people and objects within it are lit so that form and texture are revealed clearly and pleasingly. This occurs when the light comes predominantly from one direction; the shadows so essential to good modelling are then formed without confusion. The lighting should not be too directional or it will produce harsh shadows, neither should it be too diffuse or the modelling effect will be lost entirely, resulting in a very dull luminous environment.

b. Directional lighting of visual tasks

Lighting from a specific direction may reveal details within a visual task, increasing their visibility and making the task easier to perform. Veiling reflections and reflected glare should be avoided.

vi. Colour aspects

The colour qualities of a near-white lamp are characterised by two attributes:

- The colour appearance of the lamp itself,
- Its colour rendering capabilities, which affect the colour appearance of objects and persons illuminated by the lamp.

These two attributes shall be considered separately.

a. Colour appearance

The "colour appearance" of a lamp refers to the apparent colour (chromaticity) of the light emitted. It is quantified by its correlated colour temperature (TCP). Colour appearance may also be described as in Table 4.

Table 4 — Lamp colour appearance groups

Colour appearance	Correlated colour temperature T_{CP} K
Warm	below 3300 K
Intermediate	3300 to 5300 K
Cool	above 5300 K

The choice of colour appearance is a matter of psychology, aesthetics and of what is considered to be natural. The choice will depend on illuminance level, colours of the room and furniture, surrounding climate and the application. In warm climates generally a cooler light colour appearance is preferred, whereas in cold climates a warmer light colour appearance is preferred.

b. Colour rendering

It is important for visual performance and the feeling of comfort and well-being, that colours in the environment, of objects and of human skin are rendered naturally, correctly and in a way that makes people look attractive and healthy. To provide an objective indication of the colour rendering properties of a light source the general **colour rendering**

index (R_a) has been introduced. The maximum value of R_a is 100. This figure decreases with decreasing colour rendering quality. Lamps with a colour rendering index lower than 80 should not be used in interiors where people work or stay for longer periods. Exceptions may apply for some places and/or activities (e.g. high-bay lighting), but suitable measures shall be taken to ensure lighting with higher colour rendering at fixed continually occupied work places and where safety colours have to be recognised.

vii. Flicker and stroboscopic effects

Flicker causes distraction and may give rise to physiological effects such as headaches. Stroboscopic effects can lead to dangerous situations by changing the perceived motion of rotating or reciprocating machinery. Lighting systems should be designed to avoid flicker and stroboscopic effects.

Note: This can usually be achieved for example by use of DC electrical supply for incandescent lamps, or by operating incandescent or discharge lamps at high frequencies (around 30 kHz).

viii. Maintenance factor

The lighting scheme should be designed with an overall maintenance factor calculated for the selected lighting equipment, space environment and specified maintenance schedule. The recommended illuminance for each task is given as maintained illuminance. The maintenance factor depends on the maintenance characteristics of the lamp and control gear, the luminaire, the environment and the maintenance programme.

The designer shall:

- State the maintenance factor and list all assumptions made in the derivation of the value,
- Specify lighting equipment suitable for the application environment,
- Prepare a comprehensive maintenance schedule to include frequency of lamp replacement, luminaire and room cleaning intervals and cleaning method.

ix. Energy considerations

A lighting installation should meet the lighting requirements of a particular space without waste of energy. However, it is important not to compromise the visual aspects of a lighting installation simply to reduce energy consumption. This requires the consideration of appropriate lighting systems, equipment, controls and the use of available daylight.

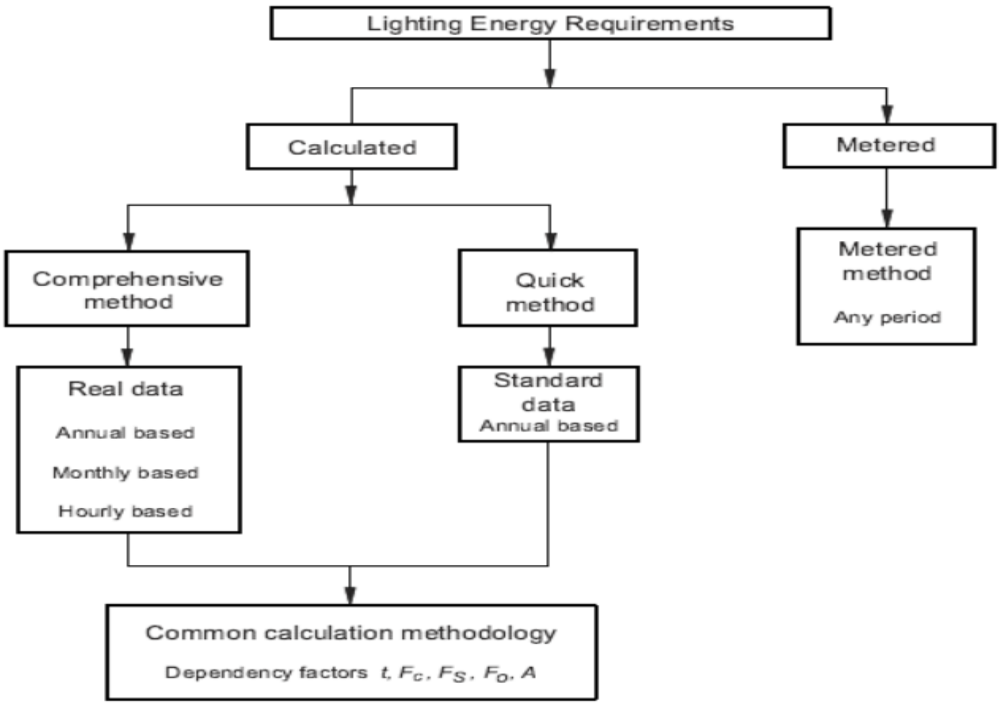


Fig. 15: *Flowchart illustrating alternative routes to determine energy use [36].*

3.0 Requirements

The following is a sample of the parameter requirements for indoor lighting as spelt out in the CSN EN_12464-1 (2012) Engineering Standard: Light and lighting – Lighting of work places – Part1: Indoor work places (page 29):

Table 5: Administrative Offices (*Table 5.26 in EN_12464-1(2012)*)

Ref. No.	Type of interior, task or activity	E_m lx	UGR_L -	U_o -	R_a -	Remarks
5.26.1	Filing, copying, etc.	300	19	0.4	80	
5.26.2	Writing, typing, reading, data processing	500	19	0.6	80	For display operations, see 4.9
5.26.3	Technical drawing	750	16	0.7	80	
5.26.4	CAD work stations	500	19	0.6	80	For display operations, see 4.9
5.26.5	Conference and meeting rooms	500	19	0.6	80	Lighting should be controllable
5.26.6	Reception desk	300	22	0.6	80	
5.26.7	Archives	200	25	0.4	80	

4.0 Methods of evaluation

4.1 Measurement

Measuring instruments

The data capture methodology employed in this study are measurement and simulation/computation. The Instruments used are: AHLBORN ALMEMO 2390-8 with V-Lambda Stralung - Typ: FL A623-VL (used for the measurements), with a measuring range of 0 to 20,000 lux intensity measuring indoor lighting. Probes have an accuracy of 5% of the measured value.

The DIALux Evo software was used to compute the illuminance based on the following inputs, namely; the date, time and nature of the sky as at the time the measurement was taken.

Fig. 16*:* *Device ALMEMO ALMEMO 2390-8*

4.2 Simulation – calculation methods

Simulation in DiaLux Evo

The open-source software (Dialux Evo) was used to produce numerical simulations at the observation points with the blinds set at particular positions to allow an even distribution of natural light into the Laboratory. The blinds were adjusted to the following different positions, namely: Fully up (100% open), 75% open, 50% open, 25% open, fully closed (0% open).

4.2.1 Model description

Fig. 17: *Model of the light laboratory with the markings of the observed points.*

