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OPTIMISATION OF LIGHT CONDITIONS IN BUILDINGS

OPTIMALIZACE SVĚTELNÝCH PODMÍNEK V BUDOVÁCH

DISERTAČNÍ PRÁCE
DISSERTATION

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Abstract

Building physics as a branch of architecture must ensure an indoor comfort of each user and inhabitant of a building object. This involves, acoustics, indoor thermal conditions and among others also daylighting and artificial lighting of buildings.

Light as a particle and an electromagnetic wave, is required by the different aspects of the human organism. It allows the living beings to see, influences skin and bones, the biorhythms, etc. Therefore, it is necessary for the engineering community to predict the correct illuminance and luminance levels acting insides.

The thesis deals with such issues. More precisely, it assesses the quality of design tools and methodologies, either against CIE reference cases described in CIE 171/2006 and against real measurements done over the working plane of an indoor space located in the attic of Building D of the Institute of Building Structures, Faculty of Civil Engineering, Brno University of Technology, too.

The tools tested throughout the solution of the dissertation did involve three computer programs: RADIANCE, WDLS v3.1 and WDLS v4.1, and one numerographical approach, namely the Daniljuk's innovated methodology (sometimes even combined with the theories of BRS).

In addition several software's have had been created alongside the process assessment, just to mention the "RADIANCE Script", "RADIANCE Data Evaluation Script" or "MuuLUX". The later was written as a communication software allowing the connection of the KONICA-MINOLTA T10 illuminance meter to a computer with the aim of data collection while long term observation. The solution did also require the establishment of a measuring element for the determination of the light reflectance values of surfaces.

The solutions, results and conclusions do describe how well did the design approaches deal while predicting the resulting awaited daylight factor levels in points over the working plane.

Abstrakt

Stavební fyzika je jedna z oblastí stavebnictví, která si klade za hlavní cíl zajistit co nejlepší pohodu uživatelů pobývajících ve vnitřních prostorech objektů. Konkrétně tato část fyziky zahrnuje vědní obory jako je stavební akustika, tepelná technika ale také denní a umělé osvětlení. Právě na poslední zmiňovanou skupinu je pak zaměřena pozornost v předkládané disertační práci.

Obecně světlo představuje paprsek nebo elektromagnetické kmitání, které je pro lidský organismus v mnohých směrech přínosné. Základní význam má samozřejmě z hlediska vidění, ovlivňuje však také kůži a její funkci, vliv má dále na kosti a obecně na biorytmy organismu.

Z výše uvedených důvodů je nezbytná možnost provedení přesného výpočtu hodnot osvětlenosti a jasů v interiéru budov.

Předložená práce se zabývá právě výše uvedenou problematikou, konkrétně pak hodnocením různých metod výpočtu potřebných parametrů. Jednotlivé metody jsou dále v rámci práce porovnány s referenčními hodnotami uvedenými v mezinárodní normě CIE 171/2006. Další srovnání je pak provedeno mezi hodnotami vypočítanými a změřenými v laboratorních podmínkách v referenčních laboratořích umístěných v podkroví budovy D Ústavu pozemního stavitelství, Fakulty stavební, VUT v Brně.

Konkrétně byly v rámci disertační práce ověřeny následující metodiky: počítačové programy RADIANCE, WDLS v3.1 a WDLS v4.1, dále numerická varianta Daniljukovi úhlové sítě (částečně byla tato metoda doplněna i výpočty na základě metodiky BRS). Dále byly vytvořeny programy jako “RADIANCE Script”, “RADIANCE Data Evaluation Script” nebo “MuuLUX“. Poslední výše jmenovaný byl sestaven jako nástroj pro řízení měřící aparatury luxmetru KONICA-MINOLTA T10 počítačem. Řešení dále vyžadovalo doplnění o měřící jednotky pro určení odrazivostí základních povrchů využívaných ve stavebnictví.

Závěry disertační práce jsou pak úzce zaměřeny na konkrétní porovnání jednotlivých metod a obecně na jejich vhodnost pro stanovení hodnot činitele denní osvětlenosti na pracovní rovině umístěné v prostoru místnosti.

Keywords

Daylight, daylight factor, luminance, illuminance, CIE sky types, CIE test cases, computer simulations, ray-tracing, RADIANCE, WDLS, Daniljuk’s diagrams, BRS methodology.

Klíčová slova

Denní osvětlení, činitel denního osvětlení, jas, osvětlenost, CIE oblohy, CIE testovací příklady, počítačové simulace, ray-tracing (metodika sledování paprsků), RADIANCE, WDLS, Daniljukova úhlová síť, metodika BRS.

Statement

I hereby state, that I wrote this dissertation work with the title “Optimisation of Light Conditions in Buildings” by myself and that I have listed the literature I used and drew information from correctly and in a full scale.

In Brno on the 21th of November 2012

……………………….
Ing. František Vajkay

Čestné prohlášení

Prohlašuji, že jsem předloženou práci na téma “Optimisation of Light Conditions in Buildings“ zpracoval samostatně a na základě vlastního výzkumu, konzultací a citovaných publikací.

V Brně, dne 21.11.2012

……………………….
Ing. František Vajkay

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Hereby, I would like to give my regards to those, who have believed in me all these years, particularly in that, that I am going to finish this thesis once in my lifetime. It handles about my wife, parents, sister and among other also my friends and colleagues with whom I am in contact with in everyday life.

Next to them, I would like to give my thanks to my supervisor Doc. Ing. Jitka Mohelníková, Ph.D. who led and nurtured me into who I am today in the field of building physics, especially in the field of daylighting of buildings.

Also I would like to mention the school grounds of the Brno University of Technology, Faculty of Civil Engineering, because it allowed me to partake in doctoral studies and allowed me to improve myself in other fields also, like programing, writing publications, etc.

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In Brno on the 21th of November 2012

………………………
Ing. František Vajkay

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1 INTRODUCTION

Light, more precisely daylight, is one of the essential factors of life on Earth. Through the process of photosynthesis it provides humanity with food, while its daily (shift in the time of sunrise and sun fall, moreover the changes of sky types throughout the day) and seasonal changes affect the habits of human beings [29], may these changes be small or big ones. This is why to erect a building with an enormous utilization of daylighting was one of the major aspects of architects from ancient times. It included the first caves, the living spaces with windows made from glass in Rome, the south oriented buildings in Greece, the aisles and indoor spaces in Egypt with shutters metal plated openings, etc. until the industrial revolution in the 19th century, which changed most of the principles used ever before.

The development of high-grade iron and later on steel with increased strength capabilities which in comparison to the basic materials like stone, bricks and timber used at those times, gave birth to slender frame based structures with huge spans and external envelopes used only with the purpose to withstand the climatic conditions acting on the peripheral structures. This allowed architects to go with their visions and fantasies of indestructible slender buildings. The big distances between the columns allowed bigger openings with corresponding glazing areas, which caused an increment in overheating and glare. Later on with the introduction of fluorescent lamps as one of the utilizations of the electricity allowed the rooms to have bigger depths. With this, the buildings became independent on windows, skylights and other daylighting elements. The architects created what they wished for without the need to think about the prices for energy, because at those times it was cheap.

In the end, the site orientated architecture together with daylighting design got into the background. This has changed in 1973 with the oil embargo, due to which the prices for energy drastically arose and the designers started to look for design principles, which were lost during the industrial revolution [16], which is still in progress even now in the 21st century. Architects, civil engineers and scientist are still seeking for innovations, possibilities and techniques for daylighting of buildings from their design throughout their realisation until they are finished. Furthermore, the research on the effects of light onto human organism is still intact. From this point of view the knowledge of the illuminance levels in rooms more precisely on the working (reference plane) is needed for engineering and medical purposes.

The daylighting design of the building depends on factors like: locality where the building will be built in the future, the type of the building and its structure, main usage, the properties of surfaces and surface finishes which will be applied in the interior and exterior and as last but not least also on the orientation.

Each of the mentioned aspects has influence to the design and creation of the case studies for daylighting. Either as we talk about computer simulations, hand calculations or precedence cases.

The content of the thesis is focused on a few aspects, like verification of methodologies of available computer aided design tools against CIE (Commission Internationale de l´Eclairage) test case definitions, including the precision of « RADIANCE »[1] [14] rendering software and « WDLS » (short for Windows Day Lighting System) [61]. « WDLS » is discussed in versions 3.1 (developed and sold around the year 2000) and 4.1 (the latest, innovated version of the software), while « RADIANCE » because no major changes were done to it is ~rtrace~[2] component in releases 3R7 and 4R1. Another aim of the thesis is to take a closer look at the above daylighting evaluation methods in comparison to data obtained by measurement under standard everyday conditions, hence with respect to determined daylight factor levels over the horizontal working plane.

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[1] The software discussed within the thesis is highlighted by the following symbols: « ».

[2] Software components are highlighted with the following signs: ~ ~.

2 INTRODUCTION TO OPTICS AND LIGHTING

- **Light and its definition**
- **Light sources**
- **Quantities, units and terms used in photometry and daylighting of buildings**
- **Humans and daylight**

2.1 LIGHT AND ITS DEFINITION

Physicists, architect and philosophers tried to describe the properties, characteristics and behaviour of light already ages ago, in the ancient times. One of the theories and definition which was a result of their research was, that light moves in the form of corpuscles from point A to point B throughout multiple reflections and transmissions, however every time in a straight line, without interference [20].

Later on newer and newer descriptions came to the surface, but these were rejected almost automatically by the scientific communities. It had gone on like this until the second half of the 17th century when the principles of a new theory did arise, namely the wave theory. Wave theory explained the movement of light through reflections and refractions in detail, unfortunately though it was also rejected in the beginning, because of the opticians and people doing science in the field couldn't explain, why light does not bend around at the corners of buildings and edges of objects if it handles about a wave based motion.

At the beginning of the 19th Century, A. Fresnel's published results did cause a huge uproar and at the same time the main breakthrough of the wave theory. With the help of measurements made on wavelengths, he was able to point out, that diffraction (bending of light at the edges of object) occurs but only for a small fragment of light and only in case of shortwaves.

The second significant change was caused by J. C. Maxwell a half a decade later, as to Maxwell was able to derive the speed of light almost exactly with the help of his measurements made on electromagnetic oscillating circuits. In spite of this though, his theory within the field of optics became recognized only after H. Hertz had published the results of his own experiments based on Maxwell founding's. Hertz had achieved to produce microwaves and had noticed a resemblance between the behaviour of electromagnetic and light waves (chapter 2.1.1).

As time moved on, another definition started to take shape. It have had been caused by A. Einstein's theory of relativity, which was further developed and investigated by Planck, who stated that light is distributed in space with the means of small particles called photons, which do have a frequency and their energy is directly dependant on their frequency. Furthermore, A. H. Compton had determined that photons and light itself do behave as bodies with a mass having a kinetic energy, hence, light could be defined with the similar corpuscular definition used in the earlier stages of science (chapter 2.1.2).

Nowadays, it is commonly believed that light is of a dualistic nature as it has the advantages of both available and widely recognized theories. Therefore, the propagation of light is explained by the wave theory and the interaction of light with materials and surfaces is described by the behaviour of photons [7], [8], [20].

2.1.1 Maxwell's theory of electromagnetic radiation [7], [8]

Maxwell's theory of electromagnetic radiation characterizes lights as a radiation given by its wavelength, even though it is widely known now, that the interaction of light with other substances is to be described with the means of another theory, namely the "Particle or photon theory of light".

The definition of Maxwell's theory is based on two perpendicular fields, which are distributed at the same time as light is transmitted into the space (see fig. 1), the electric and the magnetic field.

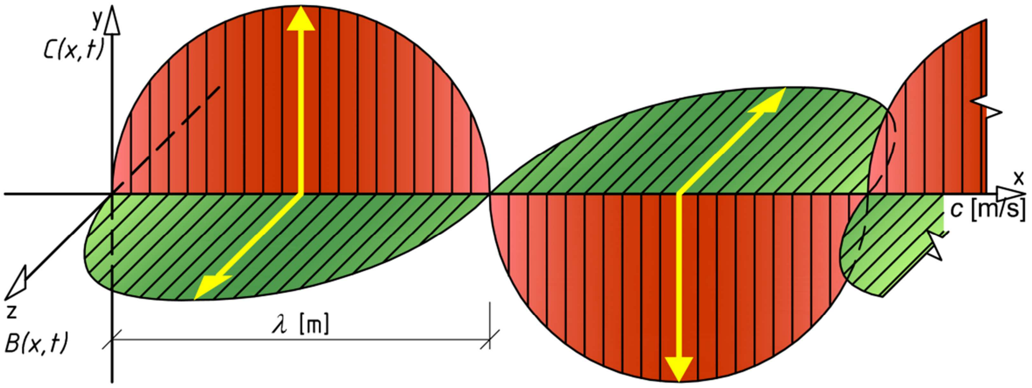


Fig. 1 *Radiation of light [8]*

If these two fields do oscillate in harmony along the direction of distribution it is said, that it handles about a monochromatic type of light. However in some special cases due to polarization of one of these subjects a complicated distribution of light occurs, nevertheless this causes, that the movement of light can be derived as a sine or cosine function of electric (eq. 1) $C(x,t)$ or magnetic radiation $B(x,t)$.

$$C(x,t) = C_m \cdot \sin\left[\omega \cdot \left(t \pm \frac{x_E}{v}\right) + \varsigma\right] \tag{1}$$

Where:

$C(x,t)$ - is the immediate deviation of electric waves;
C_m - is the amplitude of deviation;
ω - is the angular frequency of motion in radian over seconds $[rad \cdot s^{-1}]$;
t - is the time in seconds $[s]$;
x_E - is the displacement of current in meters $[m]$;
v - is the phase velocity of motion in meters over seconds $[m \cdot s^{-1}]$;
ς - is the beginning phase angle in radians $[rad]$.

Howbeit, light waves can be best characterized by their wavelengths and frequencies (eq. 2).

$$\lambda = \frac{v}{f} \tag{2}$$

Where:

λ - is the wavelength of motion in meters $[m]$;

f - is the frequency of oscillation in Hertz $[Hz]$.

At the same time, the phase velocity of motion depends on the characteristics of the environment the wave passes through at the given moment. It is possible to express this phenomenon with the means of eq. 3.

$$v = \frac{1}{\sqrt{\varepsilon \cdot \mu}} \tag{3}$$

Where:

ε - is the permittivity of the environment, in farads over meter $[F/m]$;

μ - is the permeability of the environment in Henry over metres $[H/m]$, while $1H = 1s^2 \cdot F^{-1}$.

In extraordinary cases when the electromagnetic radiation passes through environments like vacuum, it is possible to rewrite equation 3 into the form of equation 4, the result of which is a constant called the velocity of light in vacuum.

$$c_0 = \frac{1}{\sqrt{\varepsilon_0 \cdot \mu_0}} \tag{4}$$

Hence, the value of immediate deviation of the electric radiation $C(x,t)$ can be simplified to the form of equation 6, but only if the following is valid:

$$\omega = 2 \cdot \pi \cdot f \tag{5}$$

$$C(x,t) = C_m \cdot \sin 2\pi \cdot \left(\frac{t}{T} \mp \frac{x}{\lambda} \right) \tag{6}$$

Where:

T - is the time in seconds $[s]$.

The division of electromagnetic radiation based on Maxwell’s theory includes radio and TV waves, microwaves, optical radiation, then X and gamma rays. It must be however stated that the optical radiation consists of infrared radiation, visible light and ultraviolet radiation and can be expressed with the following interval $\left(10^{-3} m, 10^{-7} m\right\rangle$ [3], [13], [19].

2.1.2 Photon theory

Photon theory is to be used, when an optical phenomenon cannot be directly described by Maxwell's wave theory, like the light emission of an absolutely black body in space, because according to the modern particle based definition light is made up from a huge amount of discrete small sub-atomic elements, called photons. Each of these photons has its own energy (eq. 7), and this energy is directly connected to its frequency, so photons are part of the electromagnetic radiation.

$$e_P = H_P \cdot f_P \tag{7}$$

Where:

e_P - is the energy of a photon in electron-volts $[eV]$;

H_P - is Planck's constants in electron-volt seconds $[eV \cdot s]$. Its latest known value is $4.135667516 \cdot 10^{-15}\ eV \cdot s$ [54];

f_P - is the frequency of adequate radiation in Hertz $[Hz]$.

The wavelengths and energies of photons, together with their adequate fractions of optical radiation including the division of optical light are revealed in tab. 1.

Tab. 1 *Wavelengths and energies of photons within the scope of optical radiation [Author, with source lit. [7], [20]]*

Radiation	**Division of radiation**	**λ [nm]**	**e_P [eV]**
Ultraviolet radiation	UV-C (SW)	100 - 280	12.40 - 4.43
	UV-B (MW)	280 - 315	4.43 - 3.94
	UV-A (LW)	315 - 400	3.94 - 3.10
Visible light	Violet	380 - 435	3.26 - 2.84
	Blue	435 - 500	2.84 - 2.48
	Green	500 - 566	2.48 - 2.19
	Yellow	566 - 600	2.19 - 2.07
	Orange	600 - 630	2.07 - 1.97
	Red	630 - 780	1.97 - 1.59
Infrared radiation	IR-A (SW)	780 - 1400	1.59 - 0.89
	IR-B (MW)	1400 - 3000	0.89 - 0.41
	IR-C (LW)	3000 - 10000	0.41 - 0.12

2.2 LIGHT SOURCES

Light sources as known, can be defined with the means of two different theories:

- The first theory available states, that a light source is a matter (element) which generates light, disabling the possibility of light reflectance and transmission [20];
- The second theory defines an object generating light with a viewpoint to architectural principles, therefore divides objects into primary and secondary light sources. Within primary sources are matters which do generate light, similarly to the first defined theory. Nevertheless, according to it elements which do reflect and transmit light, do change into secondary light sources once the light leaves their surface. The reasoning behind it, is stated in the evaluation procedure of light availability in the interiors of buildings, which is dependent on the sky [7], [21].

In addition, it must be stated that architectural lighting design distinguishes two elementary types of light sources. These are the following:

- Natural light sources: are those object and elements which can be commonly seen in nature, like the Sun, and Moon but there may be others too, special cases, like the lava flow after a volcano erupts, lightning in case of a thunder, or bioluminescence of organisms and plants (see *fig. 2*);

Sun
[Author]

Cloudy sky
[Author]

Firefly
[62]

Fig. 2 *Natural light sources*

- Artificial light sources: are objects which do have one thing in common, that is, that they were created by the ingenuity of humanity, for example: torches, candles, fireplaces, oil and gas lamps and luminaries. Especially luminaries, which were often based on incandescence of filaments or luminescence [3], [7], [21]. Nowadays, because of the energy efficiency of the incandescent light bulbs only CFL’s (Compact Fluorescent Lamps), LED’s (Light Emitting Diodes) and others artificial light sources with an adequate level of luminous efficacy can be used in architecture, manufacturing and housing.

2.2.1 Incandescence

Incandescence is a process in case of which light is produced with an exchange of radiation. This means, that the amount of energy, which is absorbed by an arbitrary matter in space is then converted into another form due to an increase in the movement of atoms and interactions between them, nevertheless the absorbed and emitted radiation must be in equilibrium.

Commonly, in case of incandescence, light can be produced only by materials that can withstand a temperature of 873*K* (600°*C*) or more [21]. If the temperature would be lower, then it would come only to the emission of thermal radiation into space by the given substance.

The fundamental equation (eq. 8) describing incandesce was developed by M. Planck in the 19th century. It was the result of his experimental activities made on black bodies [7].

$$M_{e,\lambda}(\lambda,T)=c_1\cdot\lambda^{-5}\cdot\left(e^{\frac{c_2}{\lambda\cdot\theta}}-1\right)^{-1} \tag{8}$$

Where:

$M_{e,\lambda}(\lambda,T)$ - is the spectral radiant exitance of a material $[W\cdot m^{-2}/\mu m]$;

λ - is the wavelength of radiation in metres $[m]$;

θ - is the temperature in Kelvins $[K]$;

c_1 - is a constant with a value of $3.742\cdot10^{-16}W\cdot m^2$;

c_2 - is a constant with a value of $1.439\cdot10^{-2}m\cdot K$.

For short wavelengths and small temperatures, equation 8 have had been rewritten by W. Wien into the form of equation 9 [3]. Hence, this relationship is named as, Wien’s Law of Radiation.

$$M_{e,\lambda}(\lambda,T)=c_1\cdot\lambda^{-5}\cdot e^{-\frac{c_2}{\lambda\cdot\theta}} \tag{9}$$

If $\lambda\cdot T$ would be higher than 0.002*m*·*K*, then the following would be valid too:

$$M_{e,\lambda}(\lambda,T)=\frac{c_1}{c_2}\cdot\lambda^{-4}\cdot\theta \tag{10}$$

The wavelength of radiation emitted by an absolute black body can be expressed with the means of the following formulae (eq. 11):

$$\lambda_{BBody}=\frac{2.898\cdot10^{-3}}{\theta} \tag{11}$$

With the integration of eq.8 under the wavelength interval of $(0,\infty)$ the Stefan–Boltzmann Law can be derived. It compares the energy emitted by a black matter as a proportion to the fourth power of its temperature at which it radiates. Hence, the Stefan-Boltzmann Law can take the form of equation 12.

$$M_e = \sigma \cdot \theta^4 = 5.669 \cdot 10^{-8} \cdot \theta^4 \qquad (12)$$

2.2.2 The Sun

The Sun is the most known primary natural energy source working on incandescence, known by humanity. It handles about a star, located at the centre of the solar system around which the planets, including the Earth, are orbiting. It radiates energy in the whole scope of electromagnetic radiation, i.e. waves from $10^{-11}m$ up to $1m$ because of the thermonuclear chain reactions undergoing in its core. The operating temperature of the core is hence close to $15.7 \cdot 10^6 K$. This certain amount of heat is then transferred to the outermost layers of the star, by the radiative and convective zones, although it handles only about a portion of it because these zones do have other functions as well, like to hold back part of the heat radiated by the core.

The shape of the Sun is close to that of a sphere. Nevertheless, its visible form seen throughout the day is only the manifestation of the Suns photosphere, chromosphere and corona (the layers and zones of the Sun are in view in fig. 3.). The photosphere is almost the outermost layer of the Sun and it consists of gasses in a plasmatic state. The working solar temperature of this peculiar layer is around $6000K$ [54], on the contrary its effective temperature is slightly lower, just around $5770K$ [19], $5778K$ [64].

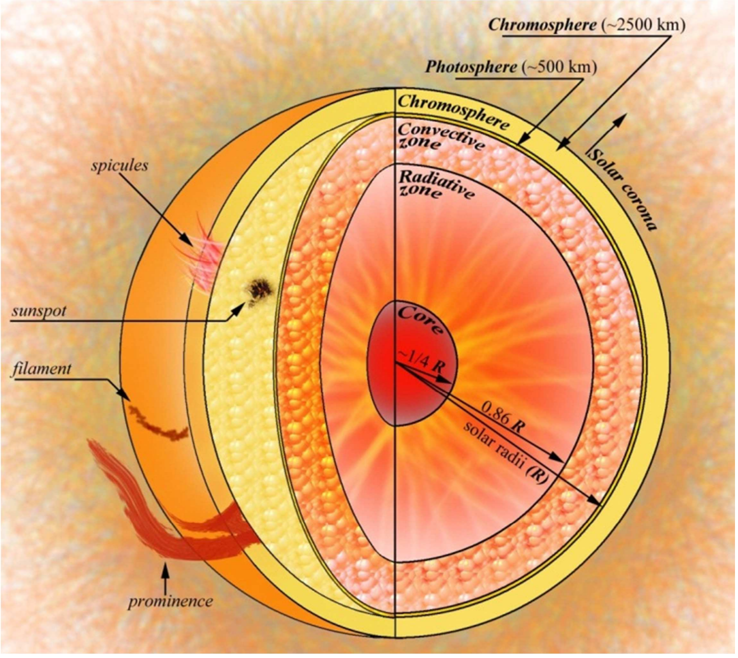


Fig. 3 *Cross-section of the Sun [55]*

The other characteristics of the Sun are observable below:

- Age: approximately $5 \cdot 10^9$ years;
- Diameter: around $1.392 \cdot 10^6 km$;
- Surface area: about $6.0877 \cdot 10^{12} km$;
- Mass: $1.9891 \cdot 10^{30} kg$;
- Average distance from the Earth: $1.496 \cdot 10^8 km$;
- Luminosity: $3.75 \cdot 10^{28} lm$;
- Solar light constant: $133800 lx$;
- Etc.

2.2.3 The atmosphere and the sky

Within the field of daylighting design of interiors, the atmosphere is often mistaken with the sky, although the sky is actually a part of the atmosphere or better said the sky is created within the atmosphere due to the scattering of incoming visible radiation. Thus, the atmosphere or at least a part of the atmosphere becomes a secondary light source.

The atmosphere itself is an air-bubble covering up the globe, supporting the life on the Earth's surface, as to the living beings primarily inhabiting the continental crust do have a need for air, heat, light, etc. The atmosphere is therefore at a huge degree made up from gasses like nitrogen, oxygen, hydrogen, carbon dioxide, and so on, though water and solid particles can be found within it also. The distribution of the particles becomes scarcer and scarcer with the distance which can be measured between them and the Earth's core, because of changes in the gravitational field.

That is why it is possible to categorize the layers of the atmosphere. There are two major layers and a few minor ones. These are the following:

- The **homosphere**, consisting of the following important minor layers:
  - The **troposphere** – it handles about the innermost layer of the atmosphere, which is in direct contact with the Earth's crust. It contains the gasses demanded by the living beings practically for breathing.
  - The **stratosphere** – this particular layer protects the Earth's surface from the harms of ultraviolet radiation, as to the Ozone layer is part of it, so it filters the incoming optical radiation.
  - The **mesosphere** – is the last layer of the homosphere, which protects the surface from the effects of incoming objects, like meteorites, comets.
- Then there is the **heterosphere**. It consists of two layers only, the thermosphere and exosphere, and it is researched by the space programs of different countries, like the NASA in the USA.

The generated sky as already mentioned is a result of light scattering within the troposphere caused by the particles of air, water and dust among others. As the molecules intercept the incoming electromagnetic radiation, more precisely the visible radiation, they do partially transmit it, partially reflect it and partially absorbed it. The phenomenon resulting in the occurrence of the blue sky is caused by the differences in the reflected, transmitted and absorbed parts of the visible radiation at different wavelengths. As to, mostly only the optical radiation representing the blue colour is reflected back to the space by the molecules. On the other hand, if the transmitted light rays are further on intercepted, by the water and solid particles within the atmosphere, the resulting colour of the sky is going to be dark, usually grey, depending on the level of turbidity within the troposphere.

At the end of the 20th century, a new set of sky standards was defined by R. Kittler and S. Darula [4], [24]. These have had been overtaken also by CIE (Commission Internationale de l´Eclairage). It handles about 15 different sky types, shown in tab. 2 [46].

The gradation and indicatrix groups from tab. 2 can be represented also in the form of curves (these are manifested in fig. 4. The curves of the 3(4) most influential sky types have had been outlined by the author with colours).

Tab. 2 *The set of standard skies defined by CIE (from 2002) [46]*

Type	**Grad. gr.**	**Ind. gr.**	**Grad. parameters**		**Scattering indicatrix parameters**			**Description of luminance distribution**
			a	**b**	**c**	**d**	**e**	
1	I	1	4.0	-0.70	0.0	-1.0	0.00	CIE Standard Overcast Sky, Steep luminance gradation towards zenith, azimuthal uniformity
2	I	2	4.0	-0.70	2.0	-1.5	0.15	Overcast, with steep luminance gradation and slight brightening towards the sun
3	II	1	1.1	-0.80	0.0	-1.0	0.00	Overcast, moderately graded with azimuthal uniformity
4	II	2	1.1	-0.80	2.0	-1.5	0.15	Overcast, moderately graded and slight brightening towards the sun
5	III	1	0.0	-1.00	0.0	-1.0	0.00	Sky of uniform luminance
6	III	2	0.0	-1.00	2.0	-1.5	0.15	Partly cloudy sky, no gradation towards zenith, slight brightening towards the sun
7	III	3	0.0	-1.00	5.0	-2.5	0.30	Partly cloudy sky, no gradation towards zenith, brighter circumsolar region
8	III	4	0.0	-1.00	10.0	-3.0	0.45	Partly cloudy sky, no gradation towards zenith, distinct solar corona
9	IV	2	-1.0	-0.55	2.0	-1.5	0.15	Partly cloudy, with the obscured sun

10	IV	3	-1.0	-0.55	5.0	-2.5	0.30	Partly cloudy, with brighter circumsolar region
11	IV	4	-1.0	-0.55	10.0	-3.0	0.45	White-blue sky with distinct solar corona
12	V	4	-1.0	-0.32	10.0	-3.0	0.45	CIE Standard Clear Sky, low luminance turbidity
13	V	5	-1.0	-0.32	16.0	-3.0	0.30	CIE Standard Clear Sky, polluted atmosphere
14	VI	5	-1.0	-0.15	16.0	-3.0	0.30	Cloudless turbid sky with broad solar corona
15	VI	6	-1.0	-0.15	24.0	-2.8	0.15	White-blue turbid sky with broad solar corona

Grad. gr. – gradation group, ind. gr. – indicatrix group

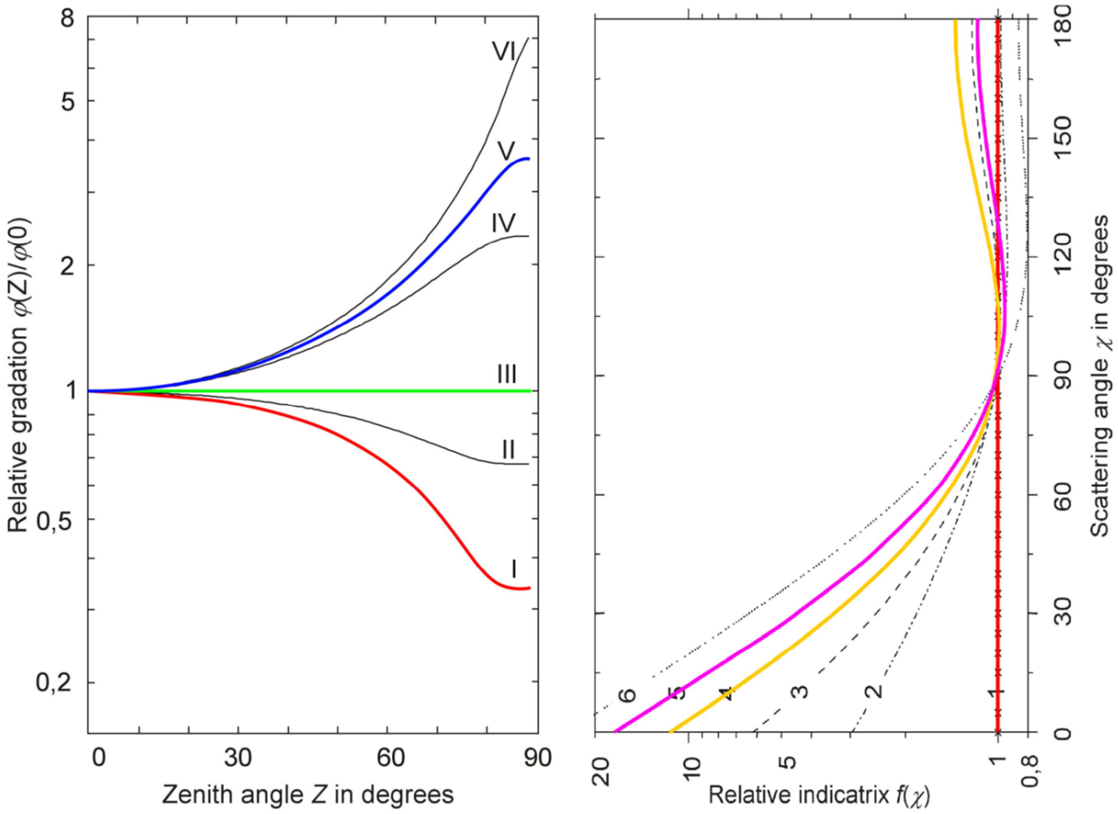


Fig. 4 *Gradation and indicatrix function groups defined in tab. 3. [46]*

These indicatrix and gradient parameters can be used in equations to obtain the luminance of the sky at an arbitrary point, or the luminance distribution of the whole sky for a given date, time and sky type. The relative luminance distribution of the "white-blue sky with distinct solar corona" is to be seen in fig. 5.

The determination procedure includes the following steps and formulas:

To obtain the angular distance between the sky element and the Sun the following relationship can be used (eq. 13).

$$\chi = \arccos\left(\cos Z_S \cdot \cos Z + \sin Z_S \cdot \sin Z \cdot \cos\left|\alpha - \alpha_S\right|\right) \quad (13)$$

Where:

Z - is the angular distance between a sky element and the zenith in radians $[rad]$;

Z_S - is the angular distance between the Sun and the zenith in radians $[rad]$;

α - is the azimuth of the sky element in radians $[rad]$;

α_S - is the azimuth of the Sun in radians $[rad]$.

However, the zenith angles can be also expressed as functions of elevations:

$$Z = \frac{\pi}{2} - \gamma \text{ and } Z_S = \frac{\pi}{2} - \gamma_S \quad (14)$$

Where:

γ - is the elevation angle of sky element in radians $[rad]$;

γ_S - is the elevation angle of the Sun in radians $[rad]$.

Thus, the ratio between the luminance levels of the sky at an arbitrary point and the zenith is equal to (eq. 15):

$$\frac{L_a}{L_Z} = \frac{f(\chi) \cdot \varphi(Z)}{f(Z_S) \cdot \varphi(0)} \quad (15)$$

Where:

L_a - is the luminance of sky at an arbitrary point in candelas over square meter $[cd \cdot m^{-2}]$;

L_Z - is the luminance of sky at the zenith in candelas over square meter $[cd \cdot m^{-2}]$;

$f(\chi)$ - is the scattering indicatrix function of an arbitrary sky element;

$f(Z_S)$ - is the scattering indicatrix function of the sky at the zenith;

$\varphi(Z)$ - is the luminance gradation function at an arbitrary sky element;

$\varphi(0)$ - is the luminance gradation function of the sky at the zenith.

Next is, to determine the value of the luminance gradation of the sky at the given sky elements location:

$$\text{arbitrarily if } 0 \le Z \le \frac{\pi}{2} \text{ then } \varphi(Z) = 1 + a \cdot \exp\left(\frac{b}{\cos Z}\right) \quad (16)$$

$$\text{at the horizon } \varphi(Z)=\varphi\left(\frac{\pi}{2}\right)=1 \tag{17}$$

$$\text{and at the zenith } \varphi(0)=1+a\cdot\exp(b) \tag{18}$$

Where:

a,b - are the luminance gradation parameters described in tab. 2.

The rest is to evaluate the scattering indicatrix at a point on the sky (eq. 19) and at the zenith (eq. 20):

$$f(\chi)=1+c\cdot\left[\exp(d\chi)-\exp\left(d\cdot\frac{\pi}{2}\right)\right]+e\cdot\cos^2\chi \tag{19}$$

$$f(Z_S)=1+c\cdot\left[\exp(dZ_S)-\exp\left(d\cdot\frac{\pi}{2}\right)\right]+e\cdot\cos^2 Z_S \tag{20}$$

Where:

c,d,e - are the scattering indicatrix parameters described in tab. 2.

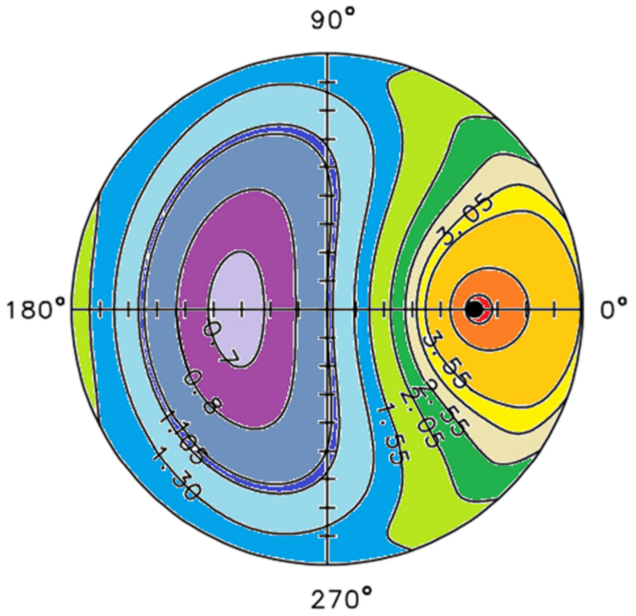


Fig. 5 *The relative sky luminance distribution of "The white-blue sky with distinct solar corona" (Grad. group: IV, Ind. group: 4,* $\gamma_S = 38.02°$ *[24].*

CIE Standard Overcast Sky

The CIE Overcast Sky must be described as an overcast sky with a luminance distribution gradation 1:3 from the horizon to the zenith in case of a dark terrain or light terrain.

The luminance distribution of three CIE standard skies are located in fig. 6.

The luminance gradation of a CIE Standard Overcast Sky in case of a dark terrain can be expressed with the means of the following formulae:

$$\frac{L_\gamma}{L_Z} = \frac{1 + 2 \cdot \sin\gamma}{3} \tag{21}$$

Where:

L_γ - is the luminance of the sky element with an elevation of γ in candelas per square meters $[cd \cdot m^{-2}]$;

L_Z - is the luminance at zenith in candelas per square meters $[cd \cdot m^{-2}]$;

Unfortunately, equation 21 is not suited for the determination of luminance values under different angles, therefore it have had been rewritten into the form of equation 22, by exchanging the luminance at the zenith with the average luminance of the sky.

$$\frac{L_\gamma}{L_A} = \frac{3 \cdot (1 + 2 \cdot \sin\gamma)}{7} \tag{22}$$

Where:

L_A - is the average luminance of the sky, in candelas per square meters $[cd \cdot m^{-2}]$.

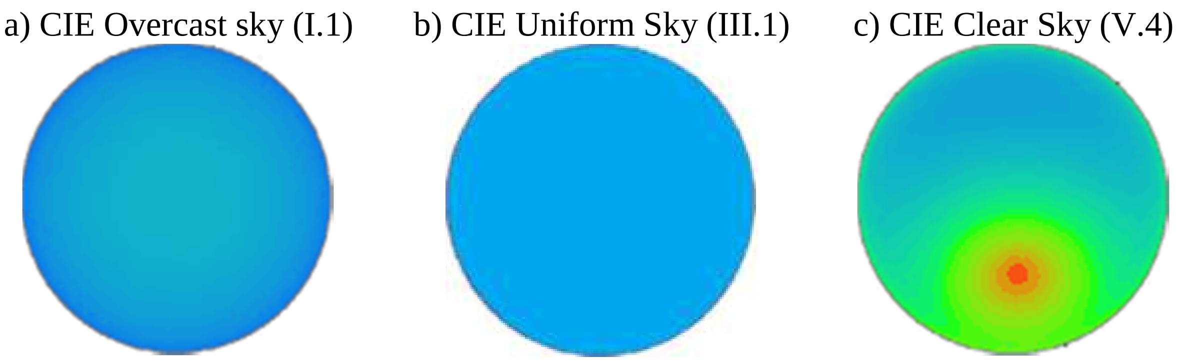

a) CIE Overcast sky (I.1) b) CIE Uniform Sky (III.1) c) CIE Clear Sky (V.4)

Fig. 6 *Luminance distribution comparison of CIE standard skies*

The evaluation of a sky elements luminance to determine whether it handles about a CIE Overcast Sky by measurements required the introduction of certain ratios and their comparison [26]. Namely, the verification of the luminance values of sky elements under the elevations of 15° and 45°.

$$\frac{L_{15}}{L_Z} = \langle 0.3, 0.6 \rangle \tag{23}$$

$$\frac{L_{45}}{L_Z} = \langle 0.7, 0.85 \rangle \tag{24}$$

Where:

L_{15} - is the luminance of sky at an angle of 15° above horizon in candelas over square meter $[cd \cdot m^{-2}]$;

L_{45} - is the luminance of sky at an angle of 45° above horizon in candelas over square meter $[cd \cdot m^{-2}]$.

If, luminance values of sky elements under the elevations of 15° and 45° would fulfil the conditions included in equations 23 and 24, then the resulting global horizontal illuminance can be obtained with the utilizations of the following relationship, based on the skies luminance at the zenith [19]:

$$E_e = \frac{7}{9} \cdot L_z \cdot \pi \tag{25}$$

Where:

E_e - is the global horizontal illuminance under a CIE Standard Overcast Sky in case of a dark terrain in lux $[lx]$.

2.3 QUANTITIES, UNITS AND TERMS USED IN PHOTOMETRY AND DAYLIGHTING OF BUILDINGS

The given chapter is going to deal with the basic quantities and units used in the field of photometry. In more detail, it is going to describe luminous intensity, luminance, illuminance among others [7], [19], [39].

2.3.1 Radiant flux

Radiant flux is a quantity used mostly in radiometry. Nonetheless, with a small transformation it can express luminous flux, too. The quantity itself is equal to the amount of energy emitted by a source within the scope of electromagnetic optical radiation (including ultraviolet, visible and infrared radiation) under a unit time. The following equation expresses radiant flux the best:

$$\Phi_e = \frac{dQ_e}{dt} \tag{26}$$

Where:

dQ_e - is the maximal radiant energy in Joules $[J]$;

dt - is the unit time in seconds $[s]$.

The SI unit of radiant flux is Watt $[W]$.

2.3.2 Relative luminous efficiency

The process of vision itself is a photochemical reaction going through within the eyes after the visible part of the electromagnetic radiation passes through the cornea, pupil and lens and hits the back of the eye bulb where the biological photoreceptors are located. These photoreceptors then transform and transmit the image perceived by them throughout the retina into the brain in neuron waves.

There are altogether two types of such photoreceptors, acting in the eyes:

- the rods;
- and the cones.

Rods are standardly responsible for the achromatic vision on the other hand the cones for coloured vision. Nevertheless, as to the wavelength of visible optical radiation varies throughout the scope of electromagnetic radiation, so does the sensibility of the eye to each of these wavelengths. It’s zero at the ends of the given interval and its peak is around *555nm* for daytime (photopic) vision and around *507nm* at night-time (scotopic) vision. These are the key elements of the “Spectral luminous efficiency functions”, either for daytime (photopic) or night-time (scotopic visions). The shortcut related to the spectral luminous efficiency curve is $V(\lambda)$.

Fig. 7 demonstrates both $V(\lambda)$ curves (On the x-axis the wavelength of visible spectrum is located, while on the y-axis the luminous efficiency).

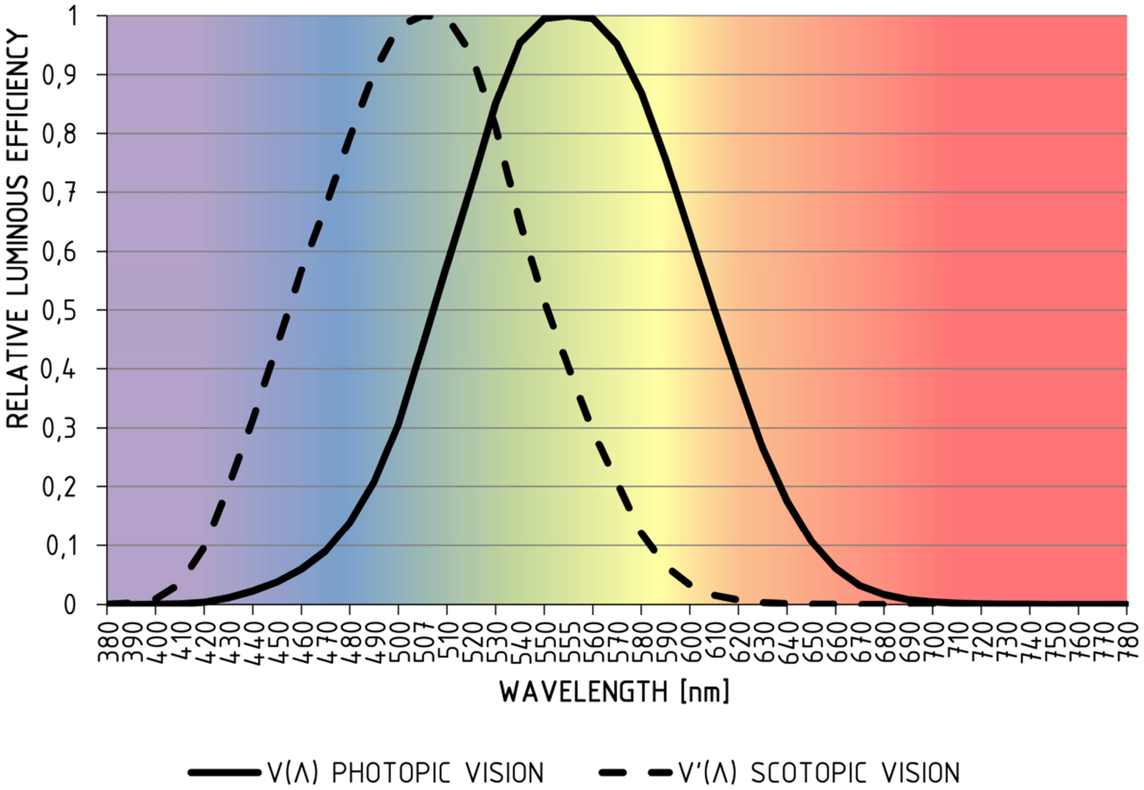


Fig. 7 *Curves of "relative luminous efficiency function" for day and night vision [Author, with source lit. [7]]*

The "spectral luminous efficiency function" is widely used by the manufacturers of luminance and illuminance meters, whereas they have to shift the visual response of the products close to that of human vision.

2.3.3 Luminous flux

Luminous flux, as already mentioned, is a portion of the radiant flux and can be expressed as the perceived power of radiant flux, which is adjusted to the scope of visible light. That is why the electromagnetic optical radiation used to get the radiant flux is reduced solely to the wavelength spectrum of the $V(\lambda)$ (relative luminous efficiency curve for daytime vision) or $V'(\lambda)$ (relative luminous efficiency curve for night vision). Luminous flux is therefore equal to:

$$\Phi_v = K_m \cdot \int_{380}^{780} \Phi_{e,\lambda} \cdot V(\lambda) \cdot d(\lambda) \qquad (27)$$

Where:

K_m - is the maximal luminous efficiency of radiation in lumen over Watts $[lm \cdot W^{-1}]$;

$\Phi_{e,\lambda}$ - is radiant flux for wavelength λ in Watts $[W]$;
$V(\lambda)$ - is the relative luminous efficiency of monochromatic photopic vision.

The SI unit of luminous flux is lumen $[lm]$.

One lumen is the luminous flux corresponding to a light source with a luminous intensity of one candela $[cd]$ spread under a solid angle of one steradian $[sr]$.

With the simplification of eq. 27, the luminous flux for daytime vision can be rewritten into the form of the weighted sum of power at the wavelengths of visible light for both, the continuous (eq. 28) and the linear (eq. 29) light spectrum.

$$\Phi_v = 683 \cdot \sum_{380}^{780} \Phi_{e,\lambda}(\lambda_i) \cdot V(\lambda_i) \cdot \Delta\lambda_i \tag{28}$$

$$\Phi_v = 683 \cdot \sum_{380}^{780} \Phi_{e,\lambda}(\lambda_i) \cdot V(\lambda_i) \tag{29}$$

2.3.4 Components of luminous flux

The incident luminous flux by passing through the interface of the two environments attenuated while it's partially reflected, partially absorbed and transmitted (eq. 30) [4]. The components of lumenous flux are graphically shown also in fig. 8.

$$\Phi_v = \Phi_{v,\rho} + \Phi_{v,\alpha} + \Phi_{v,\tau} \tag{30}$$

Where:
$\Phi_{v,\rho}$ - is the reflected comp. of the incident luminous flux in lumens $[lm]$;
$\Phi_{v,\alpha}$ - is the absorbed comp. of the incident luminous flux in lumens $[lm]$;
$\Phi_{v,\tau}$ - is the transmitted comp. of the incident lum. flux in lumens $[lm]$.

The previously mentioned components of luminous flux can be described with the means of the following factors (eq. 31, 32, 33).

Reflectance
$$\rho_v = \frac{\Phi_{v,\rho}}{\Phi_v} = \frac{\int_{380}^{780} \Phi_{e,\lambda} \cdot V(\lambda) \cdot \rho(\lambda) \cdot d(\lambda)}{\int_{380}^{780} \Phi_{e,\lambda} \cdot V(\lambda) \cdot d(\lambda)} \in \langle 0,1 \rangle \tag{31}$$

Absorbtion
$$\alpha_v=\frac{\Phi_{v,\alpha}}{\Phi_v}=\frac{\int_{380}^{780}\Phi_{e,\lambda}\cdot V(\lambda)\cdot\alpha(\lambda)\cdot d(\lambda)}{\int_{380}^{780}\Phi_{e,\lambda}\cdot V(\lambda)\cdot d(\lambda)}\in\langle 0,1\rangle \tag{32}$$

Transmittance
$$\tau_v=\frac{\Phi_{v,\tau}}{\Phi_v}=\frac{\int_{380}^{780}\Phi_{e,\lambda}\cdot V(\lambda)\cdot\tau(\lambda)\cdot d(\lambda)}{\int_{380}^{780}\Phi_{e,\lambda}\cdot V(\lambda)\cdot d(\lambda)}\in\langle 0,1\rangle \tag{33}$$

While equation 34 is valid:

$$\rho_v+\alpha_v+\tau_v+=1 \tag{34}$$

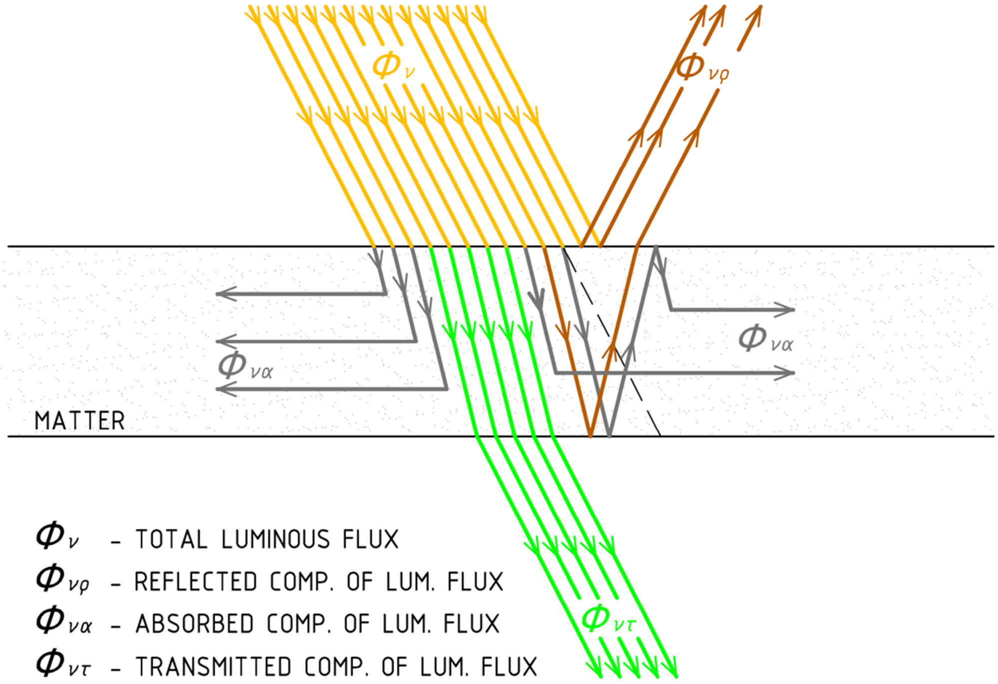


***Fig. 8** The components of luminous flux [7]*

2.3.5 Luminous intensity

Luminous intensity describes the amount of light emitted by a point source within a solid angle of one steradian $[sr]$ into space. Luminous intensity is expressed by the following equation:

$$I_v=\frac{d\Phi_v}{d\Omega} \tag{35}$$

Where:

$d\Phi_v$ - is the amount of emitted luminous flux in lumens $[lm]$;

$d\Omega$ - is the solid angle under which the light is emitted in steradians $[sr]$.

The SI unit of luminous intensity is called candela $[cd]$, and can defined as the radiant intensity equal to $1/683 W \cdot sr^{-1}$, radiated by a source emitting a monochromatic type of radiation at a frequency of $5.4 \cdot 10^{14} Hz$.

Instruments designed to measure luminous intensity can be calibrated with the help of the “etalon of candela” (see fig. 9).

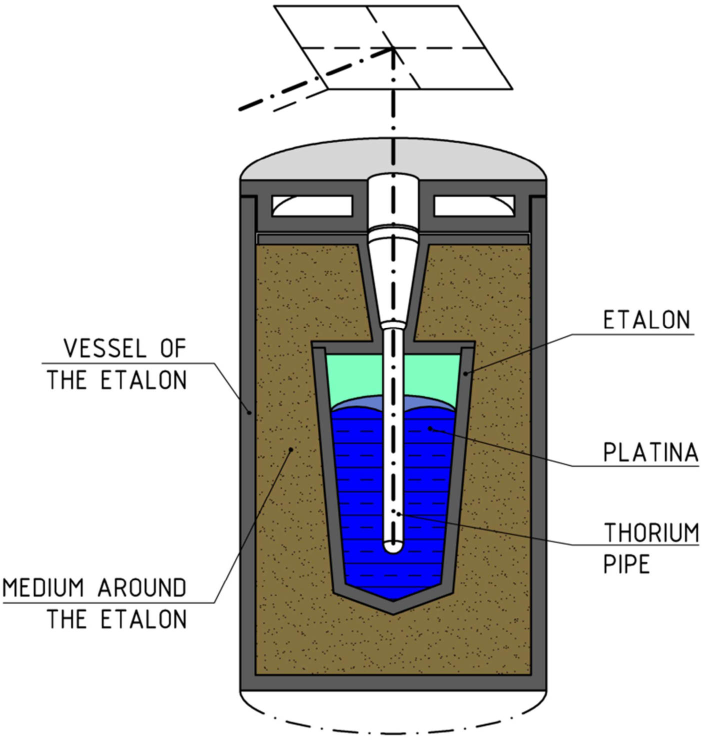


Fig. 9 *The etalon of candela [7], [8].*

2.3.6 Luminance

Luminance characterizes the amount of luminous intensity which is emitted by a given elementary surface into the space under a given solid angle and direction, thus it indicates how bright the surfaces are going to be after looking at them.

The unit of luminance is candela over square meter $[cd \cdot m^{-2}]$, and it can be determined from luminous flux by eq. 36.

$$L_v = \frac{d^2\Phi_v}{d\Omega \cdot dA \cdot \cos\Theta} \tag{36}$$

Where:

$d^2\Phi_v$ - is the luminous flux transmitted in a given direction by an elementary volume through a point in space under the solid angle $d\Omega$.

dA - is the area of the projected cross-section inheriting the point, perpendicular to the direction of spreading in square meters $[m^2]$;

Θ - is angle enclosed between the specified surfaces normal and the direction of spreading in radians $[rad]$.

Luminance therefore, with a slight modification of eq. 36 can be evaluated from:

- Luminous intensity, transmitted into the space by a light source (fig. 10a);
- Illuminance values, determined on a surface lit up by a source (fig. 10b);
- Luminous flux, if it handles about the determination of luminance values of an elementary corpuscle of light rays passing through a non-diffuse transparent environment.

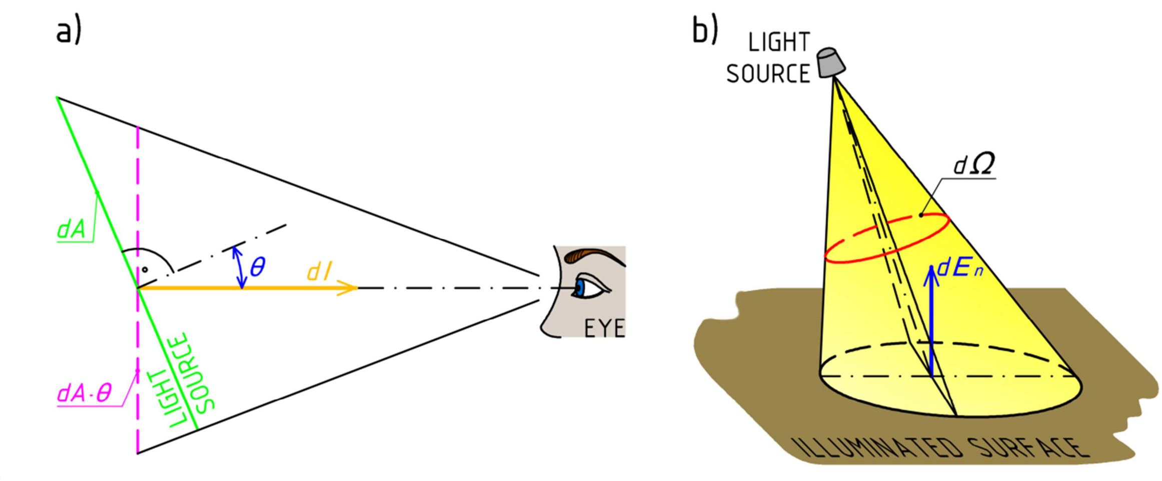


Fig. 10 *Luminance in a point of an illuminated surface [Author, with source lit. [7]].*

As to not every surface is ideal and may transmit or reflect light in a different manner a classification was created for transparent and opaque surfaces. This classification is visible in fig. 11.

Because of this division, most of the surfaces are referred to as perfectly diffuse Lambertian (may be reflective or transmissive). The luminance values of Lambertian reflective surfaces can be determined with the help of eq. 37. It handles about a simplification of equation 36.

$$L_v = \frac{\rho_d \cdot E_v}{\pi} \tag{37}$$

Where:

ρ_d - is the light reflectance value of the Lambertian surface [-];

E_v - is the illuminance determined on surface in lux $[lx]$.

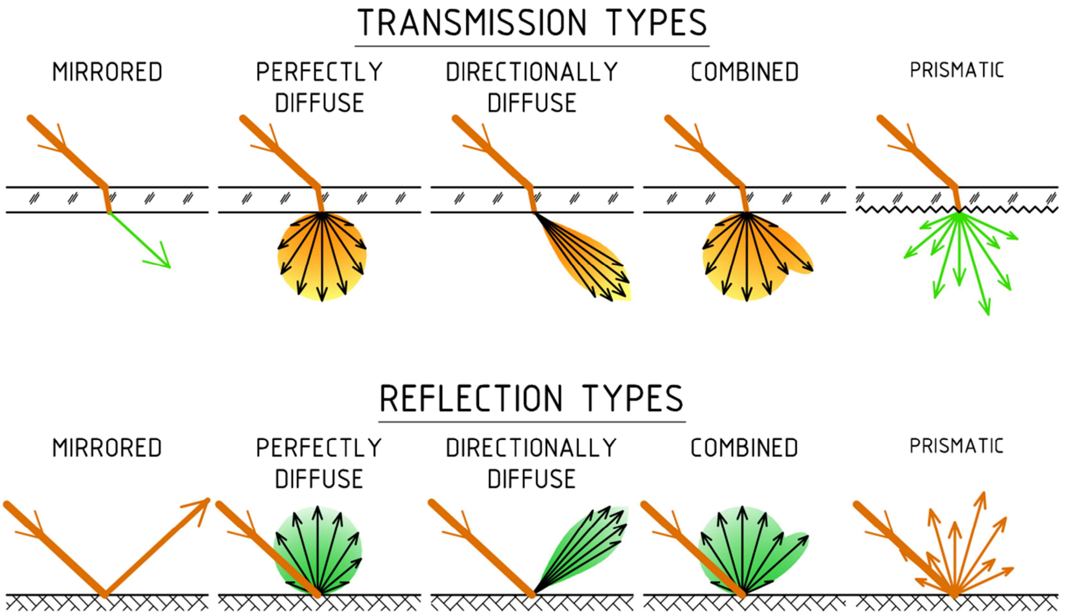


Fig. 11 *The classification of surfaces according to their characteristics in light transmission and reflection [Author, with source lit. [4]].*

2.3.7 Luminous emittance (also called as luminous exittance)

Luminous emittance is the ratio between the luminous flux emitted into the space by an elementary surface, and the area of this given surface (eq. 38). Its unit is lumen over square meters $[lm \cdot m^{-2}]$.

$$M_v = \frac{d\Phi_v}{dA} \tag{38}$$

Where:

$d\Phi_v$ - is the emitted luminous flux in lumens $[lm]$;

dA - is the area of emitting surface in square meters $[m^2]$.