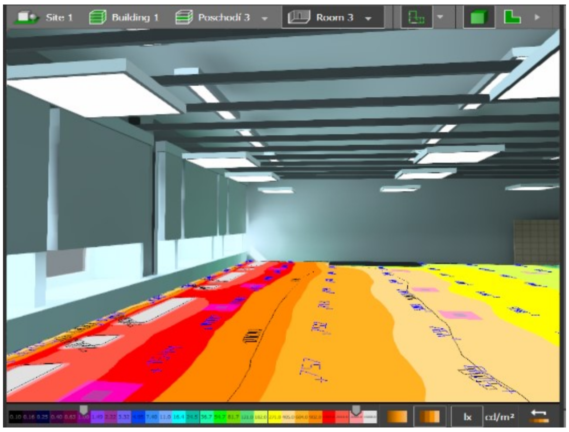


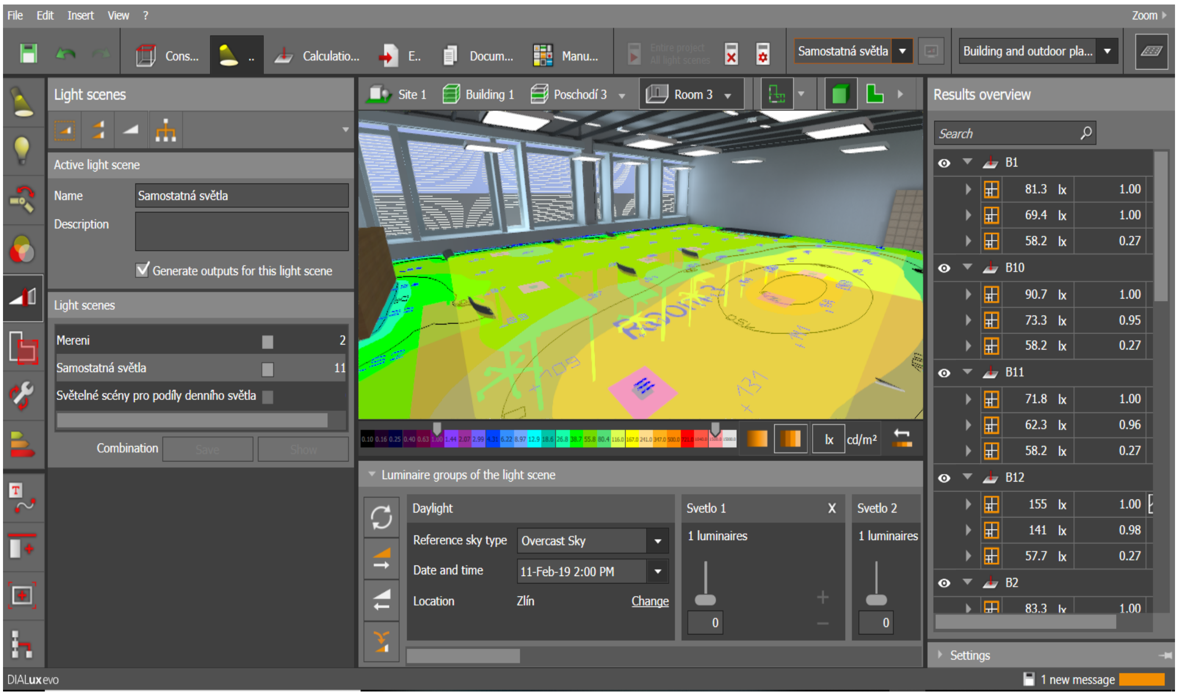
Fig. 18: *Measurement/Observation points with the respective simulated values – The Software overview*

4.2.2 Parameters setup

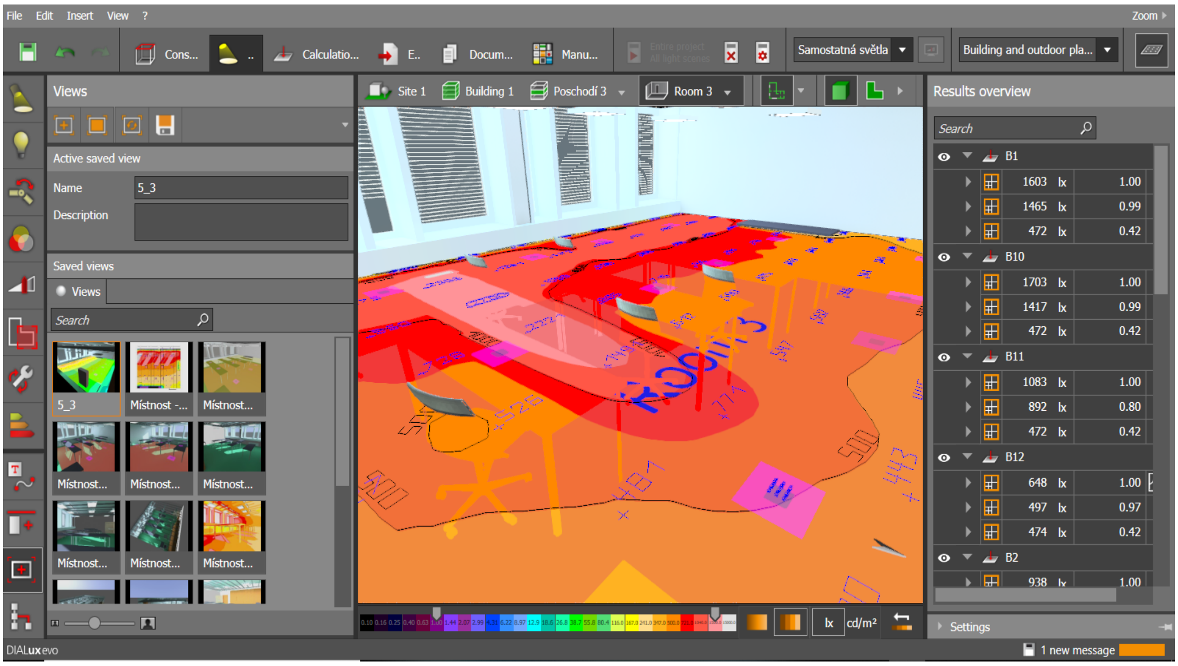
For the simulation, the nature of the sky, date, and opened level of windows were set to specific values which conform to the conditions for taking measurements with the measuring instruments. These were done in order to set the luminaire parameters to achieve uniform illumination levels on a work plane throughout the room. Setting the luminous intensity of the lights then depends primarily on their position in the room. Since the luminaires illuminate the space at a certain angle of radiation, it is obvious that if the same luminous intensity is set for all luminaires, there will be greater illumination in the middle than in the rest of the room. For this situation, the luminous intensity values were determined experimentally in order to have uniformity of illuminance on the work space.

5.0 Control systems of illumination

DIALux simulation program was used to simulate lighting conditions inside the room involving natural and artificial lights. The program allows you to define the date, time, type of sky (clear, average and overcast) and the level of opening of the windows. Sample resolts are shown below:



(a)



(b)

Fig. 19: *Sample simulation results as displayed in DIALux Evo software.*

6.0 Economic Evaluation

6.1 Acquisition costs (estimates)

Table 6: *Acquisition costs (estimates)*

Equipment	Reference	Qty.	Price per piece [Kc]	Total price [Kc]
Control unit homeLYnk	lss100100	1	32,143.00	32,143.00
Source for homeLYnk	MTN693003	1	1,690.00	1,690.00
Source for KNX	MTN684016	1	3,853.00	3,853.00
KNX-DALI gateway	MTN6725-0001	1	17,309.00	17,309.00
shutter actuator	MTN649802	1	6,026.00	6,026.00
External lighting and temperature	MTN663991	1	7,386.00	7,386.00
Buttons for blind	MTN628119	1	3,070.00	3,070.00
Buttons for lighting control	MTN617419	1	3,856.00	3,856.00
Fixtures + DALI ballasts	ZCLED39QTW / M600-OPAL + DALI	12	5,966.00	71,592.00
Drive roller blinds	J406WT	2	2 965.00	5,930.00
			Total price excluding VAT	**152,855.00**

The price does not include the cost of cabling, small material and labour.

6.2 Saving Electric Energy

To evaluate the influence of windows and sun protection to penetration of daylight using daylight factor D.

Table 7: Daylight penetration as a function of daylight factor [35]

Daylight factor D	The penetration of daylight
D > = 3%	Strongly
3%> D> = 2%	Medium
2%> D> = 1%	Faintly
D <1%	no

The factor depending on the daylight can be determined from the relation:

$$F_D = 1 - (F_{D,} \cdot F_{D,}) \qquad (1.9)$$

where: $F_{D,S}$ = factor approach of daylight.

$F_{D,}$ = official control of artificial lighting.

And daylight factor is determined from the relationship:

$$F_{D,S} = a + b \, . \, \varphi \qquad (2.0)$$

where: *a, b* = coefficients determined by the penetration of daylight into the room and the maintained illuminance,

φ = the latitude in degrees.

Table 8: Coefficients for determining factor and daylight [35]

Maintained illuminance [lx)	The penetration of daylight	*a*	*b*
300	Faintly	1.2425	-0.0117
	Medium	1.3097	-0.0106
	Strongly	1.2904	-0.0088
500	Faintly	0.9432	-0.0094
	Medium	1.2425	-0.0117
	Strongly	1.3220	-0.0110
750	Faintly	.6692	-0.0067
	Medium	1.0054	-0.0098
	Strongly	1.2812	-0.0121

Official control of artificial lighting can be determined from the table below.

Table 9: *$F_{D,C}$ factor value depending on the penetration of daylight [35]*

Method for controlling a lighting system floodlights	Values of $F_{D,C}$ ingress according to the level of daylight		
	Faintly	Medium	Strongly
Small	0.20	0.30	0.40
Automatic, depending on daylight	0.75	0.77	0.85

Depending on the occupancy, the factor F_0 in the room without presence detection system is equal to 1.

F_c constant illuminance factor is the proportion of an average power during the operation of the initial installed power.

To determine the operating time, the standard values according to standard EN 15193 is used.

Table 10: Approximate annual operating time by type of building ***[35]***

Building type	Adjusted annual hourly Business		
	tD	*tN*	*tO*
Offices	2250	250	2500
Educational	1800	200	2000
Hospitals	3000	2000	5000
Hotels	3000	2000	5000
Restaurants	1250	1250	2500
Sports facilities	2000	2000	4000
Salable	3000	2000	5000
Industrial buildings	2500	1500	4000

II PRACTICAL PART

7.0 Light laboratory description

7.1 General description

The light laboratory was built in 2017 and serves for research and development needs at FAI UTB in Zlin. The equipment of the laboratory was chosen to examine all types of lighting, natural light, artificial light, and their combination.

Fig. 20: *Interior of light laboratory at FAI TBU in Zlin.*

Fig. 21: *Inner view of the Laboratory from the software (showing the measurement/observation points)*

7.2 The building placement

The laboratory is located on the 3rd floor of the Faculty of Applied Informatics (FAI) building with windows facing south.

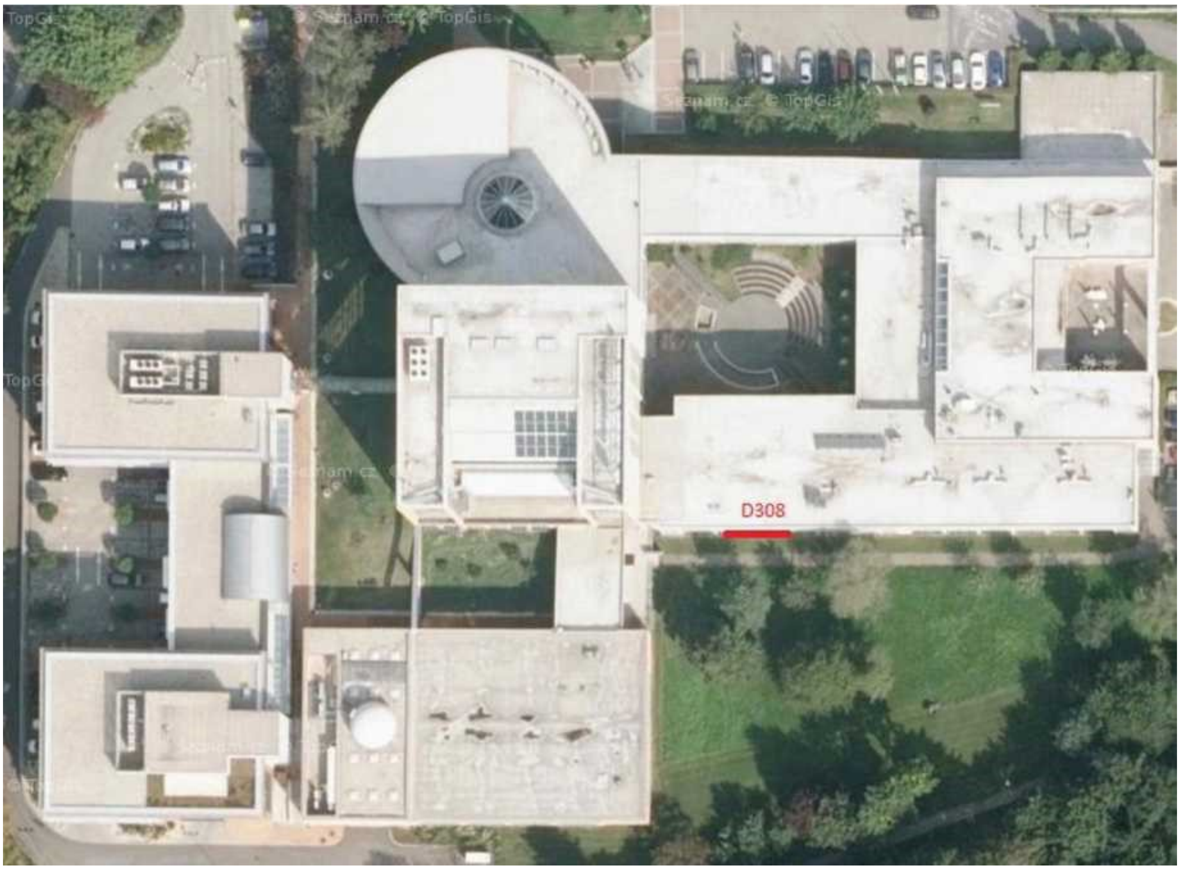


Fig. 22: *FAI TBU Building (room D308 marked in red)*

7.3 The primary objective of the Laboratory

The primary objective of this laboratory was not to specialize in testing high-end luminaries but to address the impact of their effects on indoor environments such as the interaction of natural and artificial lighting in the view of uniform illumination on the workplace and chromatic distribution through the room. Moreover, as the lab control system is conceived, it is a prerequisite to using the laboratory to verify the various control algorithms based on both direct and feedback control.

7.4 Dimensions and surroundings

The Laboratory is a room of rectangular shape with dimensions of 8.7 x 7.3 x 3.4 meters. There are work desks that define the work area at the height of 0.8 m above the floor.

7.5 Light sources and shading elements

The artificial light source consists of luminaires with dimmable electronic ballasts (12 x LED panel CCT 6060 36W, 3600lm) which are also capable of changing the colour of the light (3000 - 6500K). These luminaires are suspended on a HILTI construction that is sliding to change their vertical and horizontal position. In this situation, the lights were placed at the height of 2.5m above the floor. To control the penetration rate of daylight, there are shutters connected via a blind actor to the KNX. From the inside as secondary dimming elements, there are blinds that are operated manually. This solution allows for complete darkness in the laboratory.

7.6 Control system based on KNX (description, installation, functions)

The lighting control is performed by Digital Addressable Lighting Interface (DALI), which is specially designed to control lighting where the KNX DALI-Gateway connects KNX with electronic ballasts equipped with a DALI interface. This interface enables the luminous intensity and colour temperature adjustment for each light separately. The logic itself is based on a control algorithm whose primary objective is to control the inner illumination to a constant level, and the goal is to keep the power consumption for lighting at the minimum level and at the same time, meet the hygienic limits [14].

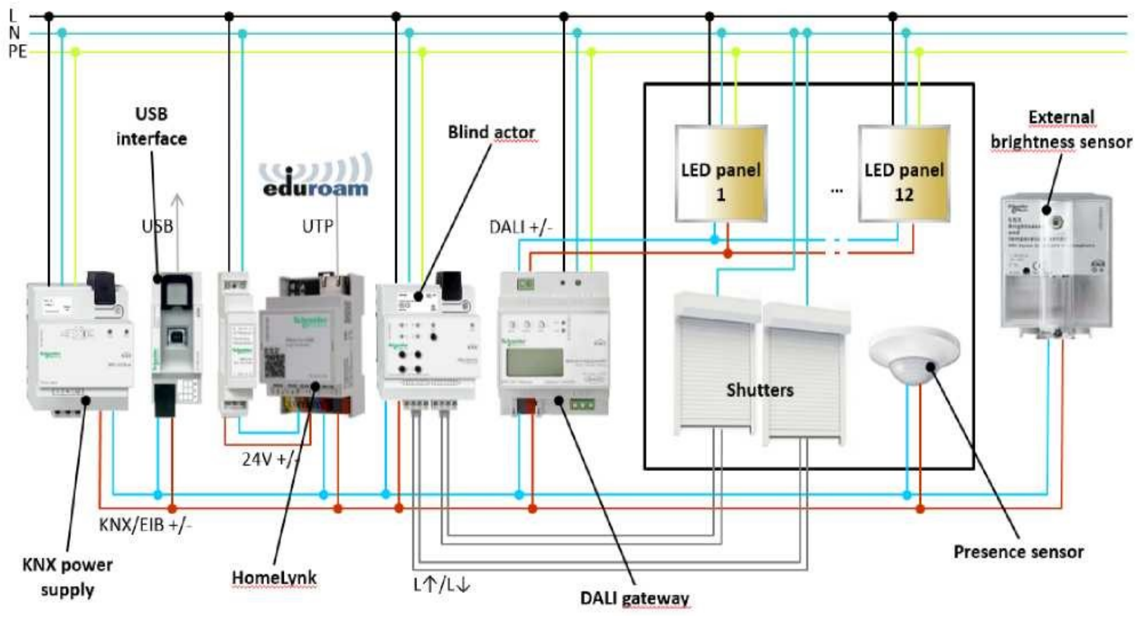


Fig. 23: *Block diagram of KNX installation.*

7.7 Visualization in HomeLynk

The basic configuration was made in ETS 5. Subsequently, the programming of individual functions was performed in the HomeLynk web environment, as well as the visualization (Fig. 3) defining the interface between the user and the application. It is a future-proof solution, developed by Schneider Electric, which allows remote control of all peripheries via computer or smartphone.

Fig. 24: *Visualization for luminaires and shading elements control.*

8.0 Requirements

The following is a sample of the parameter requirements for indoor lighting as spelt out in the CSN EN_12464-1 (2012) Engineering Standard: Light and lighting – Lighting of work places – Part1: Indoor work places (page 29):

Table 5.26 – Administrative Offices

Ref. No.	Type of interior, task or activity	E_m lx	UGR_L -	U_o -	R_a -	Remarks
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5.26.2	Writing, typing, reading, data processing	500	19	0.6	80	For display operations, see 4.9
5.26.3	Technical drawing	750	16	0.7	80	
5.26.4	CAD work stations	500	19	0.6	80	For display operations, see 4.9
5.26.5	Conference and meeting rooms	500	19	0.6	80	Lighting should be controllable
5.26.6	Reception desk	300	22	0.6	80	
5.26.7	Archives	200	25	0.4	80	

9.0 Validation of calculation method

With reference to The Study of the Combination of Natural and Artificial Lights by Ogunleye J.O, Drabel P. and Martin Zalesak (2018) the following conculsions were arrived at [10]:

i. *There were high light intensities at points close to the window because of the effect of natural light which has a higher spectrum than artificial light.*

ii. *When the blinds were down, there was higher concentration of lights at points located in the middle of the Laboratory than those close to the walls.*

iii. *It is possible to use the simulation software to predict the amount of illumination on the work space.*

iv. *The simulation software works more appropriately with artificial lights than natural lights.*

Natural light

Measurements were taken with natural lights only. The blinds were adjusted to the following different positions, namely: Fully up (100% open), 75% open, 50% open, 25% open, Fully down (0% open). Five different sets of measurements were taken; one set per blind position. One set of measurement comprises of measured values of light intensity at each of the measurement/observation positions in the Laboratory. It should be noted that measured values were zero when the blinds were fully down (0% open) because there was no artificial light involved.