The connection between luminous emittance and luminance is expressed by equation 39:

$$M_v = \int_{\Omega} L_v \cdot \cos\Theta \cdot d\Omega \tag{39}$$

Where:

L_v - is the luminance of the emitting surface in candela per square meters $[cd \cdot m^{-2}]$;

$d\Omega$ - is the solid angle under which the light is emitted in steradians $[sr]$;

Θ - is angle enclosed between the specified surfaces normal and the direction of spreading in radians $[rad]$.

2.3.8 Illuminance

Illuminance is the opposite of luminous emittance. Therefore, it can be defined as the ratio between the luminous flux incoming upon a surface of area A (eq. 40).

$$E_v = \frac{d\Phi}{dA} = \int_{\Omega} L_v \cdot \cos\Theta \cdot d\Omega \tag{40}$$

Where:

$d\Phi$ - is the luminous flux incident to a surface, in lumens $[lm]$;

dA - is the unit area of the surface, in square meters $[m^2]$.

The SI unit of the given quantity is lux $[lx]$ and corresponds to lumen per square meters $[lm \cdot m^{-2}]$.

Also its worth to mention, that illuminance is one of the photometric quantities, together with luminance, which can be measured directly with the help of a measuring device, therefore this given quantity is widely used in various fields, including luminaries design, building industry, etc.

2.3.9 Working plane (also known as workplane)

The working plane is an imaginary horizontal (or vertical) surface, which is located at a height, where the main visual activity should take place in interior, inside a room. It is usually placed in a distance of 850mm above the floor and consists of a set of points (sieve), over which the illuminance and daylight factor values are determined.

There are other derivations of the working plane, which can be used to evaluate the various aspects of daylighting indoors.

2.3.10 Daylight factor DF

Daylight factor is a quantity, which is the ratio of two illuminance levels measured at the exact same time. The first one of these values is the illuminance measured in the interior of a building on the working plane while the second one demonstrated the global horizontal illuminance level under an unobstructed CIE Standard Overcast Sky.

The daylight factor is expressed in percentages [%].

$$DF = \frac{E_i}{E_e} \cdot 100 \tag{41}$$

Where:

E_i - is the illuminance incident to a point on the working plane $[lx]$;

E_e - is the global hor. ill. under an unobstructed CIE Overcast Sky $[lx]$.

The daylight factor is made up from three components: the sky component, the externally and internally reflected components, these are shown in fig. 12 together with the illustration of illuminance values measured on the working plane and under an unobstructed CIE Overcast Sky.

$$DF = DF_s + DF_e + DF_i \tag{41}$$

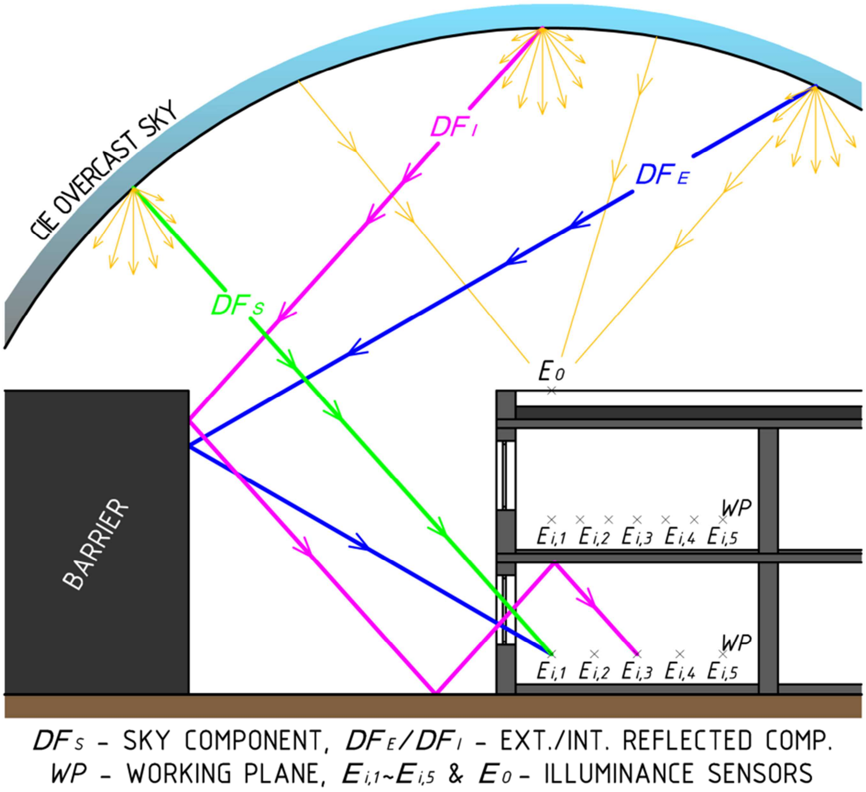


Fig. 12 *The components of daylight factor [Author]*

2.3.11 Uniformity of illuminance levels [41], [57]

The uniformity of illuminance levels demonstrates the distribution of daylight along the depth of the evaluated room or facility. Its value is determined differently for light coming from natural and artificial light sources.

Whereas in case of daylighting it is calculated from the minimal and maximal values of daylight factors attained over the working plane (eq. 42), it has a slightly different approach in case of artificial lighting when it is calculated from the minimal and mean values of illuminance levels obtained over the working plane (eq. 43).

In both of the described cases, it handles about a unit less quantity.

$$UDL = \frac{DF_{\min}}{DF_{\max}} \tag{42}$$

Where:

$DF_{\min}$ - is the minimal value of daylight factor acquired over the scope of the working plane, in percentages $[\%]$;

$DF_{\max}$ - is the maximal value of daylight factor acquired over the scope of the working plane, in percentages $[\%]$.

$$UAL = \frac{E_{w,\min}}{E_{w,m}} \tag{43}$$

Where:

$E_{w,\min}$ - is the minimal value of illuminance acquired over working plane, in lux $[lx]$;

$E_{w,\mathrm{m}}$ - is the mean value of illuminance acquired over working plane, in lux $[lx]$;

2.3.12 Index of refraction

The index of refraction is a one value characteristic representing a special property of a material, causing the light to change its direction at the interface of two matters as a result of varying velocities. Its value for materials can be determined by dividing the speed of light in vacuum with the speed of light in the certain material. It handles about a unit less quantity.

$$\frac{\eta_i}{\eta_0} = \frac{c_0}{c_i} \tag{44}$$

Where:

η_0 - is the index of refraction of light in vacuum [–];

η_i - is the index of refraction of light in a material [–];

c_0 - is the speed of light in vacuum $[m \cdot s^{-1}]$;

c_i - is the speed of light in a material $[m \cdot s^{-1}]$.

The resulting value is usually bigger than one.

3 ARCHITECTURE AND DAYLIGHT

- **Daylighting systems in architecture**
- **Evaluation of light conditions in buildings**
- **Design methods for daylighting**

From the beginnings, humanity was afraid and began to seek for shelters to protect themselves against the attacks of animals, climatic conditions and later before aggressive tribes too. Therefore they were looking for caves inhabited by creatures, which could be killed and supply them with food and living possibilities. Only later, as the weather had begun to change, got colder, they started to make door-like structures without openings moved into the entrance to these caves or holes inside of mountains. Only a while after this, they started to make door like elements with openings to shut down the entrances to the caves and at the same time allow its ventilation. As time flew by and the number of people living in the tribes arose, thus causing a deterioration of the inhabitable space, they had begun to look for other possibilities and structures to protect themselves and live in. Despite of such a hardship several building types arose from dust, especially fortifications and sheds made from wood and soil, however depending on the given location, which then influenced the overall architecture of the region for thousands of years [17].

In the biggest ancient civilizations, like Egypt, Greece, Rome, Mesopotamia, China and the Indian tribes of Central and South America (Aztecs, Mayas, and Incas), the building design was largely devoted to Gods or other un-natural phenomenon, which people of different realms believed in. The building objects they constructed were usually temples, pyramids (except for Egypt, where the pyramids were erected as tombs for the pharaohs) of different shapes, in short show-up monuments with sacred grounds and an increased amount of incoming daylight throughout openings in the auxiliary structures just to illuminate the paintings and carvings on the internal surfaces. In ancient Egypt, therefore shafts coated with gold have had been introduced. Another of these ancient masterpieces is the Pantheon in Rome, erected with the application of roman concrete and illuminated by the only opening at the top of the covering copula. The dwellings of citizens however were usually small with a handful or no openings, excluding the door used to exchange air, because almost every activity they have had to do was done outdoors. The shape and other properties of these houses depended on the location they were erected. In dry regions, flat roofs and robust structures to withstand the heat acting onto them have had been used (Egypt, Mesopotamia, etc.). The total opposite happened in colder regions of the Globe (Rome, Greece), where the massive walls and roofs were exchanged by column based structures, with a south facing main façade to increase the heat gains from the incoming solar radiation. Wooden wings, laths, furs or leather had covered the openings until the discovery of flat glass and the techniques to make it [16].

During the Dark Age, after the downfall of the Greek, Roman and Persian Empires, the building industry stagnated. It was pushed into the background because of the never-ending wars between tribes of different nations. Only under the rule of respected and strict kings was humanity able to rediscover architecture. The different eras throughout the middle age had their significant buildings, like the rotundas within the Romanesque period, churches and cathedrals throughout the Gothic times, etc. [11]. It's worth to mention, that the buildings developed until the pre-Romanesque period, though it handled about religious ones had only small openings, similarly to the housing of citizens, but their position was bound to be on the east due to religious reasons. In the Gothic period, they began to experiment with structures. They developed the vaults and arches, while transmitting the loads to the piers left within the masonries, thus leaving behind huge openings. Openings decorated by coloured glass showing chapters from the Bible, and being majestic. At the exact same time on the opposite side of the Earth, the buildings may they be one on multi-storey ones, were based on fragile frame based structures made from wood especially from bamboo logs, allowing the inhabitants to rebuild their houses on the go, under a short amount of time. The available resources, like the oil-impregnated rice paper in the Japans, had enabled them to create highly illuminated primary or secondary indoor spaces.

Until the beginning of the industrial revolution in the 18th and 19th century, daylighting had a significant position in the architectural design, as to it was needed for the handcrafts done indoors. Nevertheless, with the introduction of electricity and steel the facilities and the manufacturing process had changed forever. Architects on demand (with exceptions, like Ludwig Mies Van der Rohe or Frank Lloyd Wright) had begun to construct enormous building objects with indoor spaces of almost unlimited dimensions.

Unfortunately, it took decades until this direction have had been internationally interrupted in the 70's of the 20th century with the oil embargo, causing a rapid rise in the expenses connected to the utilization of buildings [16]. The best solution designers could come up with as soon as possible was to turn back and start to utilize daylighting at a higher rate, once again resulting in bigger openings and the development of newer daylighting systems, may they be active or passive ones, including modified glasses and glazing systems.

3.1 DAYLIGHTING SYSTEMS IN ARCHITECTURE

Daylighting systems used in architecture, therefore in the building industry went through a long evolution since the first most basic openings were introduced. Nowadays several direct (primary) and indirect (secondary) [27] types of these systems are used may they be active or passive ones, only with the aim to increase the amount of incoming visible radiation let into the indoor spaces of building objects.

3.1.1 Primary or direct daylighting systems

Voids

Voids are one of the most primitive passive direct daylighting systems used in architecture already from the beginning of its evolution. Voids are standard opening within structures without any fitting, so it can be said that it handles about holes through which light can move freely from the exterior to the interior of a building, and likewise the opposite is valid also. These structural daylighting elements can be located everywhere, inside, outside, in horizontal, vertical or aligned structures. The main feature of voids in comparison to other systems is that a significant amount of visible radiation can enter the building through them, because it does not come to any absorption, reflection or refraction of the incoming electromagnetic radiation just to transmission with a transmittance of 100% in each, and every direction. However, this is also the major disadvantage of voids. Heat and energy as much as it can enter the building, it also escapes, and nowadays when the energy efficiency is put above everything, though it handles about a direct daylighting system it can be used only as a secondary one.

Windows

The next type of passive daylighting systems are the windows. Windows are modified versions of voids, more precisely, by equipping voids with a kind of glazing and a frame holding them at a given position. In comparison to voids, the amount of light entering the room decreases because the glazing and the window frame already influences the electromagnetic radiation. Only a portion of light can pass through the glass panes. The rest is reflected and absorbed by the glazing and surrounding frame. Glasses of different types used within the building industry and mounted into the openings do have different properties with means to transparency, reflectance and absorption. It is a result of the raw materials used within the manufacturing process of flat glass. A clear glass of a thickness of 4mm can transmit as much as 92% of the incoming light, on the other hand triple glazing fitted with krypton and applied tinting on it can have a transmittance value of as low as 10%.

Several types of windows do exist according their position:

- Standard windows – located mostly in peripheral, but vertical structures or under a low pitch to the zenith;
- Roof windows – designed as a part of roof planes with the aim to illuminate attic and loft spaces next to the roof cladding;
- Clerestories – exceptional types of standard windows, which are positioned in vertical peripheral structures of a building object, but are placed higher and so the connection of the interior and exterior is limited throughout them;
- Glazed facades – full-scale windows which are mounted all over the walls of a building, and do act as a structure dividing the indoor and outdoor environment. Glazed facades do have their own load bearing elements and can resist the pressure of the wind.

Roof lights

Roof lights are daylighting systems used to illuminate indoor spaces from above, through the roof planes of a building. They are installed into the roof of industrial buildings to make the conditions necessary for work better. There are several types of them, but the only thing valid for every one of them is, that roof lights are almost every time equipped with a diffuse type of glazing just to scatter the light over the working plane inside a room while not allowing direct sunlight to pass into the interior, causing overheating and the availability of glare.

In wintertime, they do have problems with water vapour and moisture within the air, which condenses on their internal surfaces and starts to drop down onto the inhabitants and workers, or the water starts to penetrate the structures and cause problems of a different manner.

3.1.2 Secondary indirect light sources

Light guides (also known as solar tubes or light pipes)

Light guides are daylighting systems, which are both passive and indirect. The light is transferred with their help from the exterior to the interior of a building via multiple reflections.

The transmission of light with the help of light guides is made possible throughout the utilization and usage of highly reflective surfaces, made by the galvanization of metal (the galvanization goes through with the help of a silver compound of highest quality) or by special polymers used in fibre optics. This increases the reflectance value of the inner surface of these shafts, to the limits. The length and diameter of the metallic pipe can differ, but their design is arbitrarily dependant on a certain ratio of its dimensions [32].

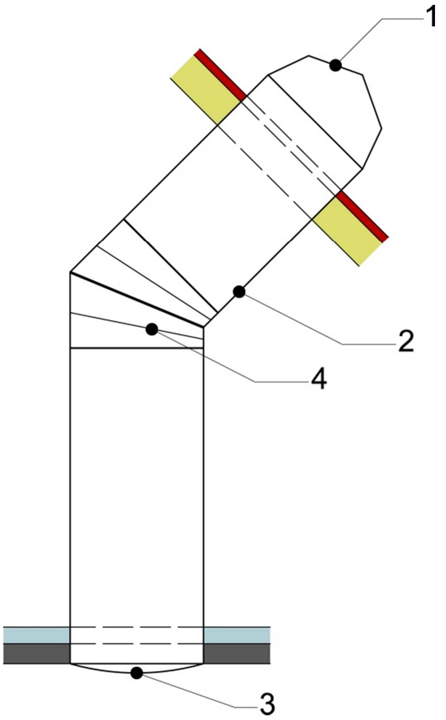


Fig. 13 *Cross-section of a light guide [4].*
1 – copula, 2 – metal pipe, 3 – diffuser, 4 – bent elements

Light guides, used within the building industry are at one end finished with a glass or plastic copula, and on the other end with a diffuse transparent material.

Several theories have had been developed for the design and application of light pipes since they have had been introduced, based either on numerical analysis or on graphical approaches, including those of study cases. Nevertheless, scientists and architects including the author of this thesis, have had tried to verify the efficiency of these systems through the utilization of ray-tracing algorithm [4], [23], [30], [31].

Atria

An atria, is an open space inside of a building objects, which is not interrupted by floors and is directly illuminated by daylight from above. The aim of their design is to bring sufficient amount of light to rooms and indoor spaces designed with openings facing a central part of a building. They do provide a visual sensation for the users of a building when there are no alternatives because of the space available and landscape, situation or by other disruptions. Quite often atria’s do have a secondary function as well, as to atria’s are used by some of the inhabitants as gardens.

Walls must enclose the atrium from all of its sides, although, they may be protected from the top too, especially by glazing.

Optic fibres

Daylighting of buildings with optic fibres is uncommon in most parts of Europe (European Union), however in the USA, Japans, and other exotic countries, they are designed and developed already from 1978-1979 [2], [53]. These systems do utilize optic fibres to transport light from point A to point B, whereas point A is located somewhere on the envelope of a building or near a building object, while point B is inside an indoor space.

The application of optic fibres result in a low loss of light (which is why they are also used in different engineering fields, like computer engineering sciences, medics, etc.) as to they are made from a transparent light transmitting core and a coating with a low index of refraction.

In addition to optic fibres manufactured in a factory, in the USA people tend to make them for domestic use in their own garages or workshops the same way they do manufacture motorcycles.

However, the placement of optic fibres is not enough. The system must be completed by a collector made up from lenses to collect daylight and by light fittings to distribute the light evenly into the indoor space.

The utilization of optic fibres in the daylighting design of buildings is shown in fig. 14.

Another possibility for the application of optic fibres inside buildings is their mixing into concrete. The resulting product is called as translucent concrete. It has high structural variability and strength, and on top of that it can transfer light [47].

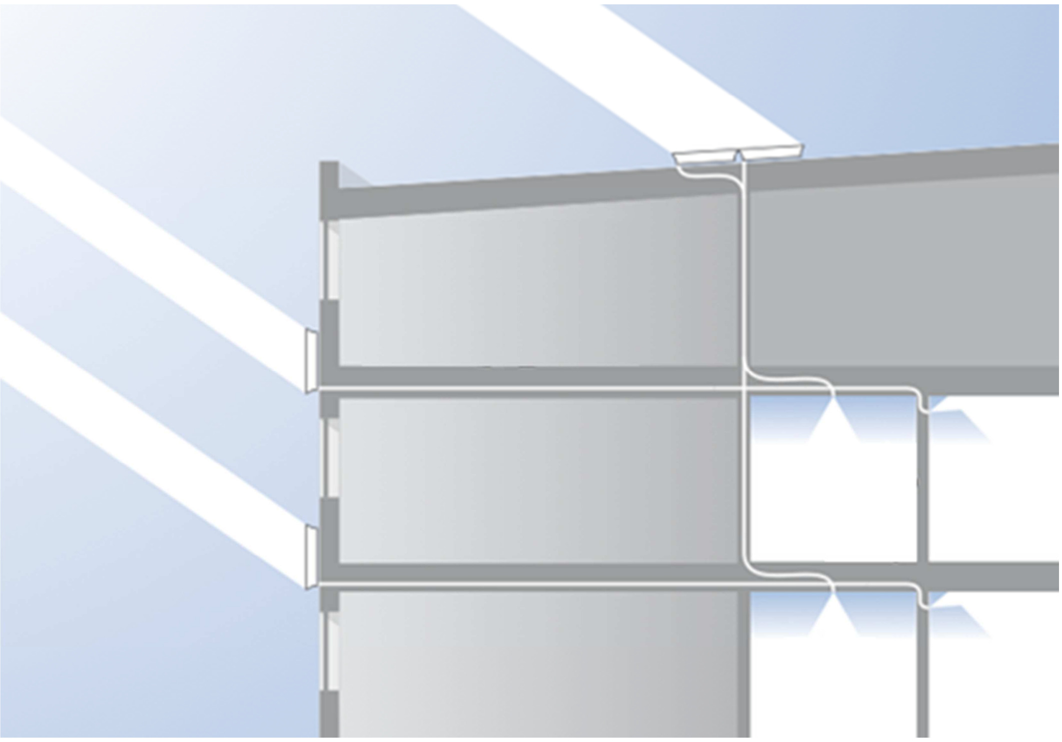


Fig. 14 *The application of optic fibres for daylighting of buildings [50]*

Corridors

Corridors come into application when the rooms inside of buildings must have a central entrance rout, which doesn’t even has to be in the proximity of external walls. The illumination process then goes on with the help of windows, doors or voids located within the external vertical, horizontal or aligned structures. The rooms next to the corridor are daylit only with the means of daylighting systems located inside the dividing structures.

A typical example of corridors can be seen in shopping centres all over Europe. A shop if sufficiently illuminated by an internal central corridor just below a roof light. Roof lights are casually equipped with diffuse glazing, scattering the light into the space evenly, resulting in a higher amount of light passing through the transparent element between the two spaces.

3.2 EVALUATION OF LIGHT CONDITIONS IN BUILDINGS

The evaluation of light conditions of buildings is a requirement of the latest laws, acts, decrees and standards. The laws do define what has to be evaluated and the related standards include the required methodologies. Therefore, the daylighting design of building is space oriented, and depends on a few aspects and information's, like:

- The assumed utilization of the given building and indoor space in the future;
- The properties of the locality;
- The type of daylighting system designed to illuminate the evaluated indoor space;
- And others.

In the Czech Republic, excluding Prague, buildings are designed with care to the requirements described within the decree 268/2009 coll. [34] (including decree no.20/2012 coll. [35]), which is about the technical requirements of buildings. For the capital city of the Czech Republic, Prague, these requirements are part of the decree 26/1999 coll. of the capital about the technical requirements of buildings in Prague. The given decrees do describe different aspects of building design to ensure the health and safety protection of the inhabitants and users of building object, for example: building acoustics, fire safety and among others also daylighting. It is said that every building must be designed in a way, that the internal spaces must be sufficiently daylit. The design of living oriented spaces are based on this given decree directly, while the design of permanent working places is connected to the government order 361/2007 coll. [36] about health protection at work, stating the following three stages of lighting design for working places:

- The working space must be illuminated solely on the basis of natural light, therefore daylight (a standard requirement which can't be accomplished);
- Integral lighting can be used to lit the indoor space;
- Luminaries are allowed to be used in overall to lit-up a space (only allowed if an indoor space is located underground or in the centre of the building, though the applicants for building permission do have to apply also for an extradition of exception).

Another point of daylighting design lies in the stage in which it can be done, as to it can be divided into three phases on the basis of the time and date when the calculations are to be made, these are the following:

- Pre-design phase of evaluation;
- In- or post-design phase of evaluation;
- Post-realization phase.

A pre-design evaluation checks the daylight availability of the construction sites and it should tell the designers, whether there are going to be problems with the placement of a newly designed building when taking into account the characteristic of the given locality. It evaluated the indoor spaces of the designed buildings as much as the spaces existing buildings too. Still it handles about a preliminary determination only.

The in-design and post-design stages do verify the daylighting conditions in the internal spaces of the designed buildings, directly. The calculation and evaluation process within this stage is done over the working plane of a room, in comparison to the pre-design phase involving only a few calculations made on the façade of the buildings. The in- and post-design phases do already derive the dimensions of daylighting elements and their parameters, for example, what kind of glazing was used within the windows frame, how much of the opening is taken up by window and door frames, and so on.

The post-realization phase verifies the daylighting (possibly integral lighting) conditions in an existing building just before issuing out the permission for their usage. It is verified on the request of Regional Public Health Authorities or acting court in case of conflicts, by measurements.

3.2.1 Daylighting design of indoor spaces

The evaluation of indoor climate with a viewpoint to daylighting is to be done in compliance with the latest ČSN 73 0580 part 1 and its follow up standards, part 2 to 4 [41], [42], [43], [44]. Each of these standards deals with a given building type:

- Part 1 deals with the foundations of daylighting design;
- Part 2 deals with daylighting of living oriented spaces;
- Part 3 deals with natural light in schools;
- Lastly, Part 4 deals with workspaces inside of industrial buildings.

This grouping had also brought along three different procedures for the evaluation of daylighting in room of different utilization:

- Method 1: is about the daylighting evaluation of rooms without special features. This approach can be used for every indoor space, except for living oriented ones. The calculations in this case are done throughout the whole scope of the working plane, whereas the resulting daylight factor values are compared with the ones included in tab. 3. [41] (fig. 15).
- Method 2: is to be used only in case of spaces with a living oriented character inside newly designed building objects. The minimal and average values of daylight factors are taken from two boundary points in the middle of the working plane (can be positioned at most in a distance of 3 metres away from the window) and are compared with the ones required by the standard. The Czech code fortunately isn’t as harsh as, let say the British one, because every room has to fulfil the same parameters, whereas in

Britain the interior is classified into kitchen, living room and bedrooms [37] and only the mean values are looked after. Fig. 16 demonstrates the evaluation of living oriented spaces in consent with the Czech standards.

- Method 3: is only used to test the effects of newly designed buildings onto the neighbouring, already existing ones. It handles about a calculation done in a point on the façade (fig. 17) in contrast to the ones made inside of buildings.

Tab. 3 *Daylight factor requirement according to ČSN 73 0580-1*

Class of visual activity; char. of visual activity; average viewing distance; Description of visual activity.	**DF req.** DF_{min} [%] DF_m [%]
Cl. I.; Unusually exact; <3330mm, - > Most exact visual activity with restricted possibility of enlargement for exclusion of mistakes.	3.50 10.00
Cl. II.; Highly exact; <1670mm, 3330mm) Exact visual activities in manufacturing processes and controls, drafting, sewing and fine artistry.	2.50 7.00
Cl. III.; Exact; <1000mm, 1670mm) Exact fabrication, drawing, trickier laboratory works, sewing	2.00 6.00
Cl. IV.; Average; <500mm, 1000mm) Middle exact fabrication, control, reading, writing, normal laboratory works, cooking, etc.	1.50 5.00
Cl. V.; Gross; <100mm, 1000mm> Gross works, manipulations with objects, eating, relaxation, etc.	1.00 3.00
Cl. VI.; Really gross; < - , 100mm> Cleaning, taking a shower, dressing, etc.	0.50 2.00
Cl. VII.; Orientational; < - > Walking, warehousing, etc…	0.25 1.00

Vis. act. – shortened version of visual activity

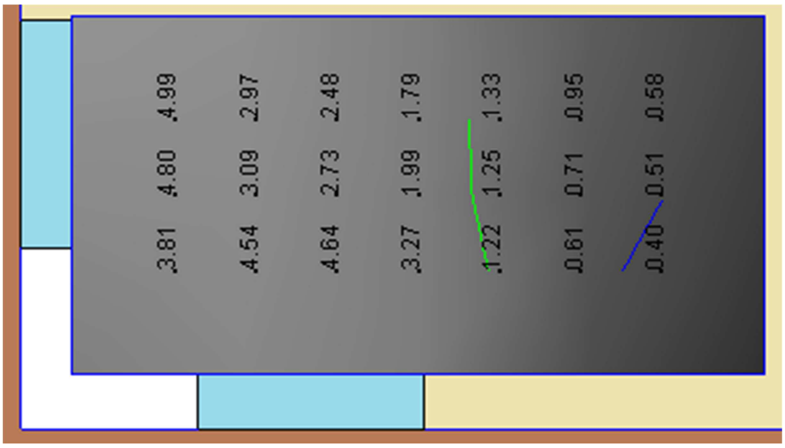


Fig. 15 *The primary daylighting evaluation technique of indoor spaces [Author].*

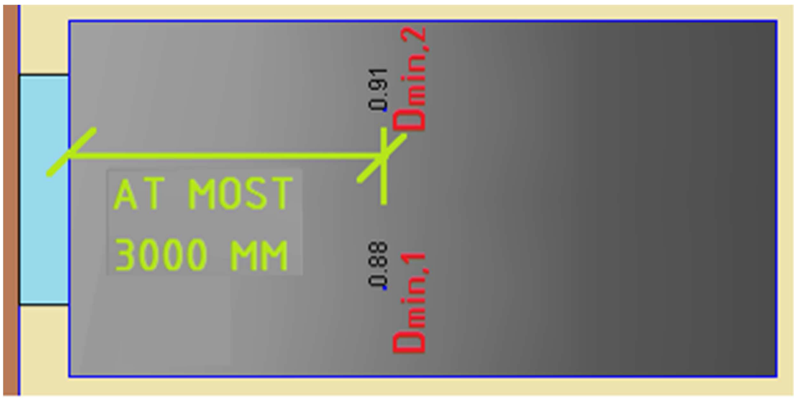


Fig. 16 *The evaluation technique for living oriented space [Author].*

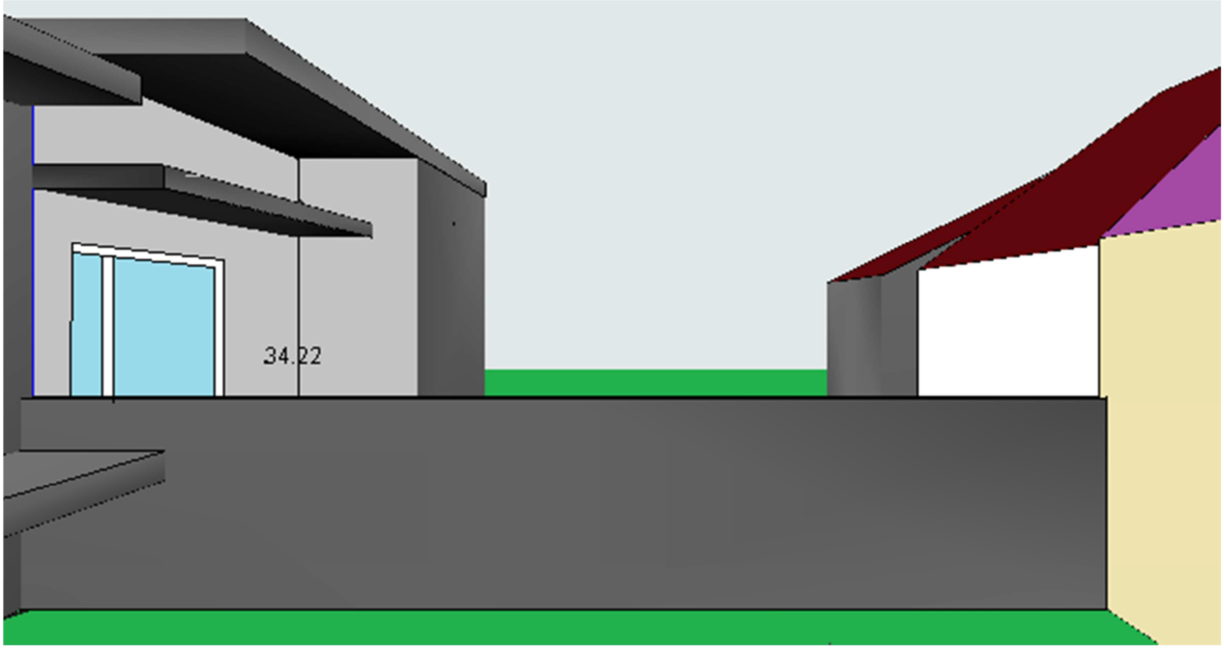


Fig. 17 *The effect of a newly designed building onto the neighbouring one [Author].*

3.2.2 Integral lighting design of indoor spaces

Integral lighting of interiors is based on the combination of natural and artificial lighting of different kinds, depending on their source (the principle behind integral lighting design can be seen in fig. 18).

Its design has to be made with care, as to the resulting uniformity cannot fluctuate too much, and has to be closer to 1.00- than in both separate cases, i.e. UDL and UAL. The daylight factor requirements are smaller (see *tab. 4.*), albeit the requirements for the uniformity were maintained.

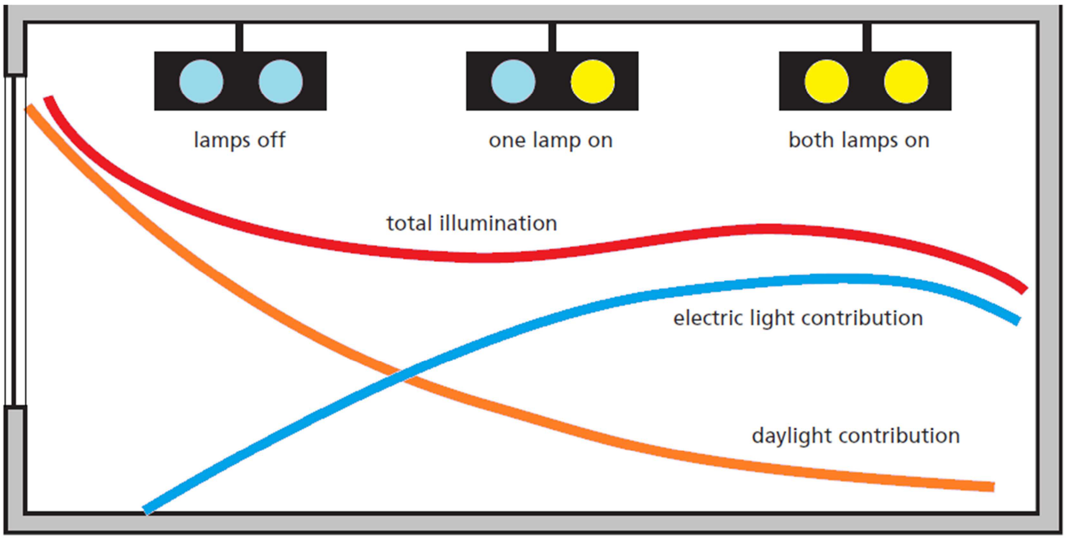


Fig. 18 *Principle behind integral lighting design [3].*

Tab. 4 *Daylight factor requirements for daylighting in case of integral lighting [40].*

Class of visual activity; char. of visual activity; average viewing distance; Description of visual activity.	**DF req.** $DF_{\min}$ [%] DF_m [%]
Cl. I.; Unusually exact; <3330mm, - > Most exact visual activity with restricted possibility of enlargement for exclusion of mistakes. *Cl. II.; Unusually exact; <1670mm, 3330mm)* Exact visual activities in manufacturing processes and controls, drafting, sewing and fine artistry.	**1.00** **2.50**
Cl. III.; Unusually exact; <1000mm, 1670mm) Exact fabrication, drawing, trickier laboratory works, sewing	0.70 2.00
Cl. IV.; Unusually exact; <500mm, 1000mm) Middle exact fabrication, control, reading, writing, normal laboratory works, cooking, etc.	0.50 1.50
Cl. V., VI and VII; Unusually exact; <100mm, 1000mm> Gross works, manipulations with objects, eating, relaxation, etc.	0.50 1.00

Vis. act. – shortened version of visual activity

3.3 DESIGN METHODS FOR DAYLIGHTING

Throughout time, builders, architects, engineers and scientists have had tried to create an evaluation procedure which would make the determination of the amount of daylight falling onto the working plane of a room possible, therefore illuminating an indoor space through windows, doors and roof lights. Thus, it would make it possible to evaluate the daylighting conditions acting in the given space. Several theories have had been introduced however only those involving the standard CIE Overcast Sky were recognized. As time moved on graphical and numerical approaches came to life, these are now gradually overthrown by computer-based algorithms, like radiosity or ray-tracing.

3.3.1 Graphical and numerical methods

It handles about an approach using graphs (diagrams) or equations (can handle about a combination too) to evaluate the sky and externally reflected components of the already discussed “daylight factor”. These diagrams are usually post in sets of two. One of the diagrams stands for the floor plan and the second one for the cross-section of a building.

The internally reflected component is then determined with the help of equations, but it handles about a value of low importance.

The most known diagrams for the evaluation of the sky and the externally reflected components are:

- The diagrams of Daniljuk;
- The protractors of Kittler;
- The BRS approach;
- Moreover, Waldram’s diagram (in its base or modified form).

The diagrams of Daniljuk

In case of Daniljuk’s diagrams (the diagrams are shown in fig. 19) the sky is divided into smaller elements, corresponding to a sky with a uniform luminance, which are then used to obtain the number of elements of the sky which aren’t shaded by any buildings objects. These, are then used for the determination of the sky component of the daylight factor. It handles about one of the most widely known and used solutions, discussed in teaching literature and books at the same time, likewise [10].

Daniljuk’s approach was in the beginning of the 21st century further evolved by J. Kaňka who had published his findings in the journal Světlo [25]. His application of the diagrams involves the determination of the angles under which natural light can enter the building through the daylighting systems (*fig. 20* demonstrates the angles needed for the calculation of the sky component) and their subsequent substitution into the equations below, to get the number of visible sky segments as much as horizontally so vertically.

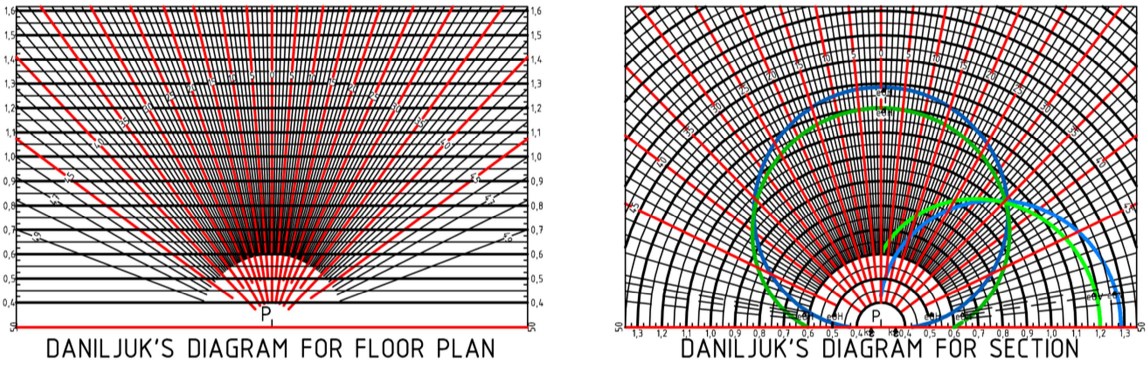


Fig. 19 *The diagrams of Daniljuk for section and floor plan [Author with source [25]].*

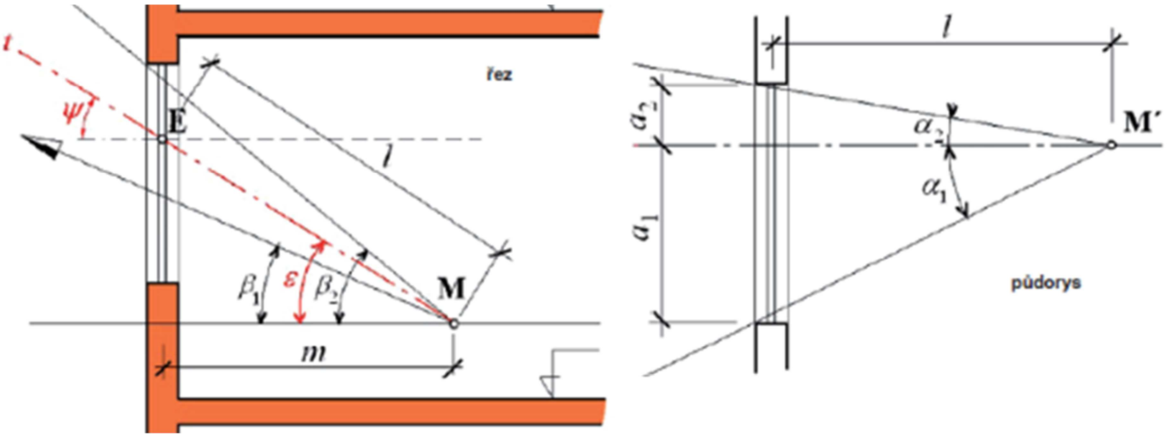


Fig. 20 *Application of Daniljuk's approach by J. Kaňka [25].*

$$n_1 = 50 \cdot (\cos\beta_1 - \cos\beta_2) \tag{45}$$

Where:

β_1, β_2 - are the angles determined in the cross-section of the building in decimal degrees [°].

$$n_2 = \frac{50}{\pi} \cdot \sum_{i=1}^{n} (2 \cdot \alpha_i + \sin(2 \cdot \alpha_i))(46) \tag{46}$$

Where:

α_i - are the angles determined in the floor plan of the building in decimal degrees [°].

The resulting sky component is then:

$$DF_s = \frac{n_1 \cdot n_2}{100} \cdot q \cdot \tau_{0,\psi} \tag{47}$$

Where:

q - is the luminance gradation factor of the sky [–];

$\tau_{0,\psi}$ - is the correction for the light transmittance of daylighting system [–].

3.3.2 Computer based algorithms

Radiosity

Radiosity as a method for the evaluation of daylight availability in buildings is to be put into the category of global illumination algorithms. It is based on finite element methods main equation, inside of which every surface is expressed as a perfectly diffuse element, a Lambertian diffuser. The algorithm or software written with it stores any kind of data involving not just lighting but heat and acoustics as well, concerning every point of a scene not just the ones inside the viewport set at the moment the evaluation started, therefore the results are viewpoint independent.

The camera can be moved within the 3D model on demand, at any time after the calculations are finished, which takes up a considerable amount of time (but it is worth the time).

The radiosity algorithm is part of LightWave rendering software and is inside the rendering tools of Autodesk and some computer games, too.

Ray-tracing

Ray-tracing is a method with the help of which it is possible to create photorealistic renderings of scenes consisting of building objects, trees and other types of elements. As the software using the given algorithm is based on the global illumination model, with ray-tracing it is also possible to determine the light levels inside or outside a given building. The light source for these calculations is of natural, artificial or combined type.

Ray-tracing can be traced back as far as to the 17th century [12], [28], [33], when the first equations and ideas describing its predecessor the "ray-casting" were developed. Even though the description of ray-casting was available for a huge period of time its global application began only in the second half of the 20th century with the implementation of computer based technologies. The main objective of its usage was to cast shadows within scenes and to calculate the distances between the observer and the points where the path of the rays intersected the geometries within the scene. Like this, it removed the hidden objects from the scene and have had interpolated the properties of the remaining surfaces (including the colour) from the surroundings. Even though this wasn’t enough to create complex renderings of scenes, by using textures assigned to surfaces and because of its low hardware requirements it became widely supported by game development studios. The first computer game which introduced the 3D world to the gamers with the help of ray-casting was Wolfenstein 3D [63].

Because of the drawbacks, ray-casting gave birth to a new methodology applicable for renderings, called as “ray-tracing”. In comparison to ray-casting, where the rays after their intersections with geometries within the scene are absorbed, ray-tracing began to follow the movement of these rays throughout inter-reflections between surfaces, which are defined accurately according to the material type they are made up from, until the ray can’t move further on (aka until the rays have been absorbed). Nonetheless, it could be possible to talk about ray-casting as of ray-tracing with ambient bounces turned off (fig. 21).

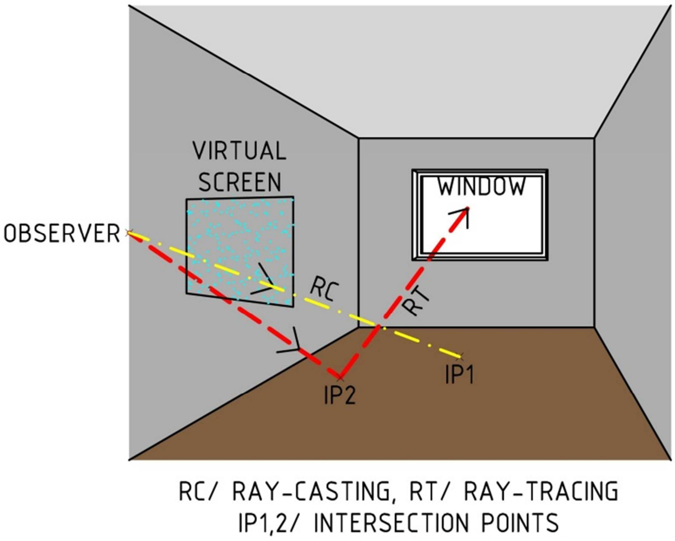


***Fig. 21** The difference between ray-casting and ray-tracing [Author]*

With time, ray-tracing advanced further on, so fulfilling the requirements put onto it by scientist, engineers and architects. This resulted in various versions of the main ray-tracing algorithm.

Between the most known versions are the forward and backward ray-tracing, followed by the combined and the stochastic one. The differences between the different ray-tracing approaches can be described in the following way:

- In case of forward ray-tracing the emitted light particle (mostly an artificial light source, but can be the sky as well) is followed throughout multiple intersections and inter-reflection with surfaces described in the scene, until it reaches the observer. There were various software developed, however the requirements for the system running them is quite high. The reason behind it is in the fact that a huge amount of rays is emitted into the scene, and only a fraction of which reaches the imaginary camera. The probability that a ray is going to be lost is around 99.9% [48].
- In case of backward ray-tracing the light particle or ray is followed from the observer until it reaches the light source through multiple reflections and intersections. Backward ray-tracing is ideal for building design, however it has its flaws also. Its main disadvantage is that in some cases it cannot find the light source, mainly if a CIE Clean Sky with a Sun description is the source. The most known representative of backward ray-tracing is POV-Ray (Persistence of Vision).
- The third option is the so called combined ray-tracing. It uses the advantages of both previously mentioned algorithms. As to forward ray-tracing begins at the light source but hardly finds the openings in

the envelopes of buildings, it is improved by the advantages of backward ray-tracing, which gives away the position of the transparent surfaces within the scene. Like this the forward ray-tracer can put the emphasis onto the particles which are emitted in the direction of those windows, doors, skylights, etc. DAYSIM uses a similar technology for the reckoning of the resulting daylight factor and anatomy values.

- The stochastic ray-tracer is created as a combination of the deterministic (backward) ray-tracing and that of Monte-Carlo combination theory for subsampling of surfaces and rays. The only disadvantage of the stochastic approach is that the values of different iterations differ. In case of illuminance or daylight factor value determination over the working plane it can also be used together with forward ray-tracing. The most known software in this field is « RADIANCE [14] ».

RADIANCE [14], [48]

« RADIANCE » was first introduced to the scientific community in the 80-s of the 20th century in California, USA as a tool for luminary and artificial lighting design. It the beginning it was developed solely by Greg Ward Larson and a dedicated group of computer engineers working for LNBL (the Lawrence Berkeley National Laboratory), as a stochastic ray-tracer (see the previous chapter).

Its main advantage however does not solely lie within the main computing equation (it handles about Kariya’s rendering formulae) and algorithm on which it is based on, but in the way « RADIANCE » itself can be used after a cloud of parameters is defined. « RADIANCE » as it is, isn’t just one program, on the contrary it’s a set of tools, basically inter-connected ones, created for architects and scientist working in the field of building, luminary, daylighting and irradiance design.

The latest official distribution of « RADIANCE » the 4R1 is made up from roughly sixty official binaries (- executable under MS Windows OS) included in the source package published by LNBL.

Every one of the official programs included in « RADIANCE » is unique and provides the user with results for different problems. Therefore, it is possible to categorize them into sets according to their behaviour:

- Generators (like ~genbox~, ~gensky~);
- Geometry converters (like ~obj2rad~, ~su2rad~);
- Geometry manipulators (like ~xform~);
- Renderers (like ~rvu~, ~rtrace~, ~dayfact~);
- Image manipulators (like ~pfilt~, ~ximage~);
- Front-ends to « RADIANCE » (like ~rad~ or ~trad~);
- And others.

On the other hand every user can use additional tools too, which are created and further improved by the members of communities constructed around « RADIANCE » or by individuals who would like to increase the overall efficiency of the rendering process. Some of these tools, though they are not part of the official distribution, are still available because of LNBL.

The source code for UNIX/ LINUX based systems is free to download from the webpages of the project http://radsite.lbl.gov/radiance. MS Windows OS based versions are compiled either inside CYGWIN or MINGW and usually do end up with a dependency issue caused by the missing X11 libraries, although only in case that an image manipulator is to be used, apart from that most of the components do work without them. If needed, even if the official X11 libraries are part of UNIX/LINUX operating systems, their equivalents can be downloaded from the web for MS Windows OS too.

4 THE AIMS OF THE THESIS

- **Setting out of the aims**
- **Reasoning behind the aims**
- **Equipment used to achieve the aims**

4.1 SETTING OUT OF THE AIMS

The given dissertation thesis deals with the optimization of daylighting design of indoor spaces inside building objects with the help of computer simulations, at different stages of building design (i.e. pre-, in-, and post- design phases), therefore the emphasis of the solution was put onto several minor aims, which are the following:

- A comprehensive comparison of available design methods against published CIE reference cases;
- Comparison of measured and calculated values of daylight factor levels.

4.2 REASONING BEHIND THE AIMS

The aims dealt with within the thesis were set out on the basis of issues connected to the engineering practice, especially expertise activities necessary to get the permission to build (according to the valid laws and regulations [34], [35]) or in case of litigations between the owners of certain neighbouring properties.

Standardly these processes are being solved by tools or design methodologies, created with the aim to determine the resulting daylight factor values over the working plane of a room or on the façade of and existing building. Nevertheless, some of them do have their foundations in one of the older approaches and not in newly developed theories and possibilities. Although, this could come with a set of disadvantages the software production studios are working on and issuing out newer and newer versions of computer tools, without wanting to invest into research.

The mostly used approaches in the Czech Republic were not even tested against real-life conditions, or against CIE reference cases [45], hence leaving the professional community in a blind spot.

Hence, the aims set to take a closer look at the techniques of daylighting design with respect CIE test cases for the assessment of computer lighting software and to verify them against values obtained by real measurements, are actual.

4.2.1 Comparison of available design methods against CIE test cases

The engineering practice in the field of daylighting is highly influenced by the quality of design techniques from which one can choose to make the appropriate calculations and later the evaluation of light conditions inside a building object. Therefore, it is necessary to test their creditability as much as their reliability, since the conclusions of an expertize activity cannot be exchanged on a whim later just because a different tool gives other, more trustworthy results.

A part of the thesis is therefore going to deal with a comprehensive comparison of standard design methods against these resources.

This step is necessary because as much as « RADIANCE » other available design techniques within the field of lighting are highly influenced by the reflections of light, and « RADIANCE » itself has about five influential ambient parameters affecting the distribution and amount of light incident to a point on the working plane.

4.2.2 Comparison of measured and calculated values of daylight factor levels inside buildings

The next issue dealt with within the thesis is associated to the differences between the measured and calculated values of daylight factor levels, as to the daylighting evaluations and expertizes are often requested by the building permission office or by the office of regional hygiene for the premises of schools. Thus, the certainty of calculations and simulations should be verified too while going against measured values in real life.

Reality is influenced by factors like:

- Surface reflectance and light transmissions of materials;
- Complexity of the indoor space;
- Location of the evaluated building object;
- And the geometry of the neighbourhood, among others.

On the other hand, simulations are done on simplified models only. For example, complex structures like windows are casually described as a glazing affected by a light transparency, maintenance factor and coefficient regarding the window frame.

That is why, there may be differences, but whereas the calculated values are smaller or equal if compared to the measured ones is a theme for research.

4.3 EQUIPMENT USED TO ACHIEVE THE AIMS

For the solution of the project only equipment available on the authors working place, in more detail in the grounds of the Institute of Building Structures of the Faculty of Civil Engineering, Brno University of Technology, including those in the ownership of the author were used, with a few exceptions only.

The measurements in the laboratories located in the loft of the main building of the institute have had been permitted by Ing. Milan Ostrý, Ph.D., later conducted by the following equipment:

- Illuminance meter KONICA-MINOLTA T10 – including three of the four receptor heads;
- Software EMlux and MuuLUX v0.98 (programmed by the author and his colleague Sándor Bágyi, from Budapest, Hungary);
- Luminance meter KONICA-MINOLTA LS-110;

- HOBO U12-012 data loggers (the data loggers have had been purchased from the budget of GAČR 01/05/H018 doctoral research project, which was finished in 2008 on the Faculty of Mechanical Engineering, Brno University of Technology);
- In addition, a reference surface for the determination of the reflectance values of surfaces (lent to the author by Doc. Ing. Jiří Plch, CSc.).

The computer simulations have had been carried out in « RADIANCE » and « WDLS » whereas AutoCAD, Ecotect, Rhinoceros, Diva for Rhino, SketchUp, SketchUp to RADIANCE and notepad were used as I/O computer programs. A few calculations were performed in MS Excel 2003, 2007 and later on 2010.

5 USED METHODOLOGY

- **Validation of computing methods**
- **Computer simulation settings**

The current chapter focuses on the description of the methodologies used along the solution of the thesis to achieve the aims described in the previous chapter. These required the following:

- To learn about new findings in the field;
- To think about and discuss computer simulations and numerical solutions;
- And to create a base idea about the measurements to make and how to take them.

Because the author have had decided to go with the innovated approach of Daniljuk, which should be widely known by now, it is not going to be discussed until the chapter inheriting the results.

5.1 VALIDATIONS OF COMPUTING METHODS

5.1.1 Validation of computing methods against CIE Test Cases scenarios described in CIE 171-2006

CIE as an organization had published several standards, from the sky definitions throughout colorimetric functions up to the one describing the test cases for the validation of computer programs. The given standard goes under the number: CIE 171/2006. The validating patterns were originally invented by F. Maamari in 2004 as a solution of his Ph.D. thesis [15] and from 2005 they have had been gradually enforced by CIE [45].

The CIE 171/2006 describes a set of scenarios, although the ones defined inside of the chapters up to #4 do validate tools for artificial lighting design, exclusively. Only test case scenarios demonstrated in chapter #5 of the standard, are to be used on software specially developed for daylighting scenarios. These do test the capabilities of a software tool in the following manner:

- Verification with respect to the sky component of the daylight factor;
- Verification with respect to the externally reflected component of the daylight factor;
- Verification of the internally reflected component of the daylight factor.

There is however a major issue within the validation of the internally reflected component, in more detail with the validation of most of the daylighting design methods, because the test cases created for this purpose do require an incident angle of 35°, 45°, … of the luminous flux, therefore a clear sky, nonetheless daylighting is evaluated under overcast sky conditions.

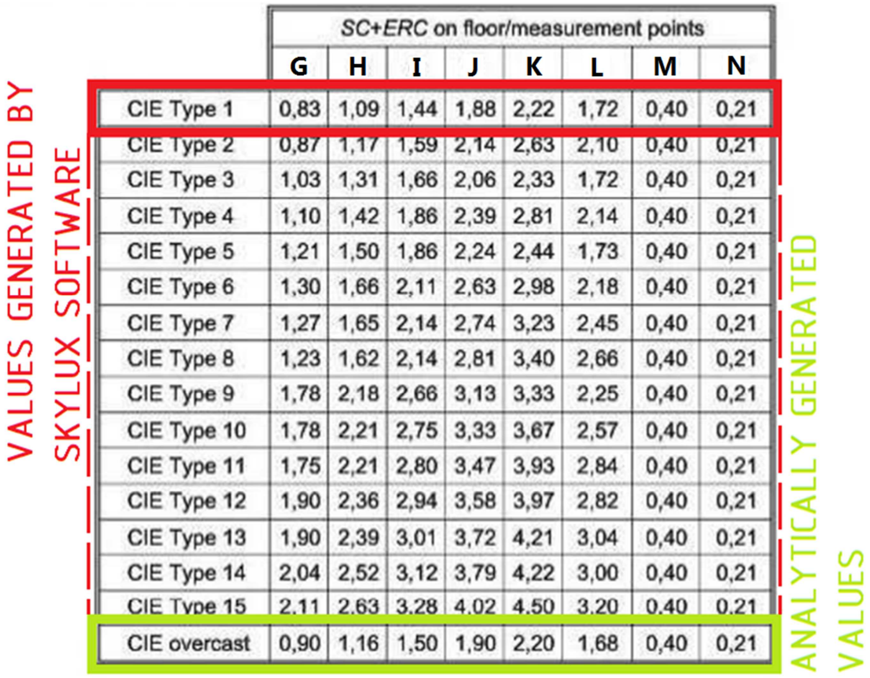
So, only test case scenarios 5.9 (R.T.A.[3] II.8), 5.10 (R.T.A. II.9), 5.11 (R.T.A. II.10), 5.12 (R.T.A. II.11), 5.13 (R.T.A. II.12), 5.14 (R.T.A. II.13) could have had been used for the validation process. These are visible in fig. 23 to 26.

---

[3] R.T.A. – Referred To As.

Because the internally reflected components are neglected, the internal surfaces are made up of a light absorbing black material, the light reflectance value of which is equal to zero. The terrain and the barriers are bound to have a reflectance value of 0.3-, which is 30%.

The reference values for the test cases are available for each of the 15 sky types, although in case of a CIE Overcast Sky there are two demonstrated data sets. The CIE Type 1 generated by Skylux software and the CIE Overcast (fig. 22), which is the fundamental data array. These were used for the validation of Skylux that is why these values were chosen by the author for the solution of the thesis, too.