The following chart shows the distribution of daylight in the room. It shows the uniformity of daylight in the room without the use of blinds.

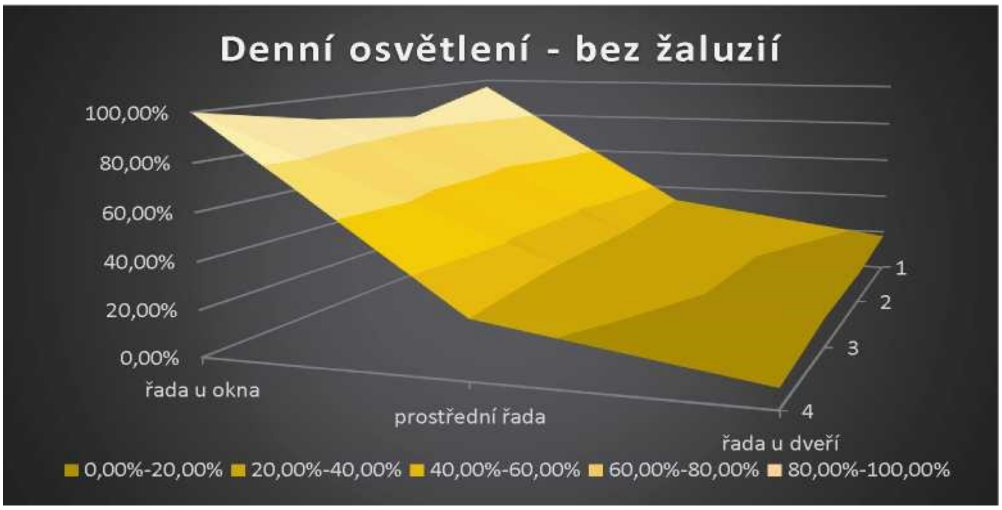
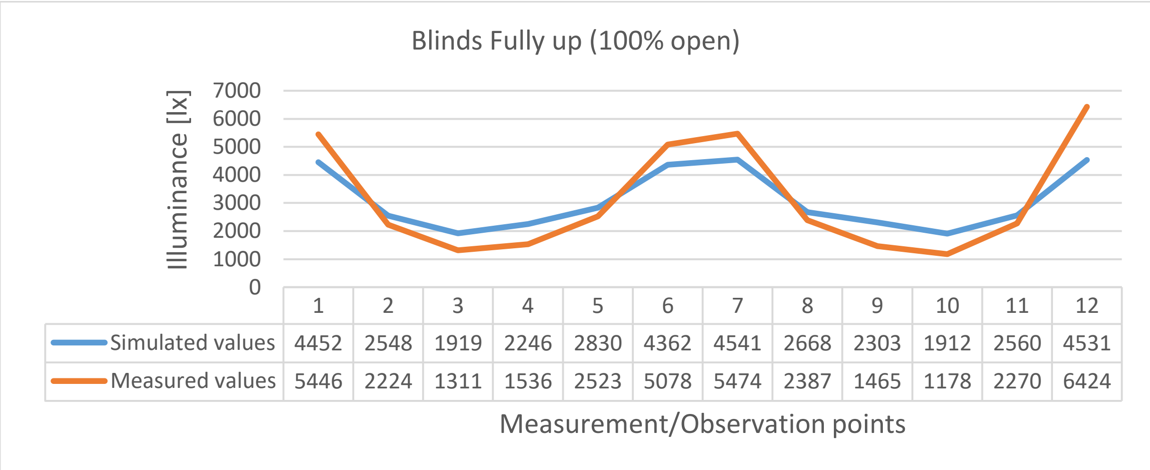


Fig. 25: *Uniformity of light without blinds*

Artificial and Natural lights

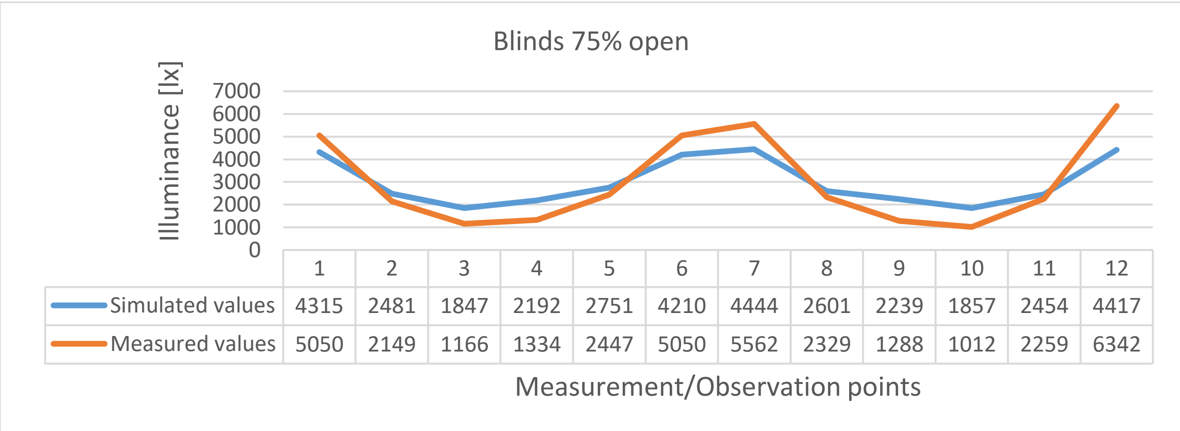
Measurements were taken with natural and artificial lights. The blinds were adjusted to the following different positions, namely: Fully up (100% open), 75% open, 50% open, 25% open, Fully closed (0% open). The luminous flux of the artificial lightings in the Laboratory was set at 3000Lumens(lm). Five different sets of measurements and simulations were taken; one set per blind position. One set of measurement and simulation comprises of measured and simulated values of light intensity at each of the measurement/observation positions in the Laboratory. Measured and simulated values were taken when the blinds were fully down (0% opened) because there was artificial light in the Laboratory.

For the purpose of this study, measurements were taken at various observation points in the Laboratory, while an open-source software (Dialux Evo) was used to produce numerical simulations at the observation points with the blinds set at various open positions, using the KNX lighting control systems. Comparisons shown in graphs (a) to (e) below:



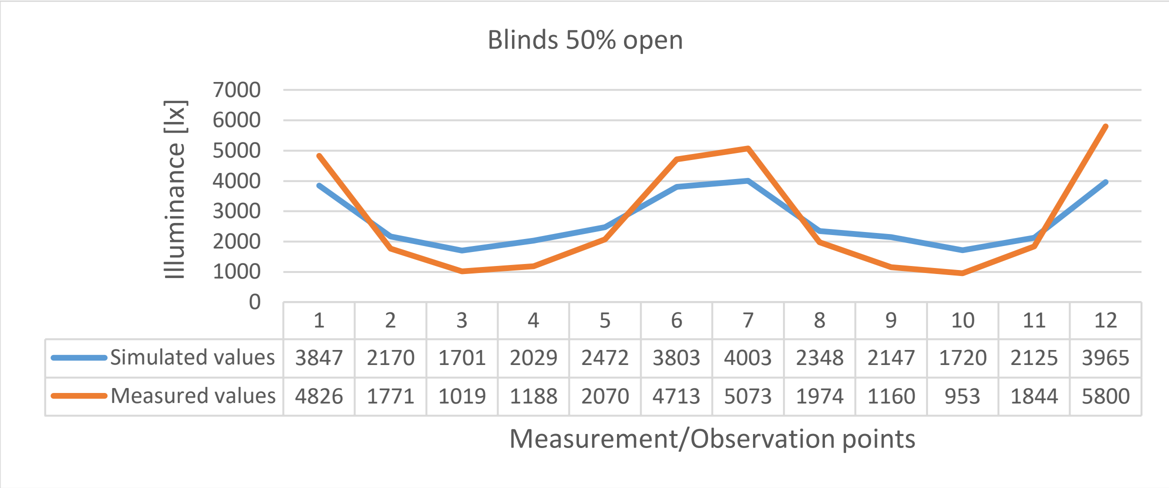
	1	2	3	4	5	6	7	8	9	10	11	12
Simulated values	4452	2548	1919	2246	2830	4362	4541	2668	2303	1912	2560	4531
Measured values	5446	2224	1311	1536	2523	5078	5474	2387	1465	1178	2270	6424

(a)



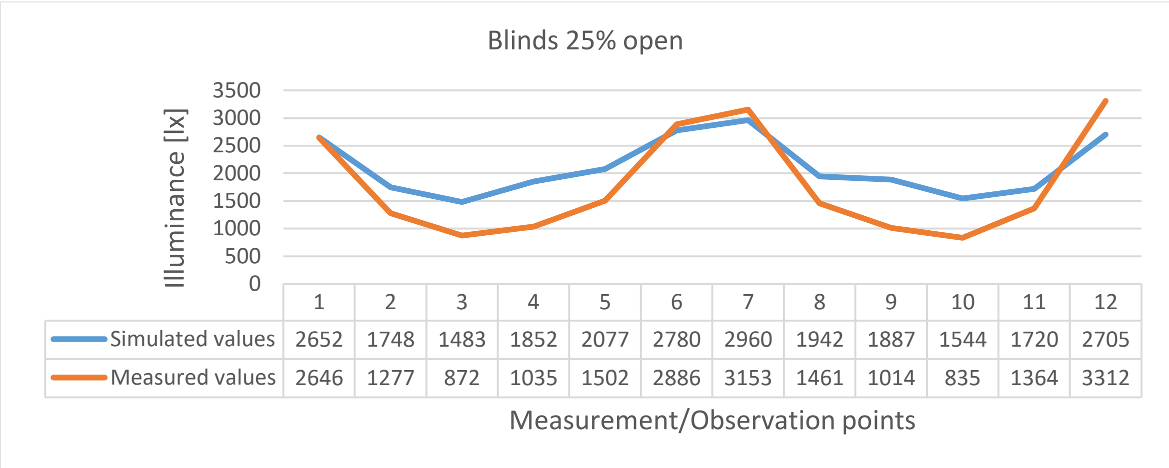
	1	2	3	4	5	6	7	8	9	10	11	12
Simulated values	4315	2481	1847	2192	2751	4210	4444	2601	2239	1857	2454	4417
Measured values	5050	2149	1166	1334	2447	5050	5562	2329	1288	1012	2259	6342

(b)



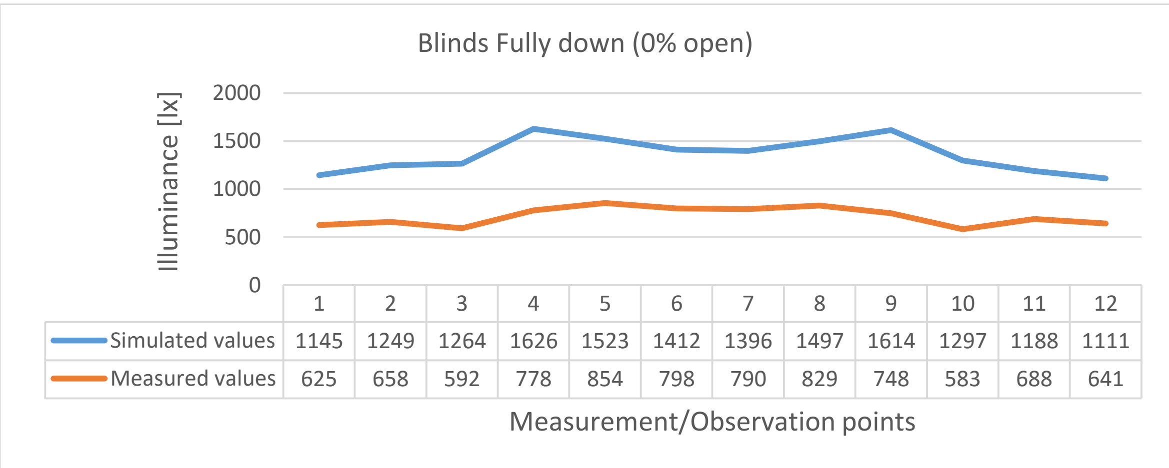
	1	2	3	4	5	6	7	8	9	10	11	12
Simulated values	3847	2170	1701	2029	2472	3803	4003	2348	2147	1720	2125	3965
Measured values	4826	1771	1019	1188	2070	4713	5073	1974	1160	953	1844	5800

(c)



	1	2	3	4	5	6	7	8	9	10	11	12
Simulated values	2652	1748	1483	1852	2077	2780	2960	1942	1887	1544	1720	2705
Measured values	2646	1277	872	1035	1502	2886	3153	1461	1014	835	1364	3312

(d)



	1	2	3	4	5	6	7	8	9	10	11	12
Simulated values	1145	1249	1264	1626	1523	1412	1396	1497	1614	1297	1188	1111
Measured values	625	658	592	778	854	798	790	829	748	583	688	641

(e)

Fig. 26: *Graphs (a) to (e) showing the comparisons of measured and simulated values of Illuminance at the observation points in the Laboratory.*

Also, Comparison of Lighting Simulation Outcomes for Electric Lights with Real Reference by Pavel Drabek and Martin Zalesak concluded that [6]:

"Simulation tools used in light analysis provide accurate results, if the sources involved are perfectly diffuse emitters or if the surfaces involved exhibit perfectly diffuse reflection".

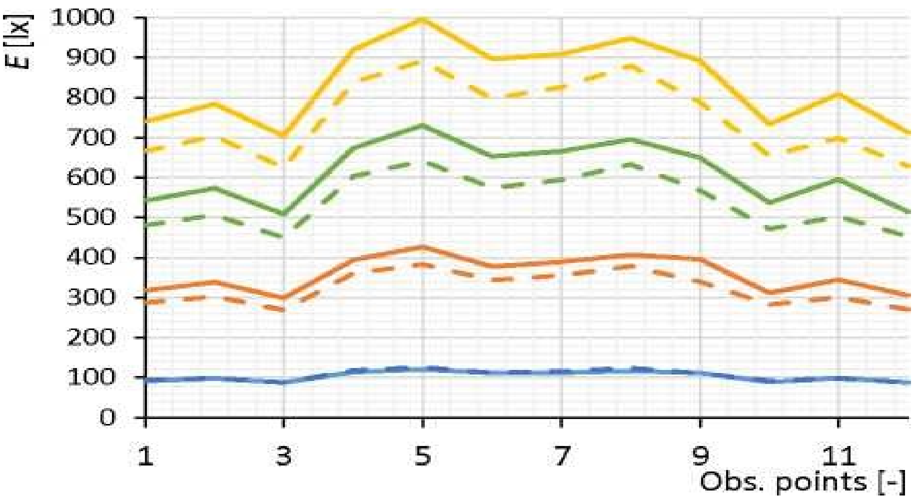


Fig. 27: Illumination values at individual observation points for different luminous intensity, T = 4000K, *0* = 3600lm, (continuous line = real measurement, dash line = simulation).

10.0 Cases

10.1 Calculation

Electricity consumption for lighting can be determined either by measurement or estimate calculation according to DIN EN 15 193 [35]. The total estimated consumption of electricity for a certain period shall be determined from the relationship:

$$W = \frac{(Pn \bullet Fc) \bullet [(F0 \bullet tD \bullet Fd) + (tN \bullet F0)]}{1000} \qquad (2.1)$$

where: W = the estimated total consumption kWh,

Pn = total installed power for lighting the room in W,

Fc = factor constant illumination

Fd = factor depending on daylight

$F0$ = factor depending on occupancy

tD = time use of daylight in hours

tN = period without using the daylight hours, The power installed for the room illumination is determined by a sum of the individual power consumption of luminaires.

$$P_n = \Sigma pi \tag{2.2}$$

where: P_n = total installed power in W,

Pi = wattage lamps in W.