	SC+ERC on floor/measurement points							
	G	H	I	J	K	L	M	N
CIE Type 1	0,83	1,09	1,44	1,88	2,22	1,72	0,40	0,21
CIE Type 2	0,87	1,17	1,59	2,14	2,63	2,10	0,40	0,21
CIE Type 3	1,03	1,31	1,66	2,06	2,33	1,72	0,40	0,21
CIE Type 4	1,10	1,42	1,86	2,39	2,81	2,14	0,40	0,21
CIE Type 5	1,21	1,50	1,86	2,24	2,44	1,73	0,40	0,21
CIE Type 6	1,30	1,66	2,11	2,63	2,98	2,18	0,40	0,21
CIE Type 7	1,27	1,65	2,14	2,74	3,23	2,45	0,40	0,21
CIE Type 8	1,23	1,62	2,14	2,81	3,40	2,66	0,40	0,21
CIE Type 9	1,78	2,18	2,66	3,13	3,33	2,25	0,40	0,21
CIE Type 10	1,78	2,21	2,75	3,33	3,67	2,57	0,40	0,21
CIE Type 11	1,75	2,21	2,80	3,47	3,93	2,84	0,40	0,21
CIE Type 12	1,90	2,36	2,94	3,58	3,97	2,82	0,40	0,21
CIE Type 13	1,90	2,39	3,01	3,72	4,21	3,04	0,40	0,21
CIE Type 14	2,04	2,52	3,12	3,79	4,22	3,00	0,40	0,21
CIE Type 15	2,11	2,63	3,28	4,02	4,50	3,20	0,40	0,21
CIE overcast	0,90	1,16	1,50	1,90	2,20	1,68	0,40	0,21

***Fig. 22** Example of excepted daylight factor values for CIE Sky types [45].*

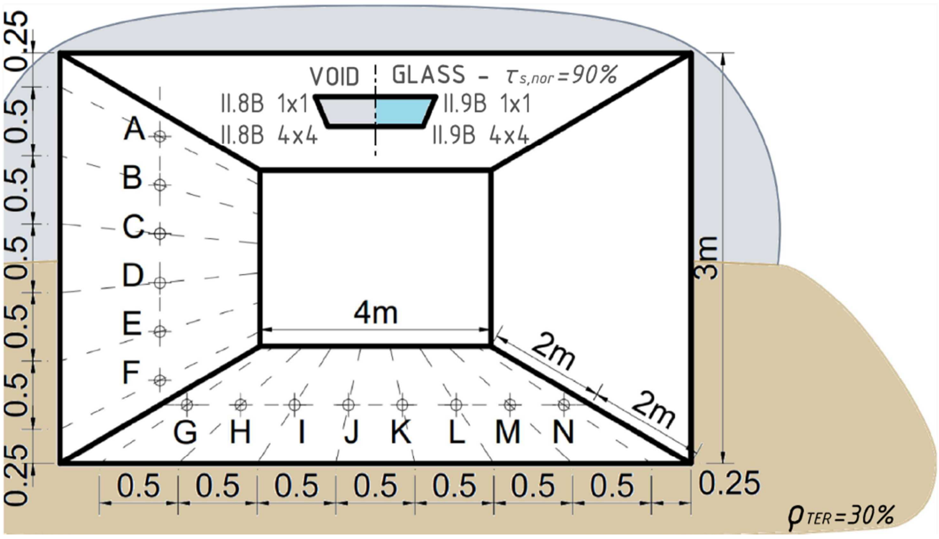


***Fig. 23** CIE Test Cases II.8 and II.9 [Author with source [45]]*

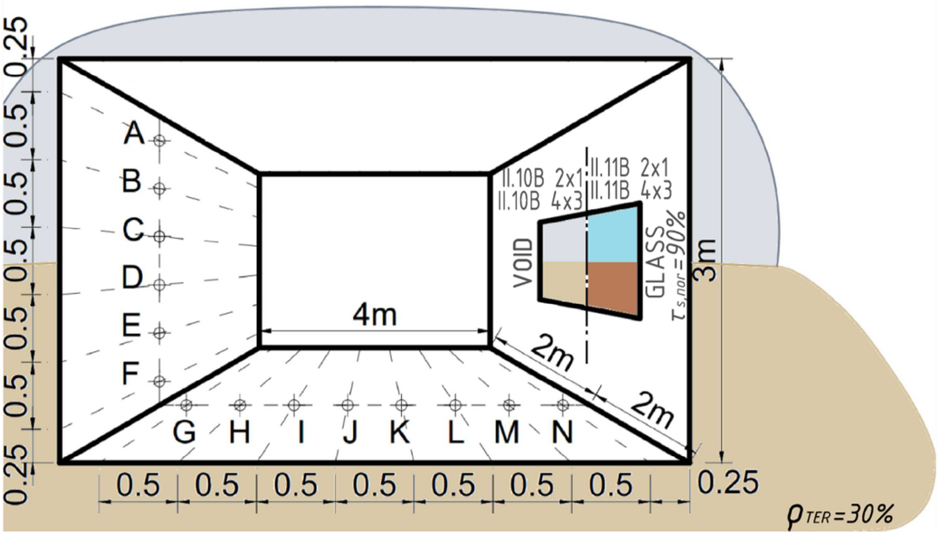


Fig. 24 *CIE Test Cases II.10 and II.11 [Author with source [45]]*

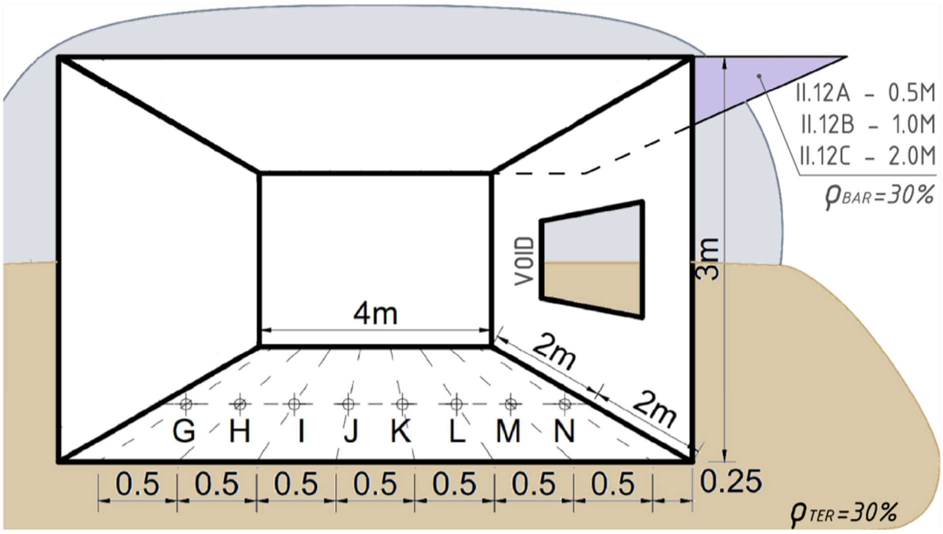


Fig. 25 *CIE Test Cases II.12 [Author with source [45]]*

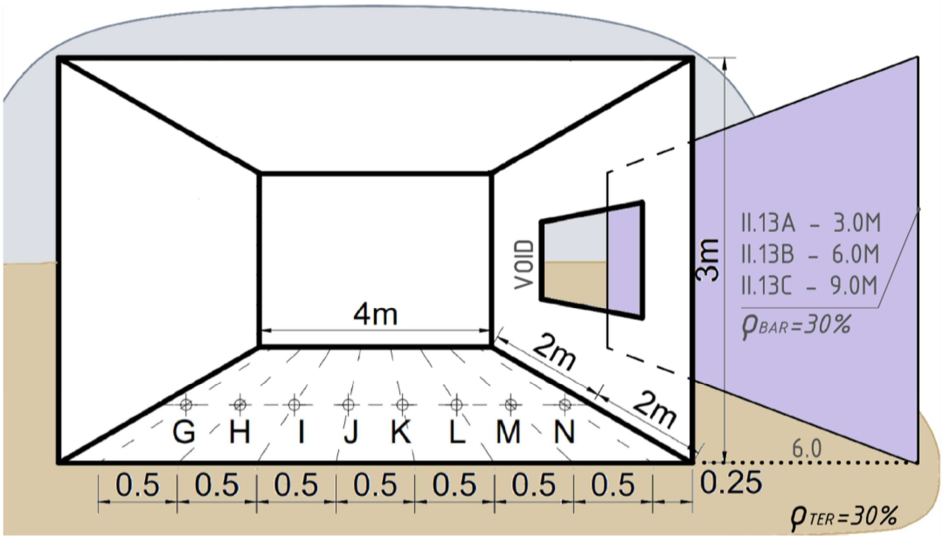


Fig. 26 *CIE Test Cases II.13 [Author with source [45]]*

5.1.2 Validation of computing methods against on site measurement

The daylighting measurements taken in the laboratories located within the grounds of the Institute of Building Structures, Faculty of Civil Engineering, BUT in Brno, supervised by Ing. Milan Ostrý, Ph.D., consisted of three separates stages regarding the different aspects of light measurement:

- The first stage did require the determination of light reflectance and transmittance values of surfaces;
- The second stage was about illuminance measurements over the working plane of the laboratory. These observations did take place in the first and fourt quarter of 2009;
- The third stage was about measurement of luminance and illuminance values regarding the CIE Overcast Sky.

The plans of the laboratories including the locations of the data loggers and receptor heads are visible in fig. 27. Fig. 28 shows the laboratories before and after the positioning of the tripods, demanded by the monitoring process.

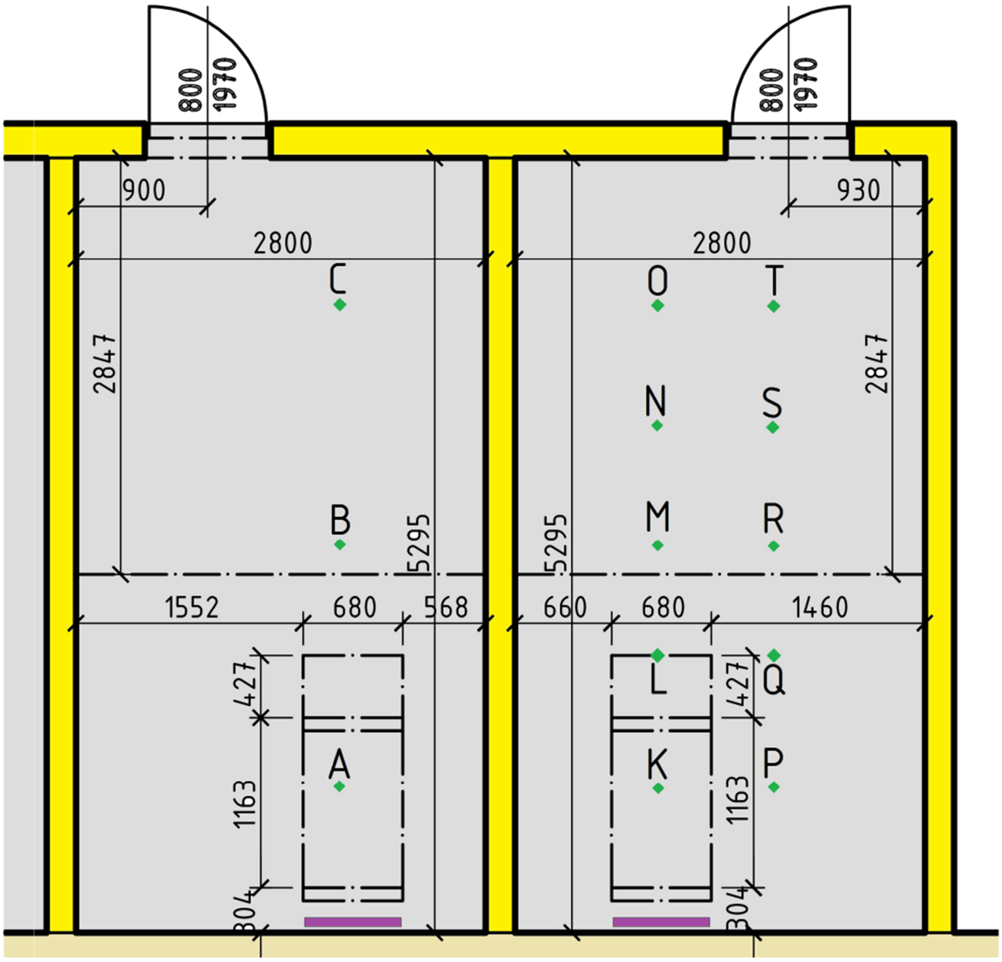


Fig. 27 *The plan of the laboratories. [Author]*
(Plan of “Laboratory No.2” on the left, plan of “Laboratory No.1” on the right)

Fig. 28 *Figures showing the laboratories [pictures by Ing. D. Bečkovský, Ph.D.] "Laboratory No.1" after the initial positioning of the tripods is on the left, "Laboratory No.2" after the installation of the PCM based panels is on the right.*

Determination of light reflectance and transmittance values

Because the laboratories within the grounds of the working place were contstructred from standard building materials with unknown light reflectance values, like: gypsum board coated with a white paint, cetris board, steel frame, etc. it was necessary to get the required informations by measurements. The results then were applied as input data within the daylighting analysis and comparison of computer simulation software and the numerical design methods.

Such measurements can be done in two different ways:

- By measurement and evaluation of illuminance and luminance values at the same time, or;
- By measurement and evaluation of luminance values only, determined on the surfaces and on an etalon with a predetermined light reflectance value.

For the first time it was decided to go with an etalon, one which was lent to the author by a colleague of his, namely Doc. Ing. Jiří Plch, CSc., who owns a few samples and was willing to help. The choice had been fallen onto a coated steel plate of light blue colour with a light reflectance value of 29%.

For the second time, because there wasn't enough time to borrow the etalon once again, the author had decided to create his own reference surface (etalon).

The light reflectance value of this particular surface was then determined with the help of the luminance and illuminance meters available at the working place.

Measurement of illuminance over the working plane

In the year of 2008, the daylighting measurements over the working plane of the laboratories have had been based on two different types of sensors. In one of the available rooms 10 pieces of HOBO U12-012 data-loggers were positioned in accordance with ČSN 36 0001, and at the same time in the second room three KONICA-MINOLTA T10 receptor heads and HOBO U12-012 data-loggers were installed.

The measuring apparatuses have had been placed into a height of 850*mm* above the floor of the given room on tripods with modified heads, so that they could hold the data-loggers in position connected to them by VELCRO fastening elements.

The distance of the measuring heads from the surrounding structures as is stated in the standards was 1000*mm*. The resulting working plane of "Laboratory No.1" have had been divided up by 10 data-loggers, creating 2 columns of 5 rows. "Laboratory No.2" in the first place was prepared for comparative measurements only with the aim to test the capabilities of the purchased data-loggers with concern to their response to visible radiation (which at the time of the purchase was unavailable).

Measurement of external luminance and illuminance

Because the locality allowed it, the luminance and illuminance values regarding the CIE Overcast Sky were determined on the roof of the faculty. At the beginning of 2009 because the receptor heads of the KONICA-MINOLTA T10 illuminance meter were in use indoors, the sky light was measured solely by the luminance meter available at the working place (a KONICA-MINOLTA LS110 device). These measurements have had been carried out in accordance with the standards and the luminance values were taken at 5 points of the sky under a short amount of time (see fig. 29). Thus, the amount of light falling onto a non-shaded dark horizontal surface could be determined from one of these luminance values, but only in the case, that a set of conditions were satisfied.

Only by the end of 2009 were the values measured locally by the illuminance meter KONICA-MINOLTA T10, because the full-scale evaluation of the data obtained at the beginning of 2009 have had been evaluated only at the end of the same year.

The location where the sky luminance and illuminance measurements took place is located atop of the faculty and is apparent from fig. 30.

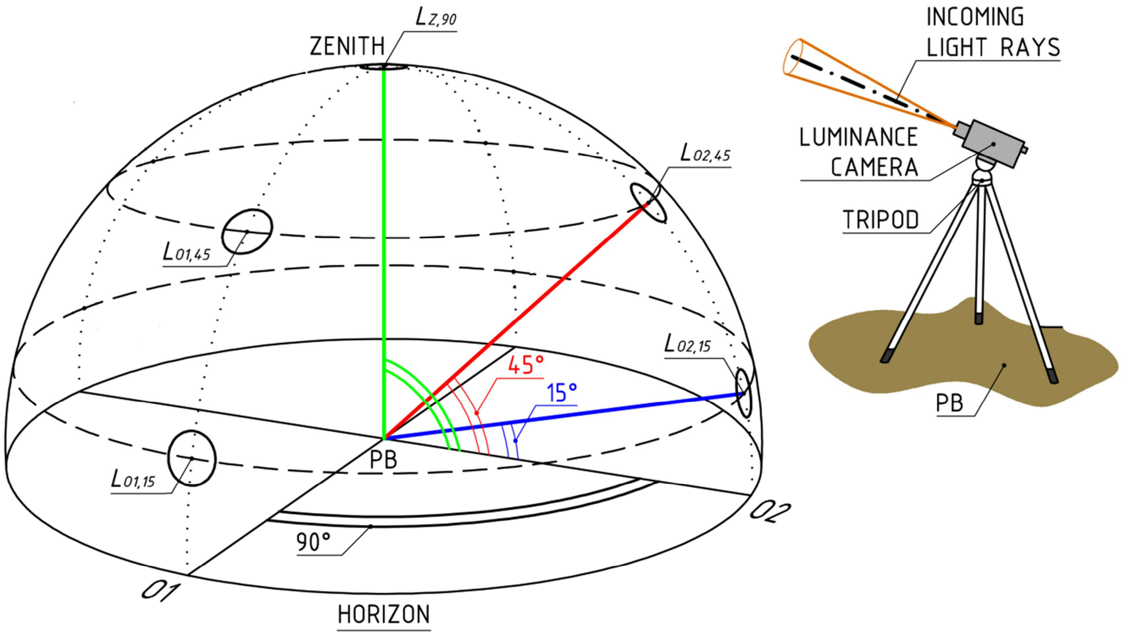


***Fig. 29** Determination of luminance over the CIE Overcast Sky [Author]*

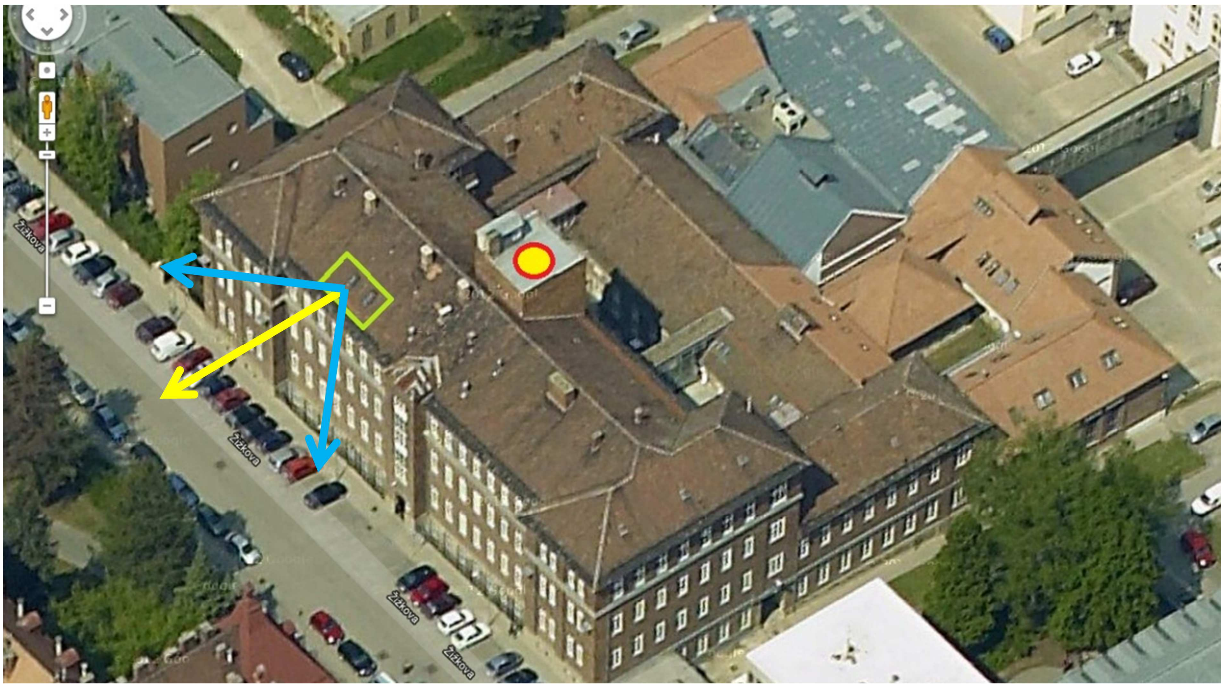


***Fig. 30** The location of sky monitoring is highlighted by the red ellipse with yellow gradient while the roof windows of the laboratories are shown by the green rectangle [source Google maps and Author].*

5.2 COMPUTER SIMULATION SETTINGS

The development of computer technologies in both viewpoints, regarding the hardware (increasing number of CPU cores, hardware acceleration by the GPU like CUDA or PhysX) and the software tools as well, did result in an increasing number of available computer programs, developed for architects, civil engineers and scientists. Some of these were written by huge studios and ome by individuals with the aim (SketchUp, 3DS Max, Maxwell renderer, V-Ray, Architectural Desktop, etc.) to allow the community to make photorealistic renders of 3D scenes either with the application of ray-tracing or radiosity algorithms. Nonetheless, most of them can do luminance/illuminance calculations too, thus helping the engineering community in the building design process.

DIALux, DIALux Evo, Relux, POV-Ray (though it handles about an older rendering software, it still belongs into the group of the best applications available) and other programs do offer complex solutions to design studios and civil engineering workstations in the form of interior and exterior design at the same time. However, the daylighting calculations inside of them have had been continuously pushed into the background by the artificial lighting design standards of foreign countries and companies manufacturing luminaries. This can be seen in the way, how a user can set-up the thickness of the peripheral structures, if it is even made possible (in DIALux v4.1 the walls must have a pre-defined thickness of 300*mm*).

Only one available newly programmed software had stayed focused on daylighting simulations and that is the Daylight Visualizer, by Velux a company manufacturing roof windows and light guides, among others. The specialty of the latest version of the given software is the approach under which the developers had begun to apply the fifteen sky types defined by CIE.

Nevertheless, the computer simulations and calculations which were done within the solution of the thesis have had been focused on the quality of « RADIANCE » and « WDLS (Windows Day Lighting System)» a Czech software, which is said to be the most widely used application in the Czech Republic for daylighting design of buildings in case of expertise activities.

5.2.1 Computer Simulations in Radiance

As to « RADIANCE » is a UNIX/LINUX operation system (U/L from now on) based package of applications, ported via CYGWIN or MinGW to MS Windows OS, its usability is the same as it was at the beginning of its development. This results in the division of 3D models (scenes) into multiple files, inheriting different sets of data and information. The file extensions are optional, because the properties of files can be hardcoded in the filename as a residue of U/L.

For example, the name of a material description file can be “glazing.mat” as well as “mat_glazing”. The same is valid for the model, sky descriptions, etc.

while the only thing required is to have an overview of them. They may be even located in separate folders too, as to it is simple to link the model together.

For a scene to be successfully rendered and evaluated, the materials, surfaces, sky and virtual sensor point sets has to be described correctly. A standard reflective surface without textures can be described either as plastic (eq. 48), metal or an alternative of them with directional effects (plastic2 and metal2). Metal, as a material is often neglected. Nevertheless, it finds its utilization in case of light guide definitions with a bit of roughness and specularity applied to it.

$$\begin{array}{l} \textit{modifier plastic id} \\ 0 \\ 0 \\ 5 \;\; \rho_{red} \;\; \rho_{green} \;\; \rho_{blue} \;\; spec.\, rough. \end{array} \tag{48}$$

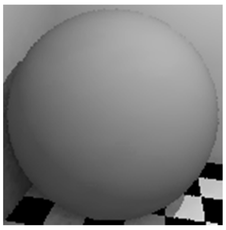
Where:

$\rho_{\mathrm{red}}, \rho_{\mathrm{green}}, \rho_{\mathrm{blue}}$ - are the reflectance values of the surface in the RGB colour model [–];

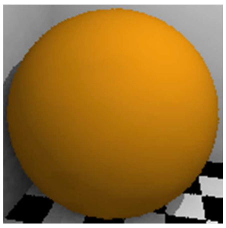
$spec.$ - describes whether the surface is going to be matte or glossy, its value is usually between 0- and 0.1-;

$rough.$ - describes whether the surface is going to be smooth or rough, its value is usually between 0- and 0.5-.

Within the thesis, the reflective surfaces with a few exceptions only have had been described as plastics with a colour varying from white to grey to black. This approach did simplify their definition a bit. For example a greyscale floor with an overall reflectance of 25% looks like eq. 49, whereas a brownish orange surface with the same reflectance value would look like eq. 50 [52].



$$\begin{array}{l} \textit{modifier plastic id} \\ 0 \\ 0 \\ 5 \;\; 0.250 \;\; 0.250 \;\; 0.250 \;\; 0.000 \;\; 0.000 \end{array} \tag{49}$$



$$\begin{array}{l} \textit{modifier plastic id} \\ 0 \\ 0 \\ 5 \;\; 0.482 \;\; 0.182 \;\; 0.000 \;\; 0.000 \;\; 0.000 \end{array} \tag{50}$$

A glazing can be described in four different ways:

- As dielectric materials – the definition of this material requires the description of transmittance values as much as the refraction index and the Hartman constant of the given transparent material;
- As a glass material – it handles about a special version of a dielectric with an index of refraction equal to *1.52*-;
- As a trans material – can be used to describe diffusely transmissive surfaces, such as Lambertian diffusers in case of light guides;
- Or, on the basis of OPTICS5 descriptions which comes in handy while describing huge models, where glazing acts as an external surface needed for the determination of the externally reflected component. It handles about the combination of two or more different glass types and coatings within one material (external VSG glazing tinted to green colour with a thickness of 6 mm + internal glazing standard white with a thickness of 4mm).

For the description of the glazing within the windows and openings throughout the computer simulations represented within the thesis, the material description called “glass” have had been used.

The light transmittance values are required in the form of light transmissivity ones (eq. 51) including a certain light loss coefficient as a requirement of ČSN implied to it, although not in each and every case, for the light transmittance of the windows illuminating the laboratories have had been determined with help of measurements.

$$t_n = \frac{\sqrt{0.8402528435 + 0.0072522239 \cdot {\tau_{s,nor}}^2} - 0.9166530661}{0.0036261119 \cdot \tau_{s,nor}} \times \tau_{loss} \qquad (51)$$

$$\tau_{loss} = \tau_{m,int} \cdot \tau_{m,ext} \cdot \tau_0 \qquad (52)$$

Where:

t_n - is the resulting transmissivity of the glazing [–];

$\tau_{s,nor}$ - is total spectral light transmittance of the glazing [–];

$\tau_{m,int}$ - is the maintenance factor on the internal side of the glazing [–];

$\tau_{m,ext}$ - is the maintenance factor on the external side of the glazing [–];

τ_0 - is the ratio between the area of transparent elements and the overall area of the opening [–].

Input/output software

Under input/output software a tool can be imagined, which is used to create the 3D scene for the rendering process and to make the results readable and understandable.

In the beginning, although the author did have a bit of experience in working in Linux OS, still fell back and tried to work with « Desktop RADIANCE », an MS Windows OS version of « RADIANCE » working over AutoCAD. However, certain issues did arise while trying to modify the parameters of the ray-tracing process. Therefore, he had begun to look for other alternative tools, programs and scripts, which could be used instead of « Desktop RADIANCE ». So, the author came across a few AutoLISP and MS Visual Basic scripts written for AutoCAD, but these tools could be used only to export the models into « RADIANCE » data format for editing in « Notepad » or other software.

Later, tools like DAYSIM and Ecotect have had been introduced to the author by the community and colleagues working for the School of Architecture, University of Sheffield, UK. It handled about a program which was made by the engineering community working in the field of building physics for architects and engineers, as to thermal design could be made inside of it as much as daylighting. Nevertheless, even after exporting the model to the « RADIANCE » data format, it still had to be modified in an editing tool, since the windows had a bad light transmittance value. The simulation process could have had been started manually too which resulted in a higher flexibility. Nowadays, the owner and developer of Ecotect is Autodesk. Hence, modules of it are already integrated into Autodesk Revit and Architectural Desktop.

As time moved on plugins called Diva for Rhino and SketchUp to RADIANCE were released. These are extensions to Rhinoceros 3D and SketchUp modelling computer programs, working just fine. Because the author owns an official copy of Rhinoceros 3D he had begun to use a combination Rhino to SketchUp to « RADIANCE ».

The simulations in « RADIANCE » package have had been done used under MS Windows OS just as much as under Linux. The mainly reason behind this approach was, that under MS Windows OS it was almost impossible to use the ~falsecolor~ subroutine.

Ambined value (-av) and ambient weight (-aw)

While studying the man pages of « RADIANCE » and the I/O software, like the Diva for Rhino, the author did come across a few parameters, which were not used by him earlier. These parameters were the –u (a switch to turn on the Monte Carlo sampling method; possible options + or -), -aw (the ambient weight parameter, mostly set to 0) and the –av (ambient value parameter, influencing the accuracy of indirect irradiance simulations).

The intermediating programs which may be used under MS Windows OS to generate the scene from 3D model spaces (like Rhinoceros 3D or SketchUp) would use the ambient value parameter with a value of 10 10 10 (in every red green and blue fields of colours) while sending the scene to the ray-tracing algorithm of « RADIANCE » software package. Nevertheless J. Mardaljevic had stated that for daylighting calculations, especially for illuminance determination, it is better to set both of these values to 0- [14], that is why the simulations presented within the thesis were done with –av and –aw parameters set to 0.

5.2.2 Computer simulations in WDLS v4.1

« WDLS » is written and developed by ASTRA MS Software Ltd. (formerly known as the software division of Astra 92 Ltd.). It is one of the oldest and mostly used applications created for specialists working in the field of daylighting in the in the Czech Republic, which is particularly the origin of the company as well. The latest version has a revision number 4.1.4.14.

Its usage and application is a bit sturdy, and it does have some disadvantages, which are:

- The rooms input must have a rectangular floor plan, complex shapes must be remodelled with internal barriers;
- The building can be modelled only in the form of blocks with a constant width, depth and height. Fortunately elevations are allowed, so at least it is possible to model saddle roofs;
- Each and every barrier in the interior and exterior results in an increase of computer time needed for the calculations to go through;
- The openings can have rectangular or aligned shapes only. Circles and arches aren't allowed, diffuse parameters can't be set either, etc.

The determination of externally reflected component requires either the:

- Luminance ratio of the surface to sky (but this approach can handle direct surface reflectance values as well);
- Or the surface reflectance and light transmittance values of the barriers.

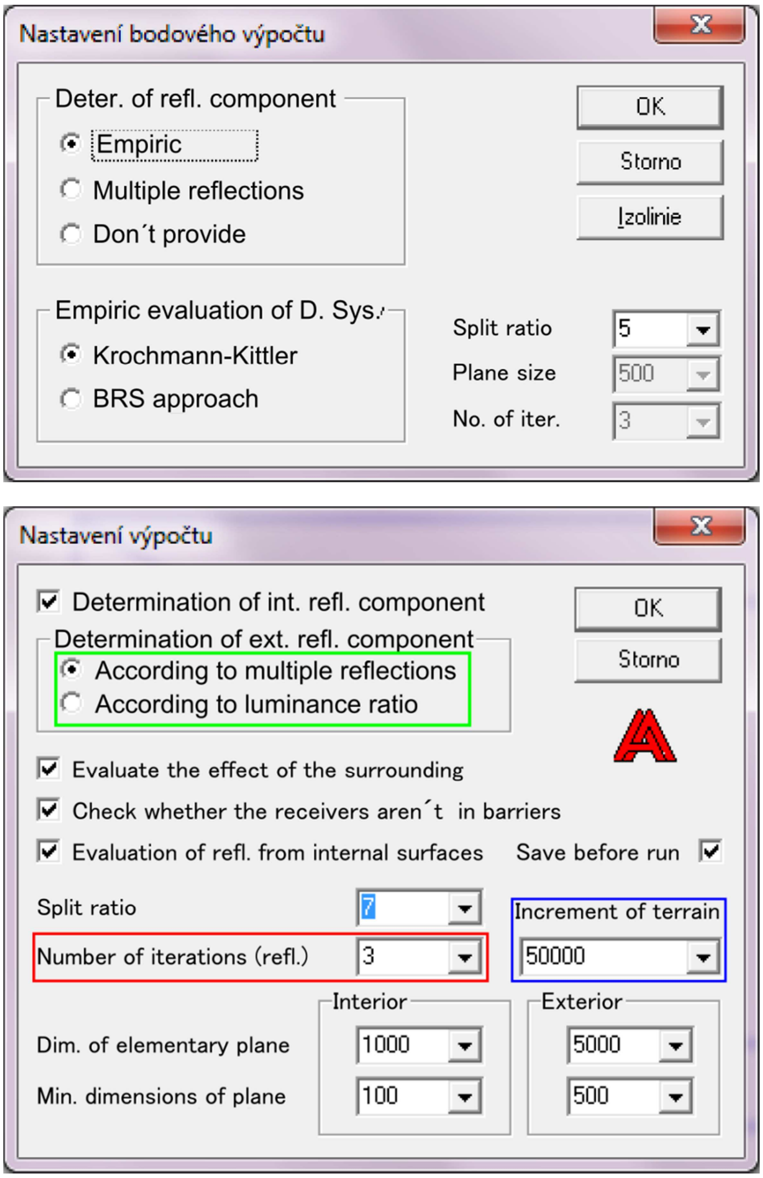
As for the evaluation within the solution of the thesis both of these approaches have had been tested. The size of the terrain surrounding the building objects was set to 30m. The number of iterations/reflection for the calculation was set to 3-. Higher numbers are unreasonable in « WDLS ».