10.2 Simulation Readings

Date	Time	Sky Type	Blind Position	Luminous Power (W)	B1 (lx)	B2 (lx)	B3 (lx)	B4 (lx)	B5 (lx)	B6 (lx)	B7 (lx)	B8 (lx)	B9 (lx)	B10 (lx)	B11 (lx)	B12 (lx)	$E_m = Avg(E_t)$	E_{min}	E_{max}	$Uo = \frac{E_{min}}{E_m}$
13-05-19	12.00pm	Average sky	100% Open	116	3663	1493	854	3549	1423	920	3419	1419	900	3734	1374	777	1960.42	777.00	3734.00	0.40
		Values with Uniformity (0.7) =>			3663	2613.8	2613.8	3549	2613.8	2613.8	3419	2613.8	2613.8	3734	2613.8	2613.8	2939.62	2613.80	3734.00	0.89
		Extra Illuminance required (difference)			0	1120.8	1759.8	0	1190.8	1693.8	0	1194.8	1713.8	0	1239.8	1836.8	979.20	1836.80		
11-02-19	2.00pm	Average sky	100% Open	116	7045	996	525	6826	879	606	6788	4789	482	6289	5854	487	3463.83	482.00	7045.00	0.14
		Values with Uniformity (0.7) =>			7045	4931.5	4931.5	6826	4931.5	4931.5	6788	4931.5	4931.5	6289	4931.5	4931.5	5533.33	4931.50	7045.00	0.89
		Extra Illuminance required (difference)			0	3935.5	4406.5	0	4052.5	4325.5	0	142.5	4449.5	0	-922.5	4444.5	2069.50	4449.50		
13-05-19	12.00pm	Clear sky	100% Open	116	3521	1677	1062	3364	1720	1194	3524	1686	1113	3836	1530	981	2100.67	981.00	3836.00	0.47
		Values with Uniformity (0.7) =>			3521	2685.2	2685.2	3364	2685.2	2685.2	3524	2685.2	2685.2	3836	2685.2	2685.2	2977.22	2685.20	3836.00	0.90
		Extra Illuminance required (difference)			0	1008.2	1623.2	0	965.2	1491.2	0	999.2	1572.2	0	1155.2	1704.2	876.55	1704.20		
11-02-19	2.00pm	Clear sky	100% Open	116	13140	1790	1039	12905	1706	1261	12664	9514	1055	11672	11605	981	6611.00	981.00	13140.00	0.15
		Values with Uniformity (0.7) =>			13140	9198	9198	12905	9198	9198	12664	9198	9198	11672	9198	9198	10330.42	9198.00	13140.00	0.89
		Extra Illuminance required (difference)			0	7408	8159	0	7492	7937	0	-316	8143	0	-2407	8217	3719.42	8217.00		
11-02-19	2.00PM	Overcast sky	100% Open	116	511	159	86.3	465	167	84.1	428	143	76.9	445	161	75.7	233.50	75.70	511.00	0.32
		Values with Uniformity (0.7) =>			511	357.7	357.7	465	357.7	357.7	428	357.7	357.7	445	357.7	357.7	392.55	357.70	511.00	0.91
		Extra Illuminance required (difference)			0	198.7	271.4	0	190.7	273.6	0	214.7	280.8	0	196.7	282	159.05	282.00		
13-05-19	12.00pm	Overcast sky	100% Open	116	1143	355	193	1041	374	188	959	321	172	997	361	169	522.75	169.00	1143.00	0.32
		Values with Uniformity (0.7) =>			1143	800.1	800.1	1041	800.1	800.1	959	800.1	800.1	997	800.1	800.1	878.40	800.10	1143.00	0.91
		Extra Illuminance required (difference)			0	445.1	607.1	0	426.1	612.1	0	479.1	628.1	0	439.1	631.1	355.65	631.10		
13-05-19	12.00pm	Average sky	75% Open	116	2438	814	430	2093	730	418	2024	810	420	2178	751	320	1118.83	320.00	2438.00	0.29
		Values with Uniformity (0.7) =>			2438	1706.6	1706.6	2093	1706.6	1706.6	2024	1706.6	1706.6	2178	1706.6	1706.6	1865.48	1706.60	2438.00	0.91
		Extra Illuminance required (difference)			0	892.6	1276.6	0	976.6	1288.6	0	896.6	1286.6	0	955.6	1386.6	746.65	1386.60		
11-02-19	2.00pm	Average sky	75% Open	116	6703	729	539	6666	739	446	6510	821	403	6133	705	391	2565.42	391.00	6703.00	0.15
		Values with Uniformity (0.7) =>			6703	4692.1	4692.1	6666	4692.1	4692.1	6510	4692.1	4692.1	6133	4692.1	4692.1	5295.73	4692.10	6703.00	0.89
		Extra Illuminance required (difference)			0	3963.1	4153.1	0	3953.1	4246.1	0	3871.1	4289.1	0	3987.1	4301.1	2730.32	4301.10		
13-05-19	12.00pm	Clear sky	75% Open	116	3128	1386	903	2913	1596	845	3454	1448	742	3262	1483	735	1824.58	735.00	3454.00	0.40
		Values with Uniformity (0.7) =>			3128	2417.8	2417.8	2913	2417.8	2417.8	3454	2417.8	2417.8	3262	2417.8	2417.8	2674.95	2417.80	3454.00	0.90
		Extra Illuminance required (difference)			0	1031.8	1514.8	0	821.8	1572.8	0	969.8	1675.8	0	934.8	1682.8	850.37	1682.80		
11-02-19	2.00pm	Clear sky	75% Open	116	12678	1325	987	12637	1332	855	12299	1461	778	11472	1271	792	4823.92	778.00	12678.00	0.16
		Values with Uniformity (0.7) =>			12678	8874.6	8874.6	12637	8874.6	8874.6	12299	8874.6	8874.6	11472	8874.6	8874.6	10006.90	8874.60	12678.00	0.89
		Extra Illuminance required (difference)			0	7549.6	7887.6	0	7542.6	8019.6	0	7413.6	8096.6	0	7603.6	8082.6	5182.98	8096.60		
13-05-19	12.00pm	Overcast sky	75% Open	116	905	285	172	810	289	164	724	269	136	808	244	173	414.92	136.00	905.00	0.33
		Values with Uniformity (0.7) =>			905	633.5	633.5	810	633.5	633.5	724	633.5	633.5	808	633.5	633.5	692.92	633.50	905.00	0.91
		Extra Illuminance required (difference)			0	348.5	461.5	0	344.5	469.5	0	364.5	497.5	0	389.5	460.5	278.00	497.50		
11-02-19	2.00pm	Overcast sky	75% Open	116	511	159	86.3	465	167	84.1	428	143	76.9	445	161	75.7	233.50	75.70	511.00	0.32
		Values with Uniformity (0.7) =>			511	357.7	357.7	465	357.7	357.7	428	357.7	357.7	445	357.7	357.7	392.55	357.70	511.00	0.91
		Extra Illuminance required (difference)			0	198.7	271.4	0	190.7	273.6	0	214.7	280.8	0	196.7	282	159.05	282.00		
13-05-19	12.00pm	Average sky	50% Open	116	1523	506	317	1325	543	329	1256	506	337	1430	501	252	735.42	252.00	1523.00	0.34
		Values with Uniformity (0.7) =>			1523	1066.1	1066.1	1325	1066.1	1066.1	1256	1066.1	1066.1	1430	1066.1	1066.1	1171.90	1066.10	1523.00	0.91
		Extra Illuminance required (difference)			0	560.1	749.1	0	523.1	737.1	0	560.1	729.1	0	565.1	814.1	436.48	814.10		
11-02-19	2.00pm	Average sky	50% Open	116	842	251	145	756	289	158	689	264	163	746	260	162	393.75	145.00	842.00	0.37
		Values with Uniformity (0.7) =>			842	589.4	589.4	756	589.4	589.4	689	589.4	589.4	746	589.4	589.4	645.68	589.40	842.00	0.91
		Extra Illuminance required (difference)			0	338.4	444.4	0	300.4	431.4	0	325.4	426.4	0	329.4	427.4	251.93	444.40		
13-05-19	12.00pm	Clear sky	50% Open	116	2157	1041	634	2062	1181	545	2169	1086	574	2249	1079	538	1276.25	538.00	2249.00	0.42
		Values with Uniformity (0.7) =>			2157	1574.3	1574.3	2062	1574.3	1574.3	2169	1574.3	1574.3	2249	1574.3	1574.3	1769.28	1574.30	2249.00	0.89
		Extra Illuminance required (difference)			0	533.3	940.3	0	393.3	1029.3	0	488.3	1000.3	0	495.3	1036.3	493.03	1036.30		
11-02-19	2.00pm	Clear sky	50% Open	116	12394	1196	691	12295	1133	702	11979	1063	671	10780	1061	612	4548.08	612.00	12394.00	0.13
		Values with Uniformity (0.7) =>			12394	8675.8	8675.8	12295	8675.8	8675.8	11979	8675.8	8675.8	10780	8675.8	8675.8	9737.87	8675.80	12394.00	0.89
		Extra Illuminance required (difference)			0	7479.8	7984.8	0	7542.8	7973.8	0	7612.8	8004.8	0	7614.8	8063.8	5189.78	8063.80		
13-05-19	12.00pm	Overcast sky	50% Open	116	566	182	118	508	187	104	459	193	119	524	167	95.3	268.53	95.30	566.00	0.35
		Values with Uniformity (0.7) =>			566	396.2	396.2	508	396.2	396.2	459	396.2	396.2	524	396.2	396.2	435.55	396.20	566.00	0.91
		Extra Illuminance required (difference)			0	214.2	278.2	0	209.2	292.2	0	203.2	277.2	0	229.2	300.9	167.03	300.90		
11-02-19	2.00pm	Overcast sky	50% Open	116	253	81.3	52.7	227	83.4	46.7	205	86.2	53	234	74.8	42.6	119.98	42.60	253.00	0.36
		Values with Uniformity (0.7) =>			253	177.1	177.1	227	177.1	177.1	205	177.1	177.1	234	177.1	177.1	194.65	177.10	253.00	0.91
		Extra Illuminance required (difference)			0	95.8	124.4	0	93.7	130.4	0	90.9	124.1	0	102.3	134.5	74.68	134.50		
13-05-19	12.00pm	Average sky	25% Open	116	1254	566	399	1044	567	328	1069	584	348	1231	612	356	696.50	328.00	1254.00	0.47
		Values with Uniformity (0.7) =>			1254	877.8	877.8	1044	877.8	877.8	1069	877.8	877.8	1231	877.8	877.8	968.37	877.80	1254.00	0.91
		Extra Illuminance required (difference)			0	311.8	478.8	0	310.8	549.8	0	293.8	529.8	0	265.8	521.8	271.87	549.80		
11-02-19	2.00pm	Average sky	25% Open	116	983	474	283	938	435	280	880	471	303	1691	448	217	616.92	217.00	1691.00	0.35
		Values with Uniformity (0.7) =>			983	1183.7	1183.7	938	1183.7	1183.7	880	1183.7	1183.7	1691	1183.7	1183.7	1163.47	880.00	1691.00	0.76
		Extra Illuminance required (difference)			0	709.7	900.7	0	748.7	903.7	0	712.7	880.7	0	735.7	966.7	546.55	663.00		
13-05-19	12.00pm	Clear sky	25% Open	116	1484	692	444	1180	732	408	1350	760	399	1392	740	395	831.33	395.00	1484.00	0.48
		Values with Uniformity (0.7) =>			1484	1038.8	1038.8	1180	1038.8	1038.8	1350	1038.8	1038.8	1392	1038.8	1038.8	1143.03	1038.80	1484.00	0.91
		Extra Illuminance required (difference)			0	346.8	594.8	0	306.8	630.8	0	278.8	639.8	0	298.8	643.8	311.70	643.80		
11-02-19	2.00pm	Clear sky	25% Open	116	1817	908	506	1776	846	512	1574	864	523	3201	834	398	1146.58	398.00	3201.00	0.35
		Values with Uniformity (0.7) =>			1817	2240.7	2240.7	1776	2240.7	2240.7	1574	2240.7	2240.7	3201	2240.7	2240.7	2191.13	1574.00	3201.00	0.72
		Extra Illuminance required (difference)			0	1332.7	1734.7	0	1394.7	1728.7	0	1376.7	1717.7	0	1406.7	1842.7	1044.55	1176.00		
13-05-19	12.00pm	Overcast sky	25% Open	116	313	131	82.3	254	125	80.1	258	129	78	276	142	65.7	161.18	65.70	313.00	0.41
		Values with Uniformity (0.7) =>			313	219.1	219.1	254	219.1	219.1	258	219.1	219.1	276	219.1	219.1	237.82	219.10	313.00	0.92
		Extra Illuminance required (difference)			0	88.1	136.8	0	94.1	139	0	90.1	141.1	0	77.1	153.4	76.64	153.40		
11-02-19	2.00pm	Overcast sky	25% Open	116	140	58.4	36.8	113	55.8	35.8	116	57.8	34.8	123	63.5	29.3	72.02	29.30	140.00	0.41
		Values with Uniformity (0.7) =>			140	98	98	113	98	98	116	98	98	123	98	98	106.33	98.00	140.00	0.92
		Extra Illuminance required (difference)			0	39.6	61.2	0	42.2	62.2	0	40.2	63.2	0	34.5	68.7	34.32	68.70		
13-05-19	12.00pm	Average sky	0% Open	116	738	399	284	673	431	251	642	412	247	817	417	204	459.58	204.00	817.00	0.44
		Values with Uniformity (0.7) =>			738	571.9	571.9	673	571.9	571.9	642	571.9	571.9	817	571.9	571.9	620.43	571.90	817.00	0.92
		Extra Illuminance required (difference)			0	172.9	287.9	0	140.9	320.9	0	159.9	324.9	0	154.9	367.9	160.85	367.90		
11-02-19	2.00pm	Average sky	0% Open	116	682	347	207	602	336	233	630	338	184	1476	369	186	465.83	184.00	1476.00	0.39
		Values with Uniformity (0.7) =>			682	1033.2	1033.2	602	1033.2	1033.2	630	1033.2	1033.2	1476	1033.2	1033.2	971.30	602.00	1476.00	0.62
		Extra Illuminance required (difference)			0	686.2	826.2	0	697.2	800.2	0	695.2	849.2	0	664.2	847.2	505.47	418.00		
13-05-19	12.00pm	Clear sky	0% Open	116	925	494	330	891	534	312	858	530	291	970	502	241	573.17	241.00	970.00	0.42
		Values with Uniformity (0.7) =>			925	679	679	891	679	679	858	679	679	970	679	679	756.33	679.00	970.00	0.90
		Extra Illuminance required (difference)			0	185	349	0	145	367	0	149	388	0	177	438	183.17	438.00		
11-02-19	2.00pm	Clear sky	0% Open	116	1254	659	412	1145	639	414	1192	621	336	2875	668	359	881.17	336.00	2875.00	0.38
		Values with Uniformity (0.7) =>			1254	2012.5	2012.5	1145	2012.5	2012.5	1192	2012.5	2012.5	2875	2012.5	2012.5	1880.50	1145.00	2875.00	0.61
		Extra Illuminance required (difference)			0	1353.5	1600.5	0	1373.5	1598.5	0	1391.5	1676.5	0	1344.5	1653.5	999.33	809.00		
13-05-19	12.00pm	Overcast sky	0% Open	116	156	108	64	150	88.8	67.8	141	86	58.4	180	86.4	57.5	103.66	57.50	180.00	0.55
		Values with Uniformity (0.7) =>			156	126	126	150	126	126	141	126	126	180	126	126	136.25	126.00	180.00	0.92
		Extra Illuminance required (difference)			0	18	62	0	37.2	58.2	0	40	67.6	0	39.6	68.5	32.59	68.50		
11-02-19	2.00pm	Overcast sky	0% Open	116	69.7	48.3	28.6	67.1	39.7	30.3	62.8	38.4	26.1	80.3	38.6	25.7	46.30	25.70	80.30	0.56
		Values with Uniformity (0.7) =>			69.7	56.21	56.21	67.1	56.21	56.21	62.8	56.21	56.21	80.3	56.21	56.21	60.80	56.21	80.30	0.92
		Extra Illuminance required (difference)			0	7.91	27.61	0	16.51	25.91	0	17.81	30.11	0	17.61	30.51	14.50	30.51		