5.2.3 Computer simulations in WDLS v3.1

It handles about an older, discontinued version of « WDLS » software, the predecessor of « WDLS v4.1 ». Its usage and application is sturdy too, and has the same disadvantages as its successor. Still there are some differences between them:

While « WDLS v4.1 » already uses the computer algorithm of numerous reflections for the determination of the internally reflected component, and can obtain the externally reflected component with the means of two different approaches, « WDLS v3.1 » has different definitions. « WDLS 3.1 » uses three different concepts for the evaluation of the internally reflected component (these are the following: Krochmann-Kittler's procedure, the BRS technique and numerical reflections) and only one for the externally reflected component. It cannot work together with computer aided design tools, and has less settings referring to the quality of the resulting values. In addition, « WDLS v3.1 » cannot handle a vertical working plane[4].

For the purpose of data collection, each of the available settings have had been tested throughout the solution of the thesis. The differences between the possible settings in « WDLS v3.1 » and « WDLS v4.1 » are distinguishable in the following figures.



Nastavení bodového výpočtu

Deter. of refl. component
● Empiric
○ Multiple reflections
○ Don´t provide

Empiric evaluation of D. Sys.
● Krochmann-Kittler
○ BRS approach

Split ratio 5
Plane size 500
No. of iter. 3

Nastavení výpočtu

☑ Determination of int. refl. component
Determination of ext. refl. component
● According to multiple reflections
○ According to luminance ratio

☑ Evaluate the effect of the surrounding
☑ Check whether the receivers aren´t in barriers
☑ Evaluation of refl. from internal surfaces
Save before run ☑

Split ratio 7
Number of iterations (refl.) 3
Increment of terrain 50000

	Interior	Exterior
Dim. of elementary plane	1000	5000
Min. dimensions of plane	100	500

***Fig. 31** The differences between the settings available in WDLS v3.1 and v4.1.*
(WDLS v3.1 is on the top, WDLS v4.1 is in the bottom)
[Screenshots and translation from Czech done by the author].

---

[4] WDLS v3.1 and Daniljuk's innovated approach aren't assessed for their quality over a vertical working plane.

6 RESULTS

- **Validation of design methods against CIE test cases;**
- **Comparison of measured and calculated values of daylight factor levels inside buildings.**

6.1 VALIDATION OF DESIGN METHODS AGAINST CIE TEST CASES

CIE as an international organization defined several sets of standards, which should be used in case of daylighting design of buildings. Such a standard is one of the earlier mentioned ones regarding the sky luminance distribution in case of the 15 sky types defined and created by S. Darula and R. Kittler in Bratislava [23], [45]. Although, there are others as well, like the CIE 171/2006 [44], which in its roots is a technical report about testing the newly created computer programs light determination capabilities.

Because the measurements made didn’t turn out as well as expected, it have had been decided to test « WDLS v3.1 », « WDLS v4.1 » and « RADIANCE » against this standard the same way as « AGI32 [5] » was checked between 2006 and 2009. Nevertheless to make the picture complete a numerographical approach was being assessed as well, which in this case was the Daniljuk’s methodology modified by J. Kaňka [24].

6.1.1 Created computer programs

RADIANCE Script

A standard rendering/illuminance-luminance ray-tracing simulation process in « RADIANCE » takes into account several sub-programs and parameters, which can be utilized to achieve the required results. For example, it is possible to discuss the ambient parameters taking into account the qualitative and quantitative properties of reflected rays throughout the scene or the time/date/location data for the generation of chosen sky-type (from CIE Overcast Sky until the CIE Clear Sky). Although the ~mkillum~ process shouldn’t be forgot about, as to it solves problematic models by transforming glazing and other transparent surfaces into secondary light sources, into an illum type artificial light source, having its advantage in highly complex models and indoor spaces in the centres of buildings.

Because the validation processes do require ambient parameters like “–ab” (ambient bounce), “-aa” (ambient accuracy), “-ad” (ambient density), … to set with care, moreover to assign more than just one value to each of them, it would result in numerous available combinations. A standard line to start the ray-tracing process looks as follows:

```
rtrace -I+ -h -w -aa 0.01 -ab 1 -ad 4096 -as 1024 -ar 2048
-aw 0 -av 0 0 0 -dj 0.65 -ds 0.1 -dt 0.05 -dc 0.75
-dr 2 -dp 4096 -u- -ov model.oct < _eval.pts |
rcalc -e $1=179*($1*0.265+$2*0.670+$3*0.065)/100 >
sd_dfact-c_simp_0301-1200_a0.01-b1-d4096-s1024-r2048.res
```

(53)

From the parameters above the options beginning with a “-d” are optional only and they do change the results of rendering processes, than the calculation ones. Their value can be the same for all of the ambient value combinations. The –I+ Boolean switch stands for the computation of irradiance at the location of the measurement points, it shouldn’t be mistaken with –i+. (The rest of the parameters can be looked up on the internet (http://radsite.lbl.gov). The file "model.oct" is the octree of the scene, _eval.pts is a file handling the virtual positions and directions of the sensors that are to be evaluated. The ~rcalc~ software translates the RGB values into one characteristic value before they are written out into the result file.

« RADIANCE » as a U/L based software is easily scriptable. One of the most basic scripting languages included in every GNU LINUX OS distribution is called as “bash”, and can be run within a terminal (in U/L exists a handful of terminals and the user can choose the one which suits his taste better) by typing the following command !#/bin/bash. The next steps do require the input of operations the script should do. This allows a user to freely use variables, loops and even to send some routines to external programs, which in case of « RADIANCE » would be ~oconv~, ~rtrace~, ~rcalc~, ~dayfact~ or simply ~rad~ with the help of a batch file created on the basis of what should be done. However, users working in the environment of MS Windows OS are not so lucky. The command line, ~cmd.exe~, doesn’t really support any scripting from the beginning, just simple file handling and some medium advanced commands, limited by the programs own commands, although some loops are allowed, like *FOR*. The system therefore requires some additionally installed tools, for example Python, Ruby, TCL or Perl. This however, results in a disadvantage of MS Windows OS users. While a user of U/L is prepared for scripting from the beginning, and let us say could just copy out some lines from books like “Rendering with RADIANCE” [14] or “RADIANCE Cookbook” [52], the one using MS Windows OS isn’t and does have problems by learning it. It is simpler to write small binaries (*.exe) in PASCAL, C or C++, than to learn scripting.

This was the case of the author too, except that he required it to run on other machines too. The workstation, on which most of the simulations have had been done works on MS Windows OS, on which additional installation of tools was not allowed by the administrators. Therefore, to simplify the combination process the author created a small program in PASCAL programming language [1] [59], without a GUI, but he plans it into the future.

Because PASCAL files can be compiled on each of the available operating systems, it can be run as much as under MS Windows OS so under U/L or Mac OS too, nevertheless it’s better to use it within an operating systems which can run « RADIANCE ».

The working scheme of this software is simple and is apparent from fig. 32. The script takes into account the possible choices for sky types, ambient parameters and simulation methods, etc.

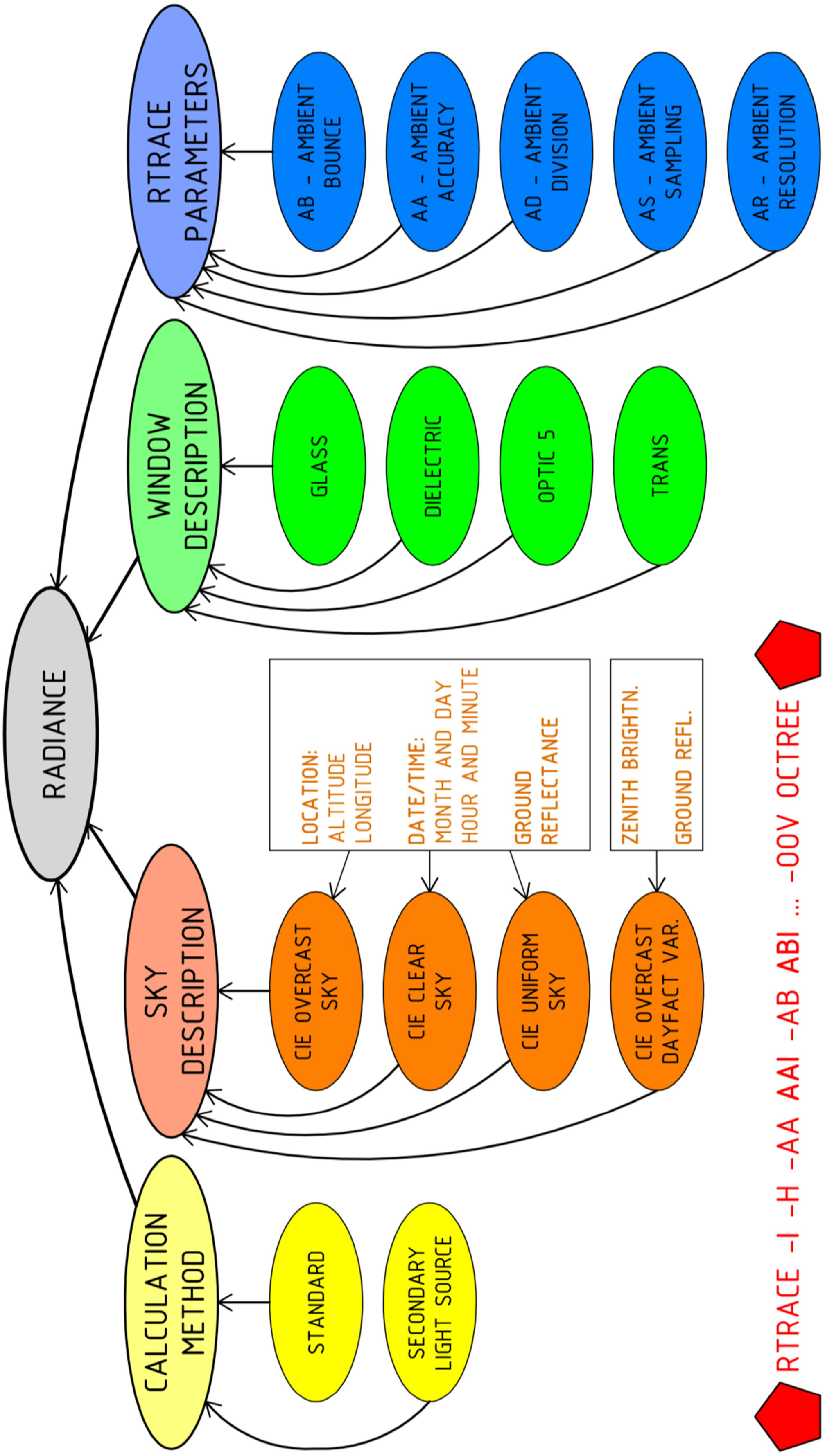
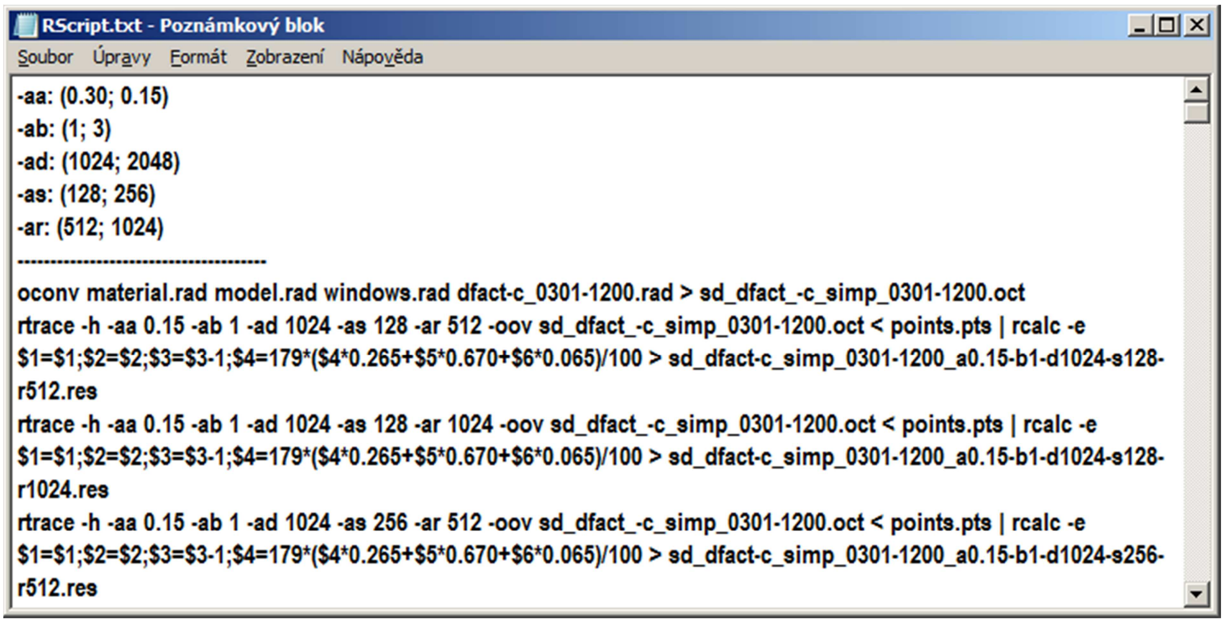


Fig. 32 *Working scheme of RADIANCE script (Author)*

"RADIANCE Script" consists of three separate, but connected procedures:

- It collects data about the location and also about the date and time for which the simulations should be done, including a choice for the sky type, as to it is able to create the sky description file, too, but instead of a standard description consisting of altitude and longitude values, the "RADIANCE Scripts" uses the Sun's position on the sky, if needed.
- Secondly, it collects data about the files, which are to be used within the ray-tracing process. The model and material description files, if the windows are in a separate file then even that one, then the file with the evaluation point definitions. Also, it tries to find out something about the type of calculation the user is after, if it's going to handle about a standard simulation or an mkillum type one, on the basis of what is the material of the glazing done (OPT5 data, dielectric, or glass), and the additional parameters required by the user, like –I+, –h, –w, etc.
- In the last step, it asks the user to input the required ambient parameters. For each of them two values, the beast and the worst.

Fig. 33 is about the "RADIANCE Script" in action, rather said, the output of the script itself.



```
-aa: (0.30; 0.15)
-ab: (1; 3)
-ad: (1024; 2048)
-as: (128; 256)
-ar: (512; 1024)
------------------------------------
oconv material.rad model.rad windows.rad dfact-c_0301-1200.rad > sd_dfact_-c_simp_0301-1200.oct
rtrace -h -aa 0.15 -ab 1 -ad 1024 -as 128 -ar 512 -oov sd_dfact_-c_simp_0301-1200.oct < points.pts | rcalc -e
$1=$1;$2=$2;$3=$3-1;$4=179*($4*0.265+$5*0.670+$6*0.065)/100 > sd_dfact-c_simp_0301-1200_a0.15-b1-d1024-s128-
r512.res
rtrace -h -aa 0.15 -ab 1 -ad 1024 -as 128 -ar 1024 -oov sd_dfact_-c_simp_0301-1200.oct < points.pts | rcalc -e
$1=$1;$2=$2;$3=$3-1;$4=179*($4*0.265+$5*0.670+$6*0.065)/100 > sd_dfact-c_simp_0301-1200_a0.15-b1-d1024-s128-
r1024.res
rtrace -h -aa 0.15 -ab 1 -ad 1024 -as 256 -ar 512 -oov sd_dfact_-c_simp_0301-1200.oct < points.pts | rcalc -e
$1=$1;$2=$2;$3=$3-1;$4=179*($4*0.265+$5*0.670+$6*0.065)/100 > sd_dfact-c_simp_0301-1200_a0.15-b1-d1024-s256-
r512.res
```

Fig. 33 *The output of the "RADIANCE Script" written by the author.*

For the validation process the following ambient parameters had resulted in 343 possible combinations, generated by "RADIANCE Script":

- $aa_{\min} = 0.01, aa_{\max} = 0.01 \rightarrow aa = 0.01$ – ambient accuracy;
- $ab_{\min} = 1,\ ab_{\max} = 1 \rightarrow ab = 1$; for test cases II.8 and II.9 as to the determined daylight factor levels couldn't be influenced by external reflections;

- $ab_{\min} = 2,\ ab_{\max} = 2 \rightarrow ab = 2$; for test cases II.10, II.11 and II.13 because the determined daylight factor levels are partially affected by external reflections (see the description of these test cases);
- $ab_{\min} = 3,\ ab_{\max} = 3 \rightarrow ab = 3$; for test cases II.12. The values in reference points on the horizontal plane are going to be influenced by two additional reflections: by a reflection on the surface of the horizontal overhanging element and by a reflection on the terrain surrounding the building;
- $ad_{\min} = 64,\ ad_{\max} = 4096$ – ambient density;
- $ar_{\min} = 32,\ ar_{\max} = 2048$ – ambient resolution;
- $as_{\min} = 16,\ as_{\max} = 1024$ – ambient sampling.

The script could be optimized in the future at a higher rate, which is a plan of the author too.

RADIANCE Data Evaluation Script[5]

The “RADIANCE Data Evaluation Script” (RadianceDataEval) is another small program which was created during the solution of the thesis, once again written in PASCAL. It works the same way as the “RADIANCE Script”, i.e. within the command line of the operating system, but unlike “RADIANCE Script”, its main advantage lies in its file and data handling capabilities.

This software have had been created because of the huge number of possible ambient combinations, which can influence the results and ray-tracing simulations. If we take into account the 343 ambient parameter variations and multiply it with the number of test cases against which the design methods have had been validated, we would get 4802 files, with 8 to 14 values each. Hence, to check the rate of the combinations would take up a considerable amount of time.

With the help of this application, it is possible to pre-determine which simulations did fail and which did pass the daylight factor prediction, while comparing the results to CIE reference data with an error margin up to 10%. After the data verification, the result files do receive a prefix, either OK or BAD.

So that the software could work as needed it is made up of cycles “*for*” and “*repeat…until*” together with file handling associated commands like: “*assign*”, “*reset*”, “*close*”, “*findfirst*”.

---

[5] The author is willing to send the source code of the software for further development to everyone, who asks for it.

6.1.2 Monte-Carlo sampling

While reading and studying the *man pages* of the ~rtrace~ program of the « RADIANCE » package in version 4R (release 4) the author did come across a Boolean switch to turn ON/OFF the Monte Carlo sampling within the ray-tracing process. This option can be used by adding a “plus” or “minus” sign next to the switch “-u” and is automatically turned on.

Because the effects of this parameter weren’t published earlier in any of the books and publication read by the author (like RADIANCE Cookbook by A. Jacobs which is published on the webpages of JALOXA [52], Rendering with RADIANCE by G.W. Larson [14] or other publications by G.W. Larson and J. Mardaljevic) he became eager to test it out.

How does this parameter change the results of calculations?

The casual Monte Carlo sampling causes the results to be more irregular by randomizing the direction of sampling rays, resulting in a random evaluation of elementary planes over their areas. Therefore, it was required to do more than just one runs of simulations for the same space (usually three or more iterations). These were then averaged to get precise values.

On the other hand, by turning this function off, the sampling process within the iterations is going to be the same. It’s not going to be randomized any more, quite the opposite, carefully chosen repeatedly throughout the ray-tracing process. Thus, the outputs of the ray-tracing processes for the same point within the space are going to turn out to have the exact same value, hence it shortens the time necessary for practical utilization of « RADIANCE » in the field of daylighting design.

The theoretical background behind the Monte Carlo based stochastic ray-tracing is to be seen in fig. 34, while its influence onto the validation process of « RADIANCE » against the CIE test cases, especially onto case II.8 – part a) can be seen in fig. 35.

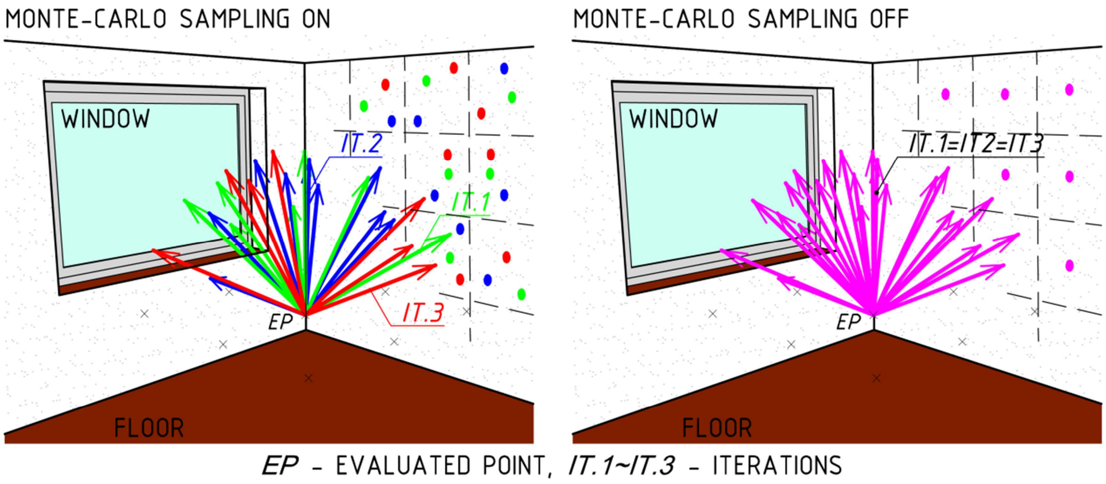


Fig. 34 *Monte Carlo sampling in ray-tracing process if turned on or off [Author]*

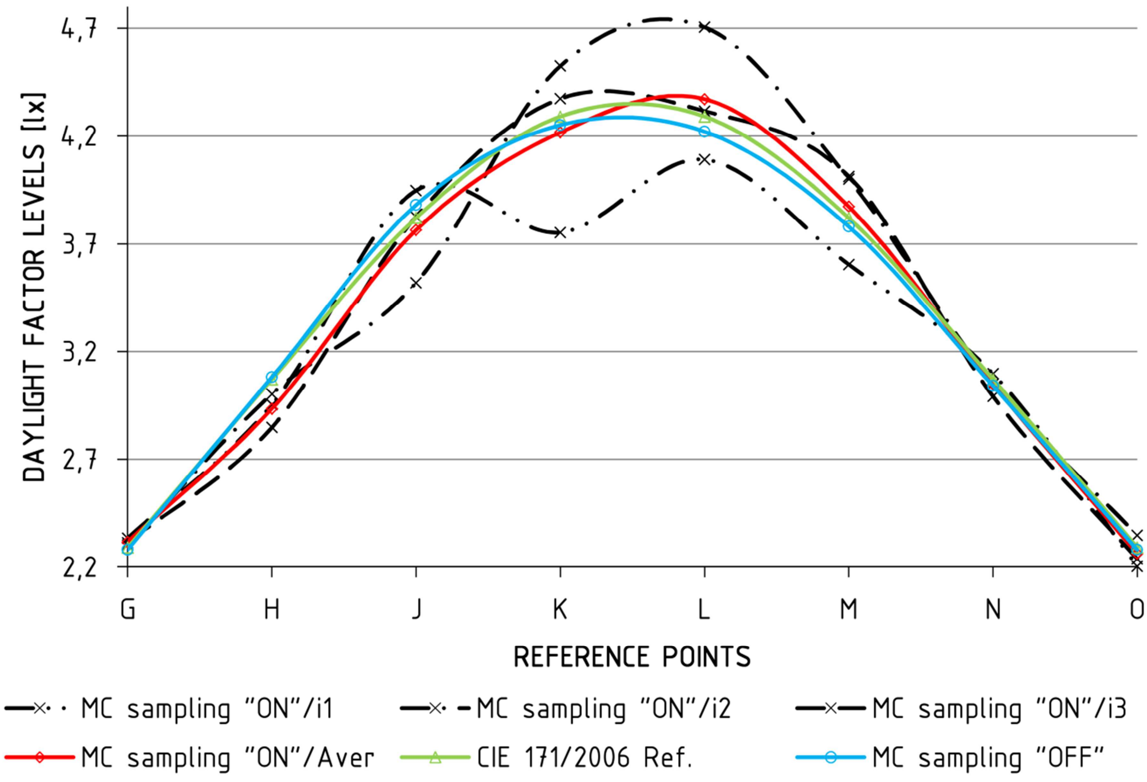


Fig. 35 *The effects of Monte Carlo sampling.*
(Results from simulations done to CIE test case II.8 – part a)

By taking a closer look at the charts within fig. 35 the differences are clearly discernible:

- The paths of charts of CIE reference values and those of simulations when the Monte Carlo sampling was turned off are almost identical, specifically parallel;
- The paths of Monte Carlo based sampling do have a high variety, even though the ambient parameters were set to high values (the main difference is still inside of the 10% error limit). Only the average of three iterations does have a plot similar to that of the CIE reference values.

By taking the effects of this Boolean into account, the results presented further on have had been obtained by standard sampling only.

6.1.3 Ground reflectance setting

~Gensky~ as the main sky generator of « RADIANCE » is dependent on three to ten parameters defining the time, location and sky type required for the tracing process by the user. The basic ~gensky~ definition inside the model description stands as follows:

!gensky **month day hour:min** (**time zone**[6]) **–sky type** –a **latitude**
–o **longitude** –m **meridian** –g **ground glow value** (54)

For Brno, here in the Czech Republic for the 1st of March at 12:00 while awaiting an overcast sky, the previously defined line would have the following form:

!gensky **3 1 12:00CET –c** –a **49.10** –o **-16.11** –m **15** (55)

If, by any change the –*g* parameter would not be set, ~gensky~ would assume it to be 0.2, standing for a ground reflectance of 20% derived into a glow type material describing the lower hemisphere of the space surrounding the objects.

That is why the terrain around an object in of a scene can be set up either as:

- A glow material defined by the –g parameter within the sky generation process (this would have an unlimited size), or;
- By turning the ground reflectance off in the sky generation process and add a surface representing the terrain to the model with a fixed size, or;
- Apply the combination of the two previously mentioned possibilities.

Therefore, there are two modifications for the sky generation line inside the model if we would like to go with the ground reflectance value of 0.3- needed for the validation process. These can be:

!gensky **3 1 12:00CET –c** –a **49.10** –o **-16.11**
–m **15** –g **0** –B **55.866**[7] (56)

!gensky **3 1 12:00CET –c** –a **49.10** –o **-16.11**
–m **15** –g **0.3** –B **55.866** (57)

The effect of available solutions can be seen on the following figures which were acquired for the vertical working plane of CIE test case II.10 – part a.

---

[6] Time zone setting is used if the meridian angle of the location is unknown, or is not set. Once it is defined the meridian angle also loses its meaning [14], [Author].

[7] The –B Boolean switch is used to apply the value of horizontal global irradiance as part of the sky generation process. It’s usually set to 55.866 if a global horizontal illuminance of 10 000 lx is needed for daylighting design (10 000/179).

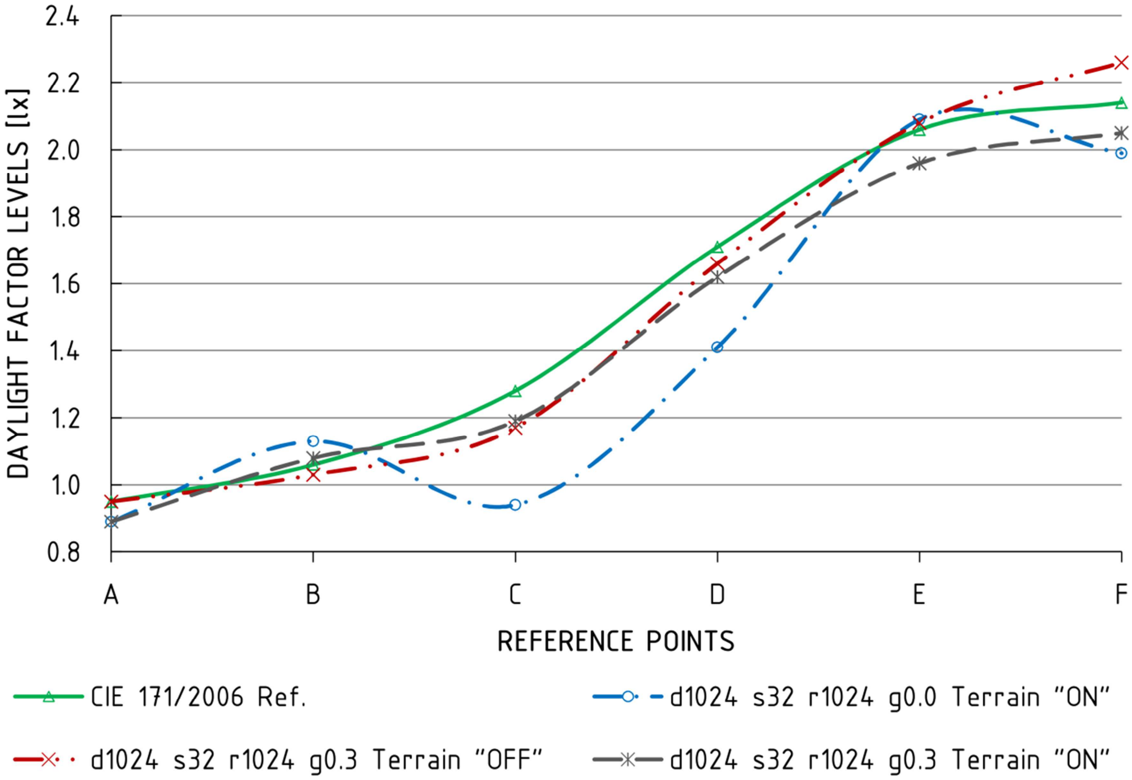


Fig. 36 *Comparison of the reference and simulated data for the three available methods of ground reflectance settings – vertical working plane*

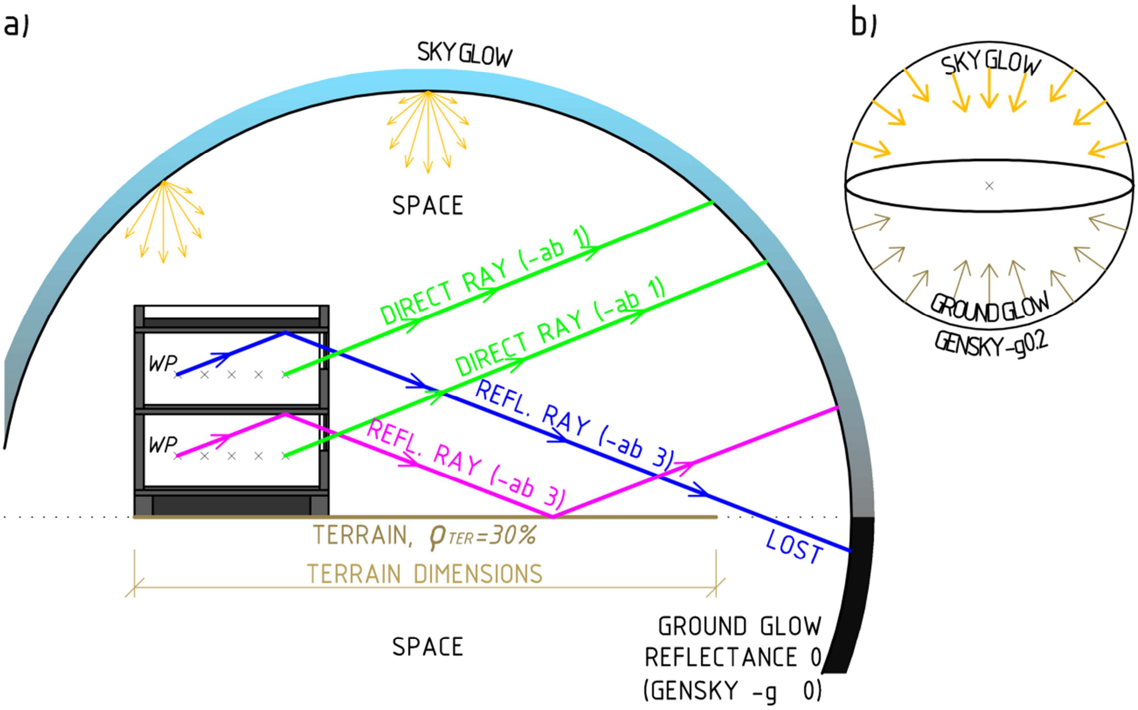


Fig. 37 *Ray-tracing - a) and sky generation with gensky - b)*

Note the fluctuation of daylight factor levels in fig. 36 when comparing the simulated ones to the reference values at positions C and D when the ground glow reflection have had been turned off and the terrain was defined as a polygonal surface around the room. The edges of the polygon are in a distance of 30m from the walls of the room in each direction. This is apparent because of the missing ground further away from the position of virtual sensors on which the tested rays could bounce off and thus reach the sky (see fig. 37).

Normally ground glow is not required within the daylighting design procedure of buildings, because:

- The daylighting design is focused on the horizontal working plane, therefore if the number of allowed inter-reflections would be equal to one (-ab 1), only direct components would be evaluated. For a horizontal plane part of the investigated rays would be absorbed by the internal surfaces of the room or by the faces of external barriers and part of them would reach sky, thus calculating the sky component of daylight factor;
- The dimensions of indoor spaces are relatively small in comparison to the sizes of the terrain plane defined as a polygon around the investigated building. So even if some reflections would be required, but the rays would be lost, the results would still turn out well.

The only examples, which would require a ground glow value other than zero, would be the ones where the daylight factor determination must go on a vertical face and the lighting system would be of void or windows type located in a vertical structure. Although the CIE test cases II.10 and II.11 are of this type, they were still tested in a different manner because of the experience of the author in simulation processes done within « RADIANCE ».

6.1.4 Results of simulations and calculations done for the CIE test cases

Test case II.8 – part a, roof void 1·1m

Tab. 5 *DF_S comparison for CIE test case scenario II.8 – part a / vert. plane*

Evaluation method	**Determined daylight factor levels [%] Deviation to reference values [%]**								**Δ_{min} Δ_{max} [%/%]**
	A	**B**	**C**	**D**	**E**	**F**	**-**	**-**	
CIE 171-2006: *Ref. values*	**0.56** -	**1.78** -	**2.32** -	**2.20** -	**1.82** -	**1.43** -	- -	- -	- -
RADIANCE: *Ray-tracing* **)	0.49 -12.5	1.77 -0.56	2.29 -1.29	2.14 -2.73	1.83 0.55	1.41 -1.40	- -	- -	**-12.5** **0.5**
WDLS 4.1: *All meth.; **th. 0***	10.12 1707	8.02 351	5.48 136	3.53 60.5	2.26 24.2	1.47 2.80	- -	- -	**2.8** **1707.1**
WDLS 4.1: *All meth.; **th. 1***	0.26 -53.6	1.52 -14.6	2.16 -6.90	1.97 -10.5	1.53 -15.9	1.12 -21.7	- -	- -	**-53.6** **-6.9**

Tab. 6 *DF_S comparison for CIE test case scenario II.8 – part a / hor. plane*

Evaluation method	**Determined daylight factor levels [%] Deviation to reference values [%]**								**Δ_{min} Δ_{max} [%/%]**
	G	**H**	**I**	**J**	**K**	**L**	**M**	**N**	
CIE 171-2006: *Ref. values*	**2.29** -	**3.07** -	**3.82** -	**4.29** -	**4.29** -	**3.82** -	**3.07** -	**2.29** -	- -
RADIANCE: *Ray-tracing* **)	2.28 -0.44	3.08 0.33	3.88 1.57	4.25 -0.93	4.22 -1.63	3.78 -1.05	3.04 -0.98	2.28 -0.44	**-1.6** **1.6**
WDLS 3.1: *All meth.; **th. 0***	2.23 -2.62	3.06 -0.33	3.84 0.52	4.33 0.93	4.33 0.93	3.84 0.52	3.06 -0.33	2.23 -2.62	**-2.6** **0.9**
WDLS 4.1: *All meth.; **th. 0***	2.65 15.7	3.34 8.79	3.97 3.93	4.36 1.63	4.36 1.63	3.97 3.93	3.34 8.79	2.65 15.7	**1.6** **15.7**
WDLS 4.1: *All meth.; **th. 1***	2.23 -2.62	3.05 -0.65	3.82 0.00	4.30 0.23	4.30 0.23	3.82 0.00	3.05 -0.65	2.23 -2.62	**-2.6** **0.2**
Numerical: *Mod. Daniljuk*	2.30 0.44	3.10 0.98	3.85 0.79	4.34 1.17	4.34 1.17	3.85 0.79	3.10 0.98	2.30 0.44	**0.4** **1.2**

**) Ray-tracing parameters: –aa 0.01 –ab 1 –ad 2048 –as 32 –ar 1024.

The tables above do show the comparison between the CIE reference values and the calculated ones. Note that the difference between them exceeds a 10% limit in several occasions. While looking at the vertical working plane « RADIANCE » evaluates a higher daylight factor only in point A, « WDLS v4.1 » at each of the points. The mean error is the biggest in case of wall thickness 0*mm*. It can be up to 1700%. In the horizontal working plane the error rate is exceeded in two cases only by « WDLS v4.1 » at wall th. 0*mm*.

Test case II.8 – part b, roof void 4·4m

Tab. 7 *DF_S comparison for CIE test case scenario II.8 – part b / vert. plane*

Evaluation method	**Determined daylight factor levels [%]** **Deviation to reference values [%]**								**Δ_{min}** **Δ_{max}** **[%/%]**
	A	**B**	**C**	**D**	**E**	**F**	**-**	**-**	
CIE 171-2006: *Ref. values*	**39.28** -	**32.32** -	**26.79** -	**21.78** -	**17.53** -	**14.05** -	- -	- -	- -
RADIANCE: *Ray-tracing* **)	37.22 -5.24	32.14 -0.56	26.67 -0.45	21.72 -0.28	17.51 -0.11	14.06 0.07	- -	- -	**-5.2** **0.1**
WDLS 4.1: *All meth.;* ***th. 0***	156.2 298	81.51 152	50.57 88.8	33.28 52.8	22.69 29.4	15.90 13.2	- -	- -	**13.2** **297.7**
WDLS 4.1: *All meth.;* ***th. 1***	26.15 -33.4	23.68 -26.7	20.24 -24.4	16.54 -24.1	13.16 -24.9	10.33 -26.5	- -	- -	**-33.4** **-24.1**

Tab. 8 *DF_S comparison for CIE test case scenario II.8 – part b / hor. plane*

Evaluation method	**Determined daylight factor levels [%]** **Deviation to reference values [%]**								**Δ_{min}** **Δ_{max}** **[%/%]**
	G	**H**	**I**	**J**	**K**	**L**	**M**	**N**	
CIE 171-2006: *Ref. values*	**31.36** -	**36.76** -	**40.71** -	**42.75** -	**42.76** -	**40.71** -	**36.76** -	**31.36** -	- -
RADIANCE: *Ray-tracing* **)	31.42 0.19	36.77 0.03	40.56 -0.37	42.66 -0.21	42.78 0.05	41.04 0.81	36.67 -0.24	31.17 -0.61	**-0.6** **0.8**
WDLS 3.1: *All meth.;* ***th. 0***	30.40 -3.06	35.95 -2.20	40.04 -1.65	42.19 -1.31	42.19 -1.33	40.04 -1.65	35.95 -2.20	30.40 -3.06	**-3.1** **-1.3**
WDLS 4.1: *All meth.;* ***th. 0***	36.48 16.3	41.70 13.4	45.52 11.8	47.54 11.2	47.54 11.2	45.52 11.8	41.70 13.4	36.48 16.3	**11.2** **16.3**
WDLS 4.1: *All meth.;* ***th. 1***	30.26 -3.51	35.81 -2.58	39.87 -2.06	42.01 -1.73	42.01 -1.75	39.87 -2.06	35.81 -2.58	30.26 -3.51	**-3.5** **-1.7**
Numerical: *Mod. Daniljuk*	34.14 8.86	40.33 9.71	44.93 10.4	47.34 10.7	47.34 10.7	44.93 10.4	40.33 9.71	34.14 8.86	**8.9** **10.7**

**) Ray-tracing parameters: –aa 0.01 –ab 1 –ad 2048 –as 32 –ar 1024.

The tables above do specify a data comparison similar to the one in the previous case. The only difference between them is, that in this case the roof openings' dimensions have had been increased to 4 metres, meaning, that the ceiling was transformed into a void. Hence, the reference values are also higher. A 10% error margin level were exceeded once again mostly by « WDLS v4.1 ». When looking at the vertical working plane for both thicknesses and on the horizontal working plane in case of wall thickness of 0*mm*. The approach of Daniljuk is on bad terms with openings without glazing.

Test case II.9 – part a, roof light 1·1m

Tab. 9 *DF_S comparison for CIE test case scenario II.9 – part a / vert. plane*

Evaluation method	**Determined daylight factor levels [%] Deviation to reference values [%]**								**Δ_{min} Δ_{max} [%/%]**
	A	**B**	**C**	**D**	**E**	**F**	**-**	**-**	
CIE 171-2006:	**0.19**	**1.26**	**1.90**	**1.87**	**1.57**	**1.24**	**-**	**-**	**-**
Ref. values	-	-	-	-	-	-	-	-	-
RADIANCE:	0.17	1.27	1.98	1.93	1.62	1.29	-	-	**-10.5**
Ray-tracing **)	-10.5	0.79	4.21	3.21	3.18	4.03	-	-	**4.2**
WDLS 4.1:	9.10	7.22	4.94	3.18	2.03	1.32	-	-	**6.5**
*All meth.; **th. 0***	4689	473	160	70.1	29.3	6.45	-	-	**4689.5**
WDLS 4.1:	0.31	1.73	2.28	1.97	1.46	1.04	-	-	**-16.1**
*All meth.; **th. 1***	63.2	37.3	20.0	5.35	-7.01	-16.1	-	-	**63.2**

Tab. 10 *DF_S comparison for CIE test case scenario II.9 – part a / hor. plane*

Evaluation method	**Determined daylight factor levels [%] Deviation to reference values [%]**								**Δ_{min} Δ_{max} [%/%]**
	G	**H**	**I**	**J**	**K**	**L**	**M**	**N**	
CIE 171-2006:	**2.00**	**2.70**	**3.36**	**3.78**	**3.78**	**3.36**	**2.70**	**2.00**	-
Ref. values	-	-	-	-	-	-	-	-	-
RADIANCE:	2.02	2.89	3.33	3.91	3.88	3.60	2.76	1.91	**-4.5**
Ray-tracing **)	1.00	7.04	-0.89	3.44	2.65	7.14	2.22	-4.50	**7.1**
WDLS 3.1:	2.01	2.72	3.41	3.88	3.88	3.41	2.72	2.01	**0.5**
*All meth.; **th. 0***	0.50	0.74	1.49	2.65	2.65	1.49	0.74	0.50	**2.6**
WDLS 4.1:	2.38	3.01	3.57	3.92	3.92	3.57	3.01	2.38	**3.7**
*All meth.; **th. 0***	19.0	11.5	6.25	3.70	3.70	6.25	11.5	19.0	**19.0**
WDLS 4.1:	2.01	2.71	3.39	3.85	3.85	3.39	2.71	2.01	**0.4**
*All meth.; **th. 1***	0.50	0.37	0.89	1.85	1.85	0.89	0.37	0.50	**1.9**
Numerical:	2.02	2.77	3.47	3.90	3.90	3.47	2.77	2.02	**1.0**
Mod. Daniljuk	1.00	2.59	3.27	3.17	3.17	3.27	2.59	1.00	**3.3**

**) Ray-tracing parameters: –aa 0.01 –ab 1 –ad 2048 –as 32 –ar 1024.

Because voids are usually equipped with a kind of fitting element like windows, doors and roof lights, test case scenario II.8 part a was slightly modified and tested for directional light transmission while verifying the sky component inside a certain room. In the tables above similar results can be seen to those obtained for test case II.8 – part a. « RADIANCE » has problems at one point of the vertical working plane only. « WDLS v4.1 » does have some serious problems with vertical working planes. The precision of Daniljuk's approach and « WDLS v3.1 » is highly noticeable, as well as « WDLS v4.1's » at th. 1*mm*.

Test case II.9 – part b, roof light 4·4m

Tab. 11 *DF_S comparison for CIE test case scenario II.9 – part b / vert. plane*

Evaluation method	**Determined daylight factor levels [%] Deviation to reference values [%]**								**Δ_{min} Δ_{max} [%/%]**
	A	**B**	**C**	**D**	**E**	**F**	**-**	**-**	
CIE 171-2006:	**29.21**	**25.63**	**22.14**	**18.43**	**15.03**	**12.15**	**-**	**-**	**-**
Ref. values	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
RADIANCE:	28.22	26.18	22.53	18.79	15.49	12.25	-	-	**-3.4**
Ray-tracing **)	-3.39	2.15	1.76	1.95	3.06	0.82	-	-	**3.1**
WDLS 4.1:	140.6	73.36	45.51	29.95	20.42	14.31	-	-	**17.8**
All meth.; ***th. 0***	381	186	106	62.5	35.9	17.8	-	-	**381.3**
WDLS 4.1:	27.46	24.59	20.61	16.49	12.85	9.89	-	-	**-18.6**
All meth.; ***th. 1***	-5.99	-4.06	-6.91	-10.5	-14.5	-18.6	-	-	**-4.1**

Tab. 12 *DF_S comparison for CIE test case scenario II.9 – part b / hor. plane*

Evaluation method	**Determined daylight factor levels [%] Deviation to reference values [%]**								**Δ_{min} Δ_{max} [%/%]**
	G	**H**	**I**	**J**	**K**	**L**	**M**	**N**	
CIE 171-2006:	**27.44**	**32.23**	**35.73**	**37.56**	**37.56**	**35.73**	**32.23**	**27.44**	**-**
Ref. values	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
RADIANCE:	28.23	33.05	36.53	38.65	38.39	36.62	32.86	27.99	**2.0**
Ray-tracing	2.88	2.54	2.24	2.90	2.21	2.49	1.95	2.00	**2.9**
WDLS 3.1:	27.65	32.48	36.01	37.84	37.84	36.01	32.48	27.65	**0.7**
All meth.; ***th. 0***	0.77	0.78	0.78	0.75	0.75	0.78	0.78	0.77	**0.8**
WDLS 4.1:	32.83	37.53	40.97	42.78	42.78	40.97	37.53	32.83	**13.9**
All meth.; ***th. 0***	19.6	16.4	14.7	13.9	13.9	14.7	16.4	19.6	**19.6**
WDLS 4.1:	27.53	32.36	35.86	37.69	37.69	35.86	32.36	27.53	**0.3**
All meth.; ***th. 1***	0.33	0.40	0.36	0.35	0.35	0.36	0.40	0.33	**0.4**
Numerical:	29.65	35.68	40.19	42.58	42.58	40.19	35.68	29.65	**8.1**
Mod. Daniljuk	8.05	10.7	12.5	13.4	13.4	12.5	10.7	8.05	**13.4**

**) Ray-tracing parameters: –aa 0.01 –ab 1 –ad 2048 –as 32 –ar 1024.

Because the roof light was equipped with a glazing of a kind (according to the authors of the CIE 171/2006 standard, with a 6mm thick glass pane) the reference values are also smaller. In case of the « RADIANCE » based simulations the error rate was below 5%. The calculated values were better only in case of calculations done for the horizontal working plane by « WDLS » software tools. This however is not valid for the vertical working plane, where « WDLS v4.1 » was once again the worst of all. The error rate of Daniljuk’s approach is higher too, but not the worst.

Test case II.10 – part a, void 2·1m

Tab. 13 *DF_S+DF_e comparison for CIE test case scenario II.10 – part a / vert. plane*

Evaluation method	**Determined daylight factor levels [%]** **Deviation to reference values [%]**								Δ_{min} Δ_{max} **[%/%]**
	A	**B**	**C**	**D**	**E**	**F**	**-**	**-**	
CIE 171-2006: *Ref. values*	**0.95** -	**1.06** -	**1.28** -	**1.71** -	**2.06** -	**2.14** -	- -	- -	- -
RADIANCE: *Ray-tracing* $^{**)}$	0.91 -4.21	1.04 -1.89	0.98 -23.4	1.38 -19.3	1.98 -3.88	2.11 -1.40	- -	- -	**-23.4** **-1.4**
WDLS 4.1: *All meth.; **th. 0***	1.01 6.32	1.10 3.77	2.40 87.5	3.60 111	4.61 124	4.16 94.4	- -	- -	**3.8** **123.8**
WDLS 4.1: *All meth.; **th. 1***	0.95 0.00	1.06 0.00	2.37 85.2	3.55 108	4.48 117	3.92 83.2	- -	- -	**0.0** **117.5**

Tab. 14 *DF_S+DF_e comparison for CIE test case scenario II.10 – part a / hor. plane*

Evaluation method	**Determined daylight factor levels [%]** **Deviation to reference values [%]**								Δ_{min} Δ_{max} **[%/%]**
	G	**H**	**I**	**J**	**K**	**L**	**M**	**N**	
CIE 171-2006: *Ref. values*	**0.95** -	**1.38** -	**2.07** -	**3.19** -	**4.97** -	**7.42** -	**9.11** -	**5.04** -	- -
RADIANCE: *Ray-tracing* $^{**)}$	0.98 3.16	1.33 -3.62	2.01 -2.90	3.24 1.57	5.03 1.21	7.55 1.75	9.19 0.88	5.04 0.00	**-3.6** **3.2**
WDLS 3.1: *All meth.; **th. 0***	0.94 -1.05	1.36 -1.45	2.01 -2.90	3.03 -5.02	4.51 -9.26	6.08 -18.1	5.77 -36.7	1.30 -74.2	**-74.2** **-1.1**
WDLS 4.1: *All meth.; **th. 0***	1.04 9.47	1.55 12.3	2.42 16.9	3.95 23.8	6.75 35.8	11.88 60.1	20.42 124	29.66 488	**9.5** **488.5**
WDLS 4.1: *All meth.; **th. 1***	0.94 -1.05	1.36 -1.45	2.01 -2.90	3.03 -5.02	4.51 -9.26	6.09 -17.9	5.77 -36.7	1.30 -74.2	**-74.2** **-1.1**
Numerical: *Mod. Daniljuk*	0.96 1.05	1.40 1.45	2.10 1.45	3.26 2.19	5.10 2.62	7.68 3.50	9.53 4.61	5.32 5.56	**1.1** **5.6**

$^{**)}$ Ray-tracing parameters: –aa 0.01 –ab 2 –ad 2048 –as 32 –ar 1024.

The daylighting systems from now on have had been exchanged by voids and windows located in one of the walls of the room. Please notice the higher deviations for the results coming from « RADIANCE » for the vertical working plane. Such error rates are caused by the improper ground reflectance settings for the evaluation of the vertical working plane. Regardless « RADIANCE » and the innovated Daniljuk’s approach do deliver the best results. « WDLS » has problem in each version. The daylight factor levels determined in points closer to the opening do have a non-realistic values.

Test case II.10 – part b, void 4·3m

Tab. 15 *DF_S+DF_e comparison for CIE test case scenario II.10 – part b / vert. plane*

Evaluation method	**Determined daylight factor levels [%] Deviation to reference values [%]**								**Δ_{min} Δ_{max} [%/%]**
	A	**B**	**C**	**D**	**E**	**F**	**-**	**-**	
CIE 171-2006:	**5.29**	**6.46**	**7.67**	**8.88**	**9.73**	**10.29**	**-**	**-**	**-**
Ref. values	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
RADIANCE:	4.18	5.34	6.67	8.07	9.23	9.65	-	-	**-21.0**
Ray-tracing **)	-21.0	-17.3	-13.0	-9.12	-5.14	-6.22	-	-	**-5.1**
WDLS 4.1:	7.99	10.82	13.22	17.60	18.82	19.47	-	-	**51.0**
*All meth.; **th. 0***	51.0	67.5	72.4	98.2	93.4	89.2	-	-	**98.2**
WDLS 4.1:	7.39	10.19	12.47	16.52	17.37	17.56	-	-	**39.7**
*All meth.; **th. 1***	39.7	57.7	62.6	86.0	78.5	70.7	-	-	**86.0**

Tab. 16 *DF_S+DF_e comparison for CIE test case scenario II.10 – part b / hor. plane*

Evaluation method	**Determined daylight factor levels [%] Deviation to reference values [%]**								**Δ_{min} Δ_{max} [%/%]**
	G	**H**	**I**	**J**	**K**	**L**	**M**	**N**	
CIE 171-2006:	**4.50**	**6.15**	**8.53**	**12.00**	**16.97**	**23.91**	**33.08**	**44.43**	**-**
Ref. values	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
RADIANCE:	4.34	6.09	8.43	11.76	16.94	23.81	33.05	44.43	**-3.6**
Ray-tracing **)	-3.56	-0.98	-1.17	-2.00	-0.18	-0.42	-0.09	0.00	**0.0**
WDLS 3.1:	4.35	5.86	7.95	10.79	14.47	18.79	23.03	26.09	**-41.3**
*All meth.; **th. 0***	-3.33	-4.72	-6.80	-10.1	-14.7	-21.4	-30.4	-41.3	**-3.3**
WDLS 4.1:	5.28	7.49	10.92	16.41	25.52	41.30	70.95	144.9	**17.3**
*All meth.; **th. 0***	17.3	21.8	28.0	36.8	50.4	72.7	114	226	**226.1**
WDLS 4.1:	4.35	5.86	7.95	10.79	14.47	18.79	23.03	26.14	**-41.2**
*All meth.; **th. 1***	-3.33	-4.72	-6.80	-10.1	-14.7	-21.4	-30.4	-41.2	**-3.3**
Numerical:	4.75	6.54	9.18	13.09	18.90	27.36	39.00	52.43	**5.6**
Mod. Daniljuk	5.56	6.34	7.62	9.08	11.4	14.4	17.9	18.0	**18.0**

**) Ray-tracing parameters: –aa 0.01 –ab 2 –ad 2048 –as 32 –ar 1024.

The results are much alike to the previous case. The only discernible difference had appeared in case of Daniljuk's methodology, where because of the luminance gradation formula the resulting daylight factor value near the opening arose above 50%. In reality, this could not happen in reality.

Test case II.11 – part a, window 2·1m

Tab. 17 *DF_S+DF_e comparison for CIE test case scenario II.11 – part a / vert. plane*

Evaluation method	**Determined daylight factor levels [%] Deviation to reference values [%]**								**Δ_{min} Δ_{max} [%/%]**
	A	**B**	**C**	**D**	**E**	**F**	**-**	**-**	
CIE 171-2006:	**0.84**	**0.94**	**1.12**	**1.50**	**1.81**	**1.89**	**-**	**-**	**-**
Ref. values	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
RADIANCE:	0.81	0.94	0.91	1.30	1.83	1.95	-	-	**-18.8**
Ray-tracing **)	-3.57	0.00	-18.8	-13.3	1.10	3.17	-	-	**3.2**
WDLS 4.1:	0.91	0.99	2.16	3.24	4.15	3.74	-	-	**5.3**
*All meth.; **th. 0***	8.33	5.32	92.9	116	129	97.9	-	-	**129.3**
WDLS 4.1:	0.84	0.95	2.12	3.17	3.98	3.47	-	-	**0.0**
*All meth.; **th. 1***	0.00	1.06	89.3	111	120	83.6	-	-	**119.9**

Tab. 18 *DF_S+DF_e comparison for CIE test case scenario II.11 – part a / hor. plane*

Evaluation method	**Determined daylight factor levels [%] Deviation to reference values [%]**								**Δ_{min} Δ_{max} [%/%]**
	G	**H**	**I**	**J**	**K**	**L**	**M**	**N**	
CIE 171-2006:	**0.83**	**1.21**	**1.81**	**2.78**	**4.28**	**6.26**	**7.02**	**2.13**	**-**
Ref. values	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
RADIANCE:	0.83	1.25	1.80	2.90	4.43	6.36	7.25	2.12	**-0.6**
Ray-tracing **)	0.00	3.31	-0.55	4.32	3.50	1.60	3.28	-0.47	**4.3**
WDLS 3.1:	0.83	1.21	1.82	2.80	4.31	6.15	6.33	1.55	**-27.2**
*All meth.; **th. 0***	0.00	0.00	0.55	0.72	0.70	-1.76	-9.83	-27.2	**0.7**
WDLS 4.1:	0.93	1.39	2.18	3.55	6.07	10.70	18.37	26.69	**12.0**
*All meth.; **th. 0***	12.0	14.9	20.4	27.7	41.8	70.9	162	1153	**1153.1**
WDLS 4.1:	0.83	1.21	1.82	2.80	4.32	6.16	6.32	1.55	**-27.2**
*All meth.; **th. 1***	0.00	0.00	0.55	0.72	0.93	-1.60	-9.97	-27.2	**0.9**
Numerical:	0.85	1.24	1.85	2.81	4.24	5.82	5.66	1.30	**-39.0**
Mod. Daniljuk	2.41	2.48	2.21	1.08	-0.93	-7.03	-19.4	-39.0	**2.5**

**) Ray-tracing parameters: –aa 0.01 –ab 2 –ad 2048 –as 32 –ar 1024.

The results were once again influenced by the glazing the same way as they were in test cases II.9. The error rate of most of the methodologies is once again higher than that of « RADIANCE » software package for the horizontal WP. This phenomenon originates in the expressions behind the determination of the directional transmittance of the glazing, i.e. under which angle does the light fall onto its surface. For « RADIANCE » is a different type of application it is not dominated by it. The other methods have had been affected only in case that the evaluated point were located closer to the opening.

Test case II.11 – part b, windows 4·3m

Tab. 19 *DF_S+DF_e comparison for CIE test case scenario II.11 – part b / vert. plane*

Evaluation method	**Determined daylight factor levels [%] Deviation to reference values [%]**								**Δ_{min} Δ_{max} [%/%]**
	A	**B**	**C**	**D**	**E**	**F**	**-**	**-**	
CIE 171-2006:	**4.65**	**5.69**	**6.75**	**7.82**	**8.56**	**9.04**	**-**	**-**	**-**
Ref. values	-	-	-	-	-	-	-	-	-
RADIANCE:	3.79	5.04	6.14	7.14	8.13	8.87	-	-	**-18.5**
Ray-tracing **)	-18.5	-11.4	-9.04	-8.70	-5.02	-1.88	-	-	**-1.9**
WDLS 4.1:	7.19	9.73	11.89	15.84	16.94	17.52	-	-	**54.6**
*All meth.; **th. 0***	54.6	71.0	76.1	103	97.9	93.8	-	-	**102.6**
WDLS 4.1:	6.59	9.08	11.08	14.69	15.47	15.70	-	-	**41.7**
*All meth.; **th. 1***	41.7	59.6	64.1	87.9	80.7	73.7	-	-	**87.9**

Tab. 20 *DF_S+DF_e comparison for CIE test case scenario II.11 – part b / hor. plane*

Evaluation method	**Determined daylight factor levels [%] Deviation to reference values [%]**								**Δ_{min} Δ_{max} [%/%]**
	G	**H**	**I**	**J**	**K**	**L**	**M**	**N**	
CIE 171-2006:	**3.94**	**5.36**	**7.41**	**10.34**	**14.42**	**19.74**	**25.70**	**30.40**	**-**
Ref. values	-	-	-	-	-	-	-	-	-
RADIANCE:	3.95	5.42	7.56	10.50	14.67	20.10	26.43	30.99	**0.3**
Ray-tracing **)	0.25	1.12	2.02	1.55	1.73	1.82	2.84	1.94	**2.8**
WDLS 3.1:	3.96	5.39	7.44	10.32	14.19	18.96	23.82	27.37	**-10.0**
*All meth.; **th. 0***	0.51	0.56	0.40	-0.19	-1.60	-3.95	-7.32	-9.97	**0.6**
WDLS 4.1:	4.75	6.74	9.82	14.77	22.97	37.17	63.85	130.5	**20.6**
*All meth.; **th. 0***	20.6	25.7	32.5	42.8	59.3	88.3	148	329	**329.3**
WDLS 4.1:	3.95	5.39	7.44	10.32	14.19	18.95	23.82	27.41	**-9.8**
*All meth.; **th. 1***	0.25	0.56	0.40	-0.19	-1.60	-4.00	-7.32	-9.84	**0.6**
Numerical:	4.20	5.74	7.95	11.12	15.57	21.48	28.50	34.58	**6.6**
Mod. Daniljuk	6.60	7.09	7.29	7.54	7.98	8.81	10.9	13.8	**13.8**

**) Ray-tracing parameters: –aa 0.01 –ab 2 –ad 2048 –as 32 –ar 1024.

The values with the smallest deviation were obtained from « RADIANCE », although the values obtained by simulations for the vertical working plane are clearly smaller than the reference ones, but still better than in case of the data obtained by « WDLS v4.1 ». Daniljuk's approach has some problems when the evaluated points are closer to the opening, once again, although this is curable. « WDLS v4.1»issues with the wall thickness do remain, nonetheless for a wall thickness of 1*mm* the results are approximately the same as the ones attained by « WDLS v3.1», hence within boundaries.