Fig. 28: *Simulation readings for blind positions and types of sky.*

		SUMMARY OF SIMULATION READINGS							
DATE	TIME	WINDOWS' OPENING	TYPE OF SKY	$E_m = Avg(E_t)$	$Uo = \frac{E_{min}}{E_m}$	Area of Lab. [m2]	Luminous Flux (lm)	Luminous Efficacy [lm/W]	Power of light [kW]
11-02-19	2.00pm	100%	Clear	**6611**	**0.89**	63.51	419864.61	49.7	**8.45**
		100%	Average	**3463.83**	**0.89**	63.51	219987.843	49.7	**4.43**
		100%	Overcast	**233.5**	**0.91**	63.51	14829.585	49.7	**0.30**
13-05-19	12.00pm	100%	Clear	**2100.67**	**0.9**	63.51	133413.552	49.7	**2.68**
		100%	Average	**1960.42**	**0.89**	63.51	124506.274	49.7	**2.51**
		100%	Overcast	**522.75**	**0.91**	63.51	33199.8525	49.7	**0.67**
11-02-19	2.00pm	75%	Clear	**4823.92**	**0.89**	63.51	306367.159	49.7	**6.16**
		75%	Average	**2565.42**	**0.89**	63.51	162929.824	49.7	**3.28**
		75%	Overcast	**233.5**	**0.91**	63.51	14829.585	49.7	**0.30**
13-05-19	12.00pm	75%	Clear	**1824.58**	**0.9**	63.51	115879.076	49.7	**2.33**
		75%	Average	**1118.83**	**0.91**	63.51	71056.8933	49.7	**1.43**
		75%	Overcast	**414.92**	**0.91**	63.51	26351.5692	49.7	**0.53**
11-02-19	2.00pm	50%	Clear	**4548.08**	**0.89**	63.51	288848.561	49.7	**5.81**
		50%	Average	**393.75**	**0.91**	63.51	25007.0625	49.7	**0.50**
		50%	Overcast	**119.98**	**0.91**	63.51	7619.9298	49.7	**0.15**
13-05-19	12.00pm	50%	Clear	**1276.25**	**0.89**	63.51	81054.6375	49.7	**1.63**
		50%	Average	**735.42**	**0.91**	63.51	46706.5242	49.7	**0.94**
		50%	Overcast	**268.53**	**0.91**	63.51	17054.3403	49.7	**0.34**
11-02-19	2.00pm	25%	Clear	**1146.58**	**0.72**	63.51	72819.2958	49.7	**1.47**
		25%	Average	**616.92**	**0.76**	63.51	39180.5892	49.7	**0.79**
		25%	Overcast	**72.02**	**0.92**	63.51	4573.9902	49.7	**0.09**
13-05-19	12.00pm	25%	Clear	**831.33**	**0.91**	63.51	52797.7683	49.7	**1.06**
		25%	Average	**696.5**	**0.91**	63.51	44234.715	49.7	**0.89**
		25%	Overcast	**161.18**	**0.92**	63.51	10236.5418	49.7	**0.21**
11-02-19	2.00pm	0%	Clear	**881.17**	**0.61**	63.51	55963.1067	49.7	**1.13**
		0%	Average	**465.83**	**0.62**	63.51	29584.8633	49.7	**0.60**
		0%	Overcast	**46.3**	**0.92**	63.51	2940.513	49.7	**0.06**
13-05-19	12.00pm	0%	Clear	**573.17**	**0.9**	63.51	36402.0267	49.7	**0.73**
		0%	Average	**459.58**	**0.92**	63.51	29187.9258	49.7	**0.59**
		0%	Overcast	**103.66**	**0.92**	63.51	6583.4466	49.7	**0.13**

Fig. 29: *Summary of Simulation Readings*

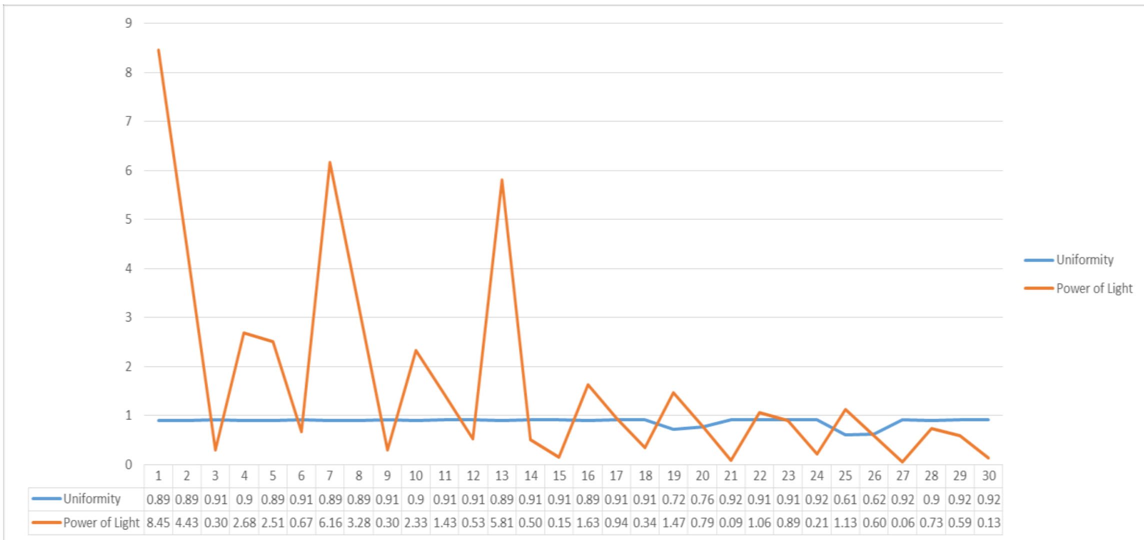
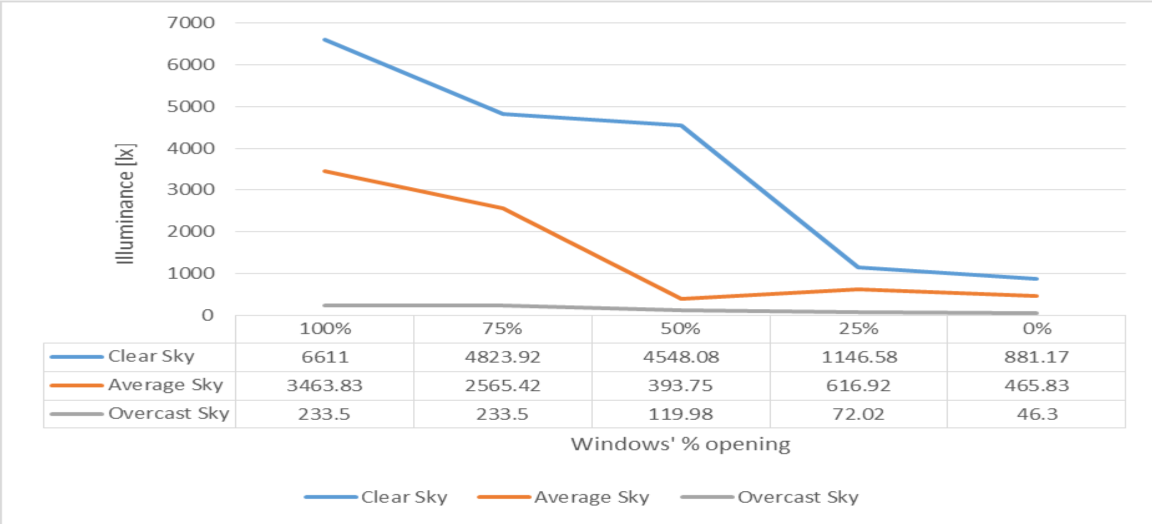


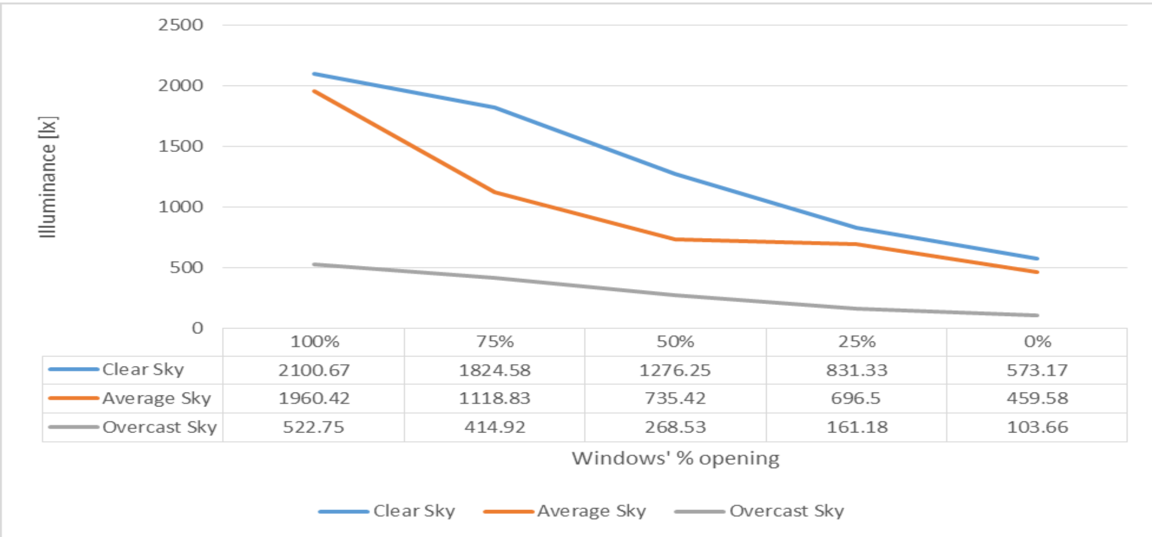
Fig. 30: *Graph showing Uniformity and Power of light*

	11-02-2019 : 2.00pm					13-05-2019 : 12.00pm				
	100%	75%	50%	25%	0%	100%	75%	50%	25%	0%
Clear	6611	4823.92	4548.08	1146.58	881.17	2100.67	1824.58	1276.25	831.33	573.17
Average	3463.83	2565.42	393.75	616.92	465.83	1960.42	1118.83	735.42	696.5	459.58
Overcast	233.5	233.5	119.98	72.02	46.3	522.75	414.92	268.53	161.18	103.66

Fig. 31: *Illuminance and Types of Sky with Windows' % openings.*



(a)



(b)

Fig. 32: *Graphs of Illuminance and Types of Sky against Windows' % openings.*

11.0 Critical consideration and evaluation

Energy Savings

Assuming there are automatic mechanisms to switch on/off the luminaires with respect to the amount of natural light reaching each observation point, which can be carried out with the aid of photosensitive sensors, a hybrid illumination system can be obtained, one that will only expend energy when and where it is really necessary. Hence, such a strategy can efficiently couple natural light devices (windows) with artificial light devices. Therefore, every use of natural light can automatically be considered a profit in terms of lesser consumption of electric energy with artificial light.

The Figure below, shows the possible four situations that can occur with a four-segment (four-circuit) configuration and their corresponding lighting profiles. *Situation A* happens when natural light levels are sufficiently high at all interior points, considering a pre-defined horizontal work plane. This is an ideal situation, when all electric circuits can be shut down and energy savings reach 100%, because only natural light is being used. Assuming the room is divided into 4 segments, *Situation B* represents periods of time when natural levels, although relatively high, are not sufficient to illuminate the most inner regions (segment 4) of the room. In this case, the farther circuit of artificial light must be turned on to help the window in its task of illuminating the room. As one of the four circuits must now be on, energy savings is therefore 75% of the maximum possible. *Situations C and D* are basically the same of situation B but representing cases where 2 and 3 circuits of artificial light must be turned on to illuminate segments 2 and 3 of the room surface, because of a shortage of natural light. Obviously, there is one last possible light profile, not shown in this figure, representing all light fixtures (four circuits) switched on, and no energy savings at all. This last situation can occur at night when there is no natural light available.

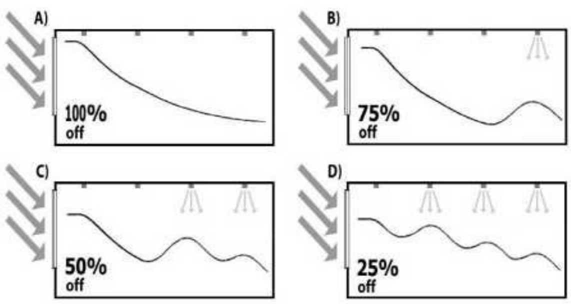


Fig. 33: *Possible energy savings when considering an artificial light system consisting of four circuits integrated with natural light use.*

Typically, during daytime these different situations can occur more or less randomly, mostly depending on sky clearness, geometric configuration of window and room, time of the year and geographic position and orientation of the building.

12.0 Economic consideration

Lighting design and practice is continuously evolving and may have substantial consequences on the energy requirement for lighting. A number of these influencing factors can be categorised under the following headings:

• ***Individual dimming:*** A lighting control system used locally to work places to provide individual lighting comfort by adjustment to meet personal preferences.

• ***Algorithmic light:*** A lighting system to take non-visual biological effects into account by automatic changing of light level, direction and colour temperature.

• ***Light pipes:*** Light pipes are reflective tubes that direct sunlight and daylight from apertures in the building roof to luminaires in the interior.

• ***Lighting installations with scene setting:*** A lighting system that permits pre-setting of various illumination scenes in time and location for different activities in a room or zone.

• ***Daylight guidance:*** Energy savings may be obtained by employing daylight-guiding systems that also allow the penetration of sufficient amounts of daylight into deeper spaces, whilst maintaining control of glare and overheating.

Simulation tools used in light analysis provide accurate results, if the sources involved are perfect diffuse emitters or if the surfaces involved exhibit perfect diffuse reflection. However, this is complicated to achieve in real building reference; hence real values will always show certain inaccuracies. The results of this work show that the basic knowledge of lighting technology and its parameters are necessary for the correct execution of simulations.

CONCLUSION

From the comparison of the measured and simulated values, it is possible to use the results from simulation tools to perform the calculation of the light power of individual luminaires, while controlling the illumination to a constant level. This thesis supports an innovative framework for automated, personalized lighting control in commercial buildings/premises based on the Dialux Evo simulation tool. The procedural computations for the achievements of energy savings and visual comfort are also not left out in the course of this research work.

Any lighting specialist who is involved in building design can interactively experiment many configurations (window sizes and positions, fixtures distribution schemes) in order to choose a better solution for the lighting systems. In other words, this allows the optimization of the lighting system and helps architects, engineers and lighting designers with the adoption of such calculations in their everyday practice in an easy and reliable way. The simulation software has the potential to support engineers in designing better and more sustainable buildings by making use of a natural renewable resource - natural light.

The result of this study is mostly suitable for a room in the northern part of the building with a clear sky. This is due to the high value of light power recorded.

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