Test case II.12 – part a, void 2·1m and horizontal shading with l=0.5m

Tab. 21 *DF_S+DF_e comparison for CIE test case over hor. plane*

Evaluation method	**Determined daylight factor levels [%] Deviation to reference values [%]**								**Δ_{min} Δ_{max} [%/%]**
	G	**H**	**I**	**J**	**K**	**L**	**M**	**N**	
CIE 171-2006:	**0.95**	**1.38**	**2.07**	**3.19**	**4.97**	**7.42**	**8.07**	**0.21**	-
Ref. values	-	-	-	-	-	-	-	-	-
RADIANCE:	0.93	1.41	2.10	3.18	4.99	7.41	8.20	0.49	**-2.1**
Ray-tracing **)	-2.11	2.17	1.45	-0.31	0.40	-0.13	1.61	133.3	**133.3**
WDLS 3.1:	0.94	1.36	2.01	3.03	4.51	6.08	5.32	0.09	**-57.1**
*All meth.; **th. 0***	-1.05	-1.45	-2.90	-5.02	-9.26	-18.1	-34.1	-57.1	**-1.1**
WDLS 4.1:	1.04	1.55	2.42	3.95	6.75	11.88	17.36	1.92	**9.5**
*M.Refl.; **th. 0***	9.47	12.3	16.9	23.8	35.8	60.1	115	814	**814.3**
WDLS 4.1:	0.93	1.35	2.02	3.11	4.80	6.84	6.32	0.10	**-52.4**
*M.Refl.; **th. 1***	-2.11	-2.17	-2.42	-2.51	-3.42	-7.82	-21.7	-52.4	**-2.1**
WDLS 4.1:	1.04	1.55	2.42	3.95	6.75	11.88	17.36	1.92	**9.5**
*L.Rat.; **th. 0***	9.47	12.3	16.9	23.8	35.8	60.1	115	814	**814.3**
WDLS 4.1:	0.93	1.35	2.02	3.11	4.80	6.84	6.32	0.10	**-52.4**
*L.Rat.; **th. 1***	-2.11	-2.17	-2.42	-2.51	-3.42	-7.82	-21.7	-52.4	**-2.1**
Numerical:	0.96	1.40	2.10	3.26	5.10	7.68	8.41	0.15	**-28.6**
Mod. Daniljuk	1.05	1.45	1.45	2.19	2.62	3.50	4.21	-28.6	**4.2**

**) Ray-tracing parameters: –aa 0.01 –ab 3 –ad 4096 –as 256 –ar 2048.

The given test case have had been developed to check the quality of computer simulations software, while taking into account light reflections in the exterior of building objects.

Although, some of the previously verified test cases did already introduce glazing within the openings, this particular test case and the following ones without any. These test cases do also care about the light levels incident to the horizontal working plane only.

A specialty of this test case though is that the reflections are caused by an overhanging element of a building, which could be a balcony, cornice or a porch in reality.

As for the calculations, the error rate is high for most of the available design methods. For example, at point N « RADIANCE » does have a deviation of 133%, « WDLS v3.1» above -57% and « WDLS v4.1» for a wall thickness of 1mm exceeding -52%. The daylight factor levels for the rest of the points have had been determined by « RADIANCE » and Daniljuk's numerical approach, the best. In the latter case, the equation to achieve the externally reflected component have had been slightly modified (the overhanging element reflects an already reflected light particle).

Test case II.12 – part b, void 2·1m and horizontal shading with l=1m

Tab. 22 *DF_S+DF_e comparison for CIE test case over hor. plane*

Evaluation method	**Determined daylight factor levels [%] Deviation to reference values [%]**								**Δ_{min} Δ_{max} [%/%]**
	G	**H**	**I**	**J**	**K**	**L**	**M**	**N**	
CIE 171-2006:	**0.87**	**1.31**	**2.02**	**3.20**	**4.68**	**5.69**	**4.08**	**0.21**	-
Ref. values	-	-	-	-	-	-	-	-	-
RADIANCE:	0.93	1.40	2.08	3.18	4.69	5.61	4.03	0.49	**-1.4**
Ray-tracing **)	6.90	6.87	2.97	-0.63	0.21	-1.41	-1.23	133	**133.3**
WDLS 3.1:	0.94	1.36	2.01	3.03	4.51	4.61	2.99	0.09	**-57.1**
All meth.; ***th. 0***	8.05	3.82	-0.50	-5.31	-3.63	-19.0	-26.7	-57.1	**8.0**
WDLS 4.1:	1.04	1.55	2.42	3.95	6.75	7.66	6.41	2.93	**18.3**
M.Refl.; ***th. 0***	19.54	18.32	19.80	23.44	44.23	34.62	57.11	1295	**1295.2**
WDLS 4.1:	0.94	1.36	2.01	3.03	4.51	4.33	2.29	0.12	**-43.9**
M.Refl.; ***th. 1***	8.05	3.82	-0.50	-5.31	-3.63	-23.9	-43.9	-42.9	**8.0**
WDLS 4.1:	1.04	1.55	2.42	3.95	6.75	7.48	5.84	1.92	**18.3**
L.Rat.; ***th. 0***	19.54	18.32	19.80	23.44	44.23	31.46	43.14	814	**814.3**
WDLS 4.1:	0.94	1.36	2.01	3.03	4.51	4.23	2.15	0.08	**-61.9**
L.Rat.; ***th. 1***	8.05	3.82	-0.50	-5.31	-3.63	-25.7	-47.3	-61.9	**8.0**
Numerical:	0.96	1.40	2.10	3.26	4.70	5.68	4.09	0.15	**-28.6**
Mod. Daniljuk	10.34	6.87	3.96	1.87	0.43	-0.18	0.25	-28.6	**10.3**

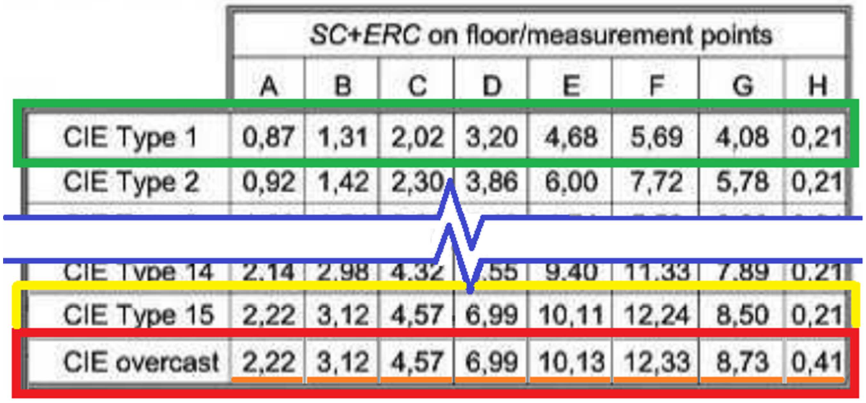
**) Ray-tracing parameters: –aa 0.01 –ab 3 –ad 4096 –as 256 –ar 2048.

While verifying the « Velux Daylight Visualizer », the engineering community doing the assessment refused to check, whether the software could predict the daylight factor levels correctly or not, because of the mistypes included in the appendices of the CIE 171/2006 standard.

The reference values in the table above do belong to a different set, though for a CIE Standard Overcast Sky but it does not handle about the ones obtained by numerical analysis, but those obtained by « Skylux » software.

Fig. 38 displays the reference values for the given test case for sky types 1, 2 and 15, and for CIE overcast sky (which is CIE sky type 1). By comparing the reference values the errata is directly visible for the CIE Overcast Sky. The analytically generated values are close to those attained for CIE sky type 15 (CIE Clear Sky).

As for the comparison of the obtained data from calculations and simulations with respect to these reference values, a considerable deviation (error margin) is apparent, and that not just in case of « RADIANCE » based simulations but also in case of calculations done by hand as part of the numerical analysis or by « WDLS 3.1 and 4.1 ». Yet « RADIANCE » and the Daniljuk's innovated approach could not foretell the daylight factor precisely only in case of reference point H, whereas « WDLS » in more than just one location.



	SC+ERC on floor/measurement points							
	A	B	C	D	E	F	G	H
CIE Type 1	0,87	1,31	2,02	3,20	4,68	5,69	4,08	0,21
CIE Type 2	0,92	1,42	2,30	3,86	6,00	7,72	5,78	0,21
CIE Type 14	2,14	2,98	4,32	.55	9,40	11,33	7,89	0,21
CIE Type 15	2,22	3,12	4,57	6,99	10,11	12,24	8,50	0,21
CIE overcast	2,22	3,12	4,57	6,99	10,13	12,33	8,73	0,41

Fig. 38 *The reference data table for test case II.12 – part b [44]*

Test case II.12 – part c, void 2·1m and horizontal shading with l=2m

Tab. 23 *DF_S+DF_e comparison for CIE test case over hor. plane*

Evaluation method	**Determined daylight factor levels [%] Deviation to reference values [%]**								**Δ_{min} Δ_{max}**
	G	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**[%/%]**
CIE 171-2006:	**0.90**	**1.16**	**1.50**	**1.90**	**2.20**	**1.68**	**0.40**	**0.21**	-
Ref. values	-	-	-	-	-	-	-	-	-
RADIANCE:	0.88	1.18	1.53	1.91	2.21	1.87	1.02	0.47	**-2.2**
Ray-tracing $^{**)}$	-2.22	1.72	2.00	0.53	0.45	11.31	155.0	123.8	**155.0**
WDLS 3.1:	0.94	1.36	1.47	1.49	1.95	1.51	0.46	0.09	**-57.1**
All meth.; ***th. 0***	4.44	17.2	-2.00	-21.6	-11.4	-10.1	15.0	-57.1	**17.2**
WDLS 4.1:	1.04	1.55	1.54	1.92	3.46	3.39	2.19	3.07	**1.1**
M.Refl.; ***th. 0***	15.6	33.62	2.67	1.05	57.3	101.8	448	1362	**1361.9**
WDLS 4.1:	0.94	1.36	1.33	1.58	2.53	2.04	0.62	0.13	**-38.1**
M.Refl.; ***th. 1***	4.44	17.24	-11.3	-16.8	15.0	21.4	55.0	-38.1	**55.0**
WDLS 4.1:	1.04	1.55	1.49	1.81	3.28	2.97	1.34	1.92	**-4.7**
L.Rat.; ***th. 0***	15.56	33.62	-0.67	-4.74	49.1	76.8	235	814	**814.3**
WDLS 4.1:	0.94	1.36	1.29	1.49	2.42	1.84	0.38	0.08	**-61.9**
L.Rat.; ***th. 1***	4.44	17.2	-14.0	-21.6	10.0	9.52	-5.00	-61.9	**17.2**
Numerical:	0.91	1.17	1.51	1.91	2.21	1.66	0.34	0.15	**-28.6**
Mod. Daniljuk	1.11	0.86	0.67	0.53	0.45	-1.19	-15.0	-28.6	**1.1**

$^{**)}$ Ray-tracing parameters: –aa 0.01 –ab 3 –ad 4096 –as 256 –ar 2048.

When looking at the table including the results of evaluation for the accuracy of design tools, the same occurrences are apparent as in the earlier cases:

- « WDLS 4.1 » has continuing issues when the wall thickness is set to 0mm;

- The numerical approach, using the innovated Daniljuk’s methodology turns out to have the best results, with an accuracy of results varying between 1.1% and -28.6%;
- The CIE 171/2006 given values are either too small or too big for reference points M and N. Unfortunately the scinetific committee of CIE, had not done a thorough investigation of the test cases, till now.

Test case II.13 – part a, void 2·1m and vertical barrier with h=3m

Tab. 24 *DF_S+DF_e comparison for CIE test case over hor. plane*

Evaluation method	**Determined daylight factor levels [%] Deviation to reference values [%]**								**Δ_{min} Δ_{max} [%/%]**
	G	**H**	**I**	**J**	**K**	**L**	**M**	**N**	
CIE 171-2006: *Ref. values*	**0.88** -	**1.34** -	**2.07** -	**3.19** -	**4.97** -	**7.42** -	**9.11** -	**5.04** -	- -
RADIANCE: *Ray-tracing* **)	0.86 -2.27	1.36 1.49	2.07 0.00	3.21 0.63	5.00 0.60	7.39 -0.40	9.08 -0.33	4.94 -1.98	**-2.3** **1.5**
WDLS 3.1: *All meth.; **th. 0***	0.94 6.82	1.36 1.49	2.01 -2.90	3.03 -5.02	4.51 -9.26	6.08 -18.1	5.77 -36.7	1.30 -74.2	**-74.2** **6.8**
WDLS 4.1: *M.Refl.; **th. 0***	1.04 18.2	1.55 15.7	2.42 16.9	3.95 23.8	6.75 35.8	11.88 60.1	20.42 124	29.66 488	**15.7** **488.5**
WDLS 4.1: *M.Refl.; **th. 1***	0.94 6.82	1.36 1.49	2.01 -2.90	3.03 -5.02	4.51 -9.3	6.09 -17.9	5.77 -36.7	1.30 -74.2	**-74.2** **6.8**
WDLS 4.1: *L.Rat.; **th. 0***	1.04 18.2	1.55 15.7	2.42 16.9	3.95 23.8	6.75 35.8	11.88 60.1	20.42 124	29.66 488	**15.7** **488.5**
WDLS 4.1: *L.Rat.; **th. 1***	0.94 6.82	1.36 1.49	2.01 -2.90	3.03 -5.02	4.51 -9.26	6.09 -17.9	5.77 -36.7	1.30 -74.2	**-74.2** **6.8**
Numerical: *Mod. Daniljuk*	0.88 0.00	1.36 1.49	2.10 1.45	3.26 2.19	5.10 2.62	7.68 3.50	9.53 4.61	5.33 5.75	**0.0** **5.8**

**) Ray-tracing parameters: –aa 0.01 –ab 2 –ad 4096 –as 1024 –ar 512.

While observing the results included in tab. 24 the following is visible:

- The simulations using ray-tracing had turned out to have the smallest inconsistency while confronting them to the reference data array;
- The accuracy of the numerical approach is really high, it can be compared to that of « RADIANCE » based calculations;
- « WDLS » in both versions and calculation approaches does have some problems, when the reference point is near the opening.

Test case II.13 – part b, void 2·1m and vertical barrier with h=6m

Tab. 25 *DF_S+DF_e comparison for CIE test case over hor. plane*

Evaluation method	**Determined daylight factor levels [%] Deviation to reference values [%]**								**Δ_{min} Δ_{max} [%/%]**
	G	**H**	**I**	**J**	**K**	**L**	**M**	**N**	
CIE 171-2006:	**0.42**	**0.48**	**0.81**	**1.78**	**3.65**	**7.19**	**9.11**	**5.04**	-
Ref. values	-	-	-	-	-	-	-	-	-
RADIANCE:	0.31	0.57	1.03	2.18	4.26	7.38	9.10	4.94	**-26.2**
Ray-tracing **)	-26.2	18.8	27.2	22.5	16.7	2.64	-0.11	-1.98	**27.2**
WDLS 3.1:	0.36	0.42	0.52	1.80	3.30	6.08	5.77	1.30	**-74.2**
All meth.; ***th. 0***	-14.3	-12.5	-35.8	1.12	-9.59	-15.4	-36.7	-74.2	**1.1**
WDLS 4.1:	0.53	0.72	1.09	2.90	6.02	11.88	20.42	29.66	**26.2**
M.Refl.; ***th. 0***	26.2	50.0	34.6	62.9	64.9	65.2	124.1	488	**488.5**
WDLS 4.1:	0.47	0.62	0.90	2.18	3.93	6.09	5.77	1.30	**-74.2**
M.Refl.; ***th. 1***	11.9	29.2	11.1	22.5	7.67	-15.3	-36.7	-74.2	**29.2**
WDLS 4.1:	0.40	0.49	0.76	2.64	5.89	11.88	20.42	29.66	**-6.2**
L.Rat.; ***th. 0***	-4.76	2.08	-6.17	48.3	61.4	65.2	124.1	488	**488.5**
WDLS 4.1:	0.36	0.42	0.61	1.97	3.82	6.09	5.77	1.30	**-74.2**
L.Rat.; ***th. 1***	-14.3	-12.5	-24.7	10.7	4.66	-15.3	-36.7	-74.2	**10.7**
Numerical:	0.27	0.45	0.96	2.12	4.18	7.54	9.53	5.32	**-35.7**
Mod. Daniljuk	-35.7	-6.25	18.5	19.1	14.52	4.87	4.61	5.56	**19.1**

**) Ray-tracing parameters: –aa 0.01 –ab 2 –ad 4096 –as 256 –ar 2048.

Test case scenario II.13 – part b should be investigated by a specialized committee. The aim of the commission would be to verify whether the reference data are correct or not. The results are varying too much especially for points G, H, I, J and K. The accuracy of the predicted values could be said is bad, for all of the design methods.

While ray-tracing gives a steady erratum of ±26.6% (if averaged) for these locations, Daniljuk's approach does have an even higher fluctuation. The inaccuracy increases rapidly when taking into account the outcome of « WDLS v3.1 » and « WDLS v4.1 » software's, too.

Test case II.13 – part c, void 2·1m and vertical barrier with h=9m

For test case II.13-part c a similar question arises, than in case of II.12-part b, when the reference data had to be exchanged with another set from the appendices of the CIE standard.

Could reference points G and H really have such high of a rate, when already fully shaded by the external barrier?

When the external barriers height was only 3meters, the reference value was already smaller when compared to II.10 – part a. By increasing the barriers height to 6 meters, the value did sink from 0.88% to 0.42% because of the smaller visible portion of the sky. However, for the reference value to increase back to 0.80% while making the barrier taller is somewhat inaccurate. There are no internal reflections, since the light reflectance values of indoor surfaces are already 0-.

By taking the value for point G from test case II.10 – part a, which is equal to 0.93% and for sky component only, it would be possible to easily determine the externally reflected component at full shading, by multiplying it with 0.3-, which is the average surface reflectance of the barrier. Although, this is a simplified approach, the reference value should not exceed that of 0.39%.

Is it correct?

Another issue can be seen while looking at point K. If it would be assumed that, the calculations done by the numerical approach are the closest to reality then a daylight factor level equal to 1.32% would be nonsense. It does not reflect the conditions on site.

Tab. 26 *DF_S+DF_e comparison for CIE test case over hor. plane*

Evaluation method	**Determined daylight factor levels [%] Deviation to reference values [%]**								**Δ_{min} Δ_{max} [%/%]**
	G	**H**	**I**	**J**	**K**	**L**	**M**	**N**	
CIE 171-2006:	**0.80**	**0.93**	**1.08**	**1.23**	**1.32**	**3.93**	**9.11**	**5.04**	-
Ref. values	-	-	-	-	-	-	-	-	-
RADIANCE:	0.31	0.56	0.90	1.54	2.80	5.77	9.12	4.94	**-61.3**
Ray-tracing $^{**)}$	-61.3	-39.8	-16.7	25.2	112.1	46.8	0.11	-1.98	**112.1**
WDLS 3.1:	0.36	0.42	0.52	1.40	1.75	4.84	5.77	1.31	**-74.0**
*All meth.; **th. 0***	-55.0	-54.8	-51.9	13.8	32.6	23.2	-36.7	-74.0	**32.6**
WDLS 4.1:	0.53	0.72	1.08	2.50	3.66	9.43	20.42	29.66	**-33.8**
*M.Refl.; **th. 0***	-33.8	-22.6	0.00	103	177	140	124	488	**488.5**
WDLS 4.1:	0.47	0.62	0.89	1.89	2.39	4.61	5.77	1.30	**-74.2**
*M.Refl.; **th. 1***	-41.3	-33.3	-17.6	53.7	81.1	17.3	-36.7	-74.2	**81.1**
WDLS 4.1:	0.40	0.49	0.76	2.15	3.11	9.02	20.42	29.66	**-50.0**
*L.Rat.; **th. 0***	-50.0	-47.3	-29.6	74.8	136	130	124	488	**488.5**
WDLS 4.1:	0.36	0.42	0.61	1.62	2.00	4.35	5.77	1.30	**-74.2**
*L.Rat.; **th. 1***	-55.0	-54.8	-43.5	31.7	51.5	10.7	-36.7	-74.2	**51.5**
Numerical:	0.27	0.45	0.78	1.38	2.41	5.51	9.53	5.32	**-66.3**
Mod. Daniljuk	-66.3	-51.6	-27.8	12.2	82.6	40.2	4.61	5.56	**82.6**

$^{**)}$ Ray-tracing parameters: –aa 0.01 –ab 2 –ad 4096 –as 256 –ar 2048.

6.2 COMPARISON OF MEASURED AND CALCULATED VALUES OF DAYLIGHT FACTOR LEVELS INSIDE BUILDINGS

6.2.1 Determination of light reflectance values

Within the attic of the faculty, two indoor spaces are located. These are referred to as laboratories and have had been erected to allow Ph.D. students to make measurements for their research projects. Therefore, it was decided earlier, that some of the available measuring equipment could be placed into these rooms, too.

The laboratories are erected from the same building materials, like:

- Gypsum boards for partitions and ceilings;
- Cetris boards for floor;
- Steel doorframe with a coating of a dark tint (actual colour is somewhere around reddish-brown) equipped with white single wing doors;
- An electric heating equipment of white colour just under the roof windows;
- And a timber framed roof window with standard thermo-insulating double glazing the light transmission of which was determined to have a value of 0.7-, including the maintenance factors on both sides of it.

The only difference between the two rooms is in their purpose. While “Laboratory No.1” is to be used to obtain reference data by continuous measurements for each of the research projects, “Laboratory No.2” can be modified within reason by new technologies, which are to be monitored. At the time of the measurements done by the author of the thesis, “Laboratory No.2” have had been already equipped by PCM (Phase change material) filled alumina panels on most of the surfaces as part of an on-going research project of Ing. Milan Ostrý, Ph.D. and Ing. David Bečkovský, Ph.D..

Because “Laboratory No.2” have had been used by the author for comparative measurements only to determine the differences in the visual response of the available illuminance sensors the surface reflectance values of the PCM based panels hadn’t been obtained only just a few weeks after the primary monitoring process had been finished, for safety.

Laboratory No.1

For the determination of the surface reflectances inside of “Laboratory No.1” an etalon lend to the author by Doc. Ing. Jiří Plch, CSc. was used consecutively on the 6 materials, making up the room. The surface reflectance values then were achieved by calculations from the obtained luminance values on both the etalon and the original surfaces by the KONICA-MINOLTA LS110 luminance meter, after three sets of chosen iterations.

The results of these measurements in the form of luminance and resulting reflectance values can be seen in tab. 27.

Tab. 27 *The determined surface reflectance values of "Laboratory No.1"*

Surface type (Colour)	**Luminance levels in three steps (L_{ref}/L_{surf}) [cd/m^2]**			**Refl. [%]**
	Try 1	**Try 2**	**Try 3**	
Walls/Soffit (White paint)	0.888 1.741	0.831 1.694	1.054 2.078	**57.7**
Floor (Cetris board - gray)	2.905 1.926	2.680 1.783	2.884 1.911	**19.2**
Door frame (Dark brownish-red)	0.158 0.041	0.156 0.041	0.160 0.041	**7.5**
Door wing (Snow white)	0.508 0.900	0.510 0.907	0.507 0.899	**51.5**
Window frame (Pine tree)	3.768 3.968	3.915 4.142	3.905 4.155	**30.7**
Heatin element (White matte coating)	1.685 2.820	1.538 2.592	1.199 1.998	**48.6**

Laboratory No.2

The surface reflectance values of "Laboratory No.2" have had been re-measured because of the alumina panels located on the walls and ceiling. Since the etalon used previously was not at disposition anymore, a new approach was required. This had brought about the creation of a reference surface, the theory behind the determination of this given surfaces light reflectance is in fig. 39.

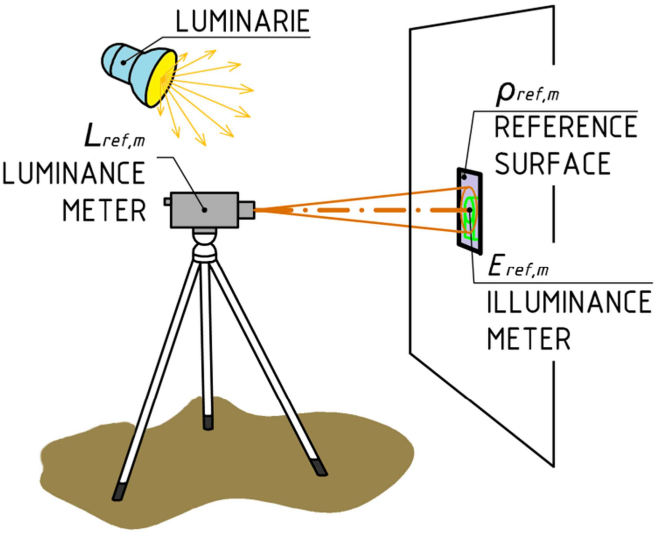


Fig. 39 *The measuring process for the determination of the reference surfaces light reflectance value, in theory [Author].*

This given reference surface was based on a material similar to that used for the luminance value measurement in “Laboratory No.1”. The surface reflectance of this surface was determined with the help of a homemade box from cardboard. The main purpose of this box was to house the receptor head of the KONICA-MINOLTA T10 illuminance meter for a small amount of time, essential to obtain the data for the surface reflectance determination. So that these measurements could take place, the top of the cardboard box have had been cut open at two positions. One of the holes was for the receptor head to go through the wall of the box, while the other was for the display to be readable. Before this though, a thin film a self-adhesive foil (the same material, which have had been used to create the reference surface) was glued onto the surface of the cardboard box, to decrease the influence of the paper while the reference surface was located on top of it.

The actual measurements then took place in one of the rooms of the faculty, carefully chosen, for the monitoring process did require a light source with a constant luminous flux (small fluctuations though, were allowed). This meant, that these measurements could not have been done under natural light, as to daylight is dynamic. The housing box for the illuminance meter was then located at a height of 85*cm* (circa) on the door wing, and the luminance meter was placed in a distance of 1m away from the position of the top of the receptor head on a tripod with its optics focused onto the centre of the illuminance meter.

After everything have had been put into place, the lights were turned on and were left shining for 30minutes, roughly, before the actual measurements took place.

The whole process including the theory behind the measurements are shown in and fig. 40.

The reflectance value of the reference surface then was determined from three sets of data with the help of eq. 58, which is a modified version of eq. 37:

$$\rho_{ref,m} = \sum_{i=1}^{N} \left(\frac{L_{ref,i} \cdot \pi}{E_{ref,i}} \right) \Big/ N \tag{58}$$

Where:

$\rho_{ref,m}$ - is the mean surface reflectance of the reference surface $[-]$;

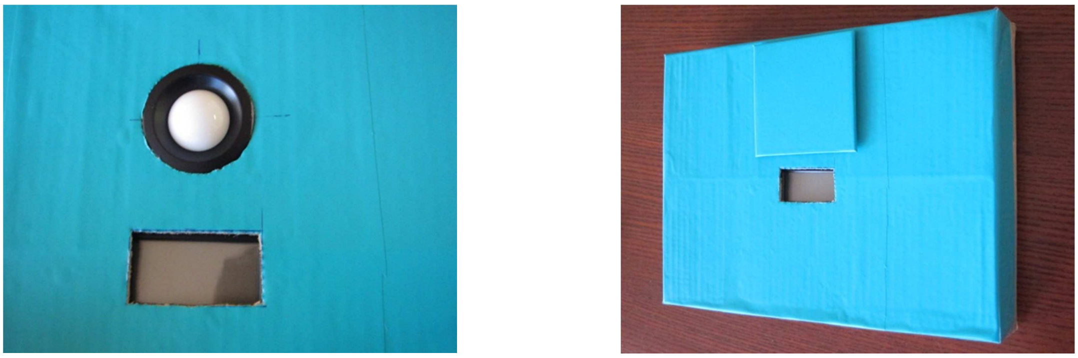
$L_{ref,i}$ - is the luminance of the reference surface $[cd \cdot m^{-2}]$;

$E_{ref,i}$ - is the illuminance incident to the reference surface $[lx]$.

The calculated resulting surface reflectance is:

$$\rho_{ref,m} = \pi \cdot \left(\frac{1.594}{28.70} + \frac{1.620}{29.21} + \frac{1.599}{28.95} \right) \Big/ 3 = 0.174079 \cong 0.174\,[-] \tag{59}$$

Making of the box. Coating of the surface of the box.



Mutual relationship between the illuminance meter and the holes. The receptor head covered up by the reference surface.

The measuring process. View through the optics of the luminance meter.

Fig. 40 *The making of the apparatus and the process of subsequent monitoring.*

The surface reflectance determination done to the PCM based alumina panels turned out following values:

Tab. 28 *The determined surface reflectance value for "Laboratory No.2" – PCM panel*

Surface type (Colour)	**Luminance levels in three steps (L_{ref}/L_{surf}) [cd/m^2]**			**Refl. [%]**
	Try 1	**Try 2**	**Try 3**	
PCM panels (Brushed alumina)	1.861 4.290	1.816 4.185	1.839 4.219	**40.0**

6.2.2 EMlux and MuuLUX

EMlux (a screenshot of the software is shown below), is a software which is coupled to the KONICA-MINOLTA T10 illuminance meter by the Czech distributor when buying the measuring apparatus. The software was primarily written and developed by Ing. Petr Baxant, Ph.D., an employee of The Faculty of Electrical Engineering and Communication of Brno University of Technology, though it is being sold by a company called EMdat, even today.

The computer program is described to be stable, and does have some advanced features. The first tries and measurements made by it did however display the complete opposite, unfortunately. In particular, an unstable, slow and slightly complicated side of the software. Although the data should have been saved to the hard drive continuously, the crumbles of the program still caused a data loss, which means that most of it was stored at a temporary location, like the RAM of the machine. Hence, the measurements had to be-redone for most of the time.

As to this happened a few times while still learning the know-hows of EMlux it have had been decided that it's going to be better to depart with it in the beginnings and create a new free computer tool.

Ref: 100

Ccf: 1,000

Rozsah: AUTO

Rychlost: SLOW

Hlavice: 0

x [m]: 0

y [m]: 0

ref: 00 č: 1/1 E=

Fig. 41 *A shot of the KONICA-MINOLTA T10 illuminance meter (on the left) and a screenshot of EMlux software on the right [51]*

Thus MuuLUX was born.

Nevertheless, because of low programming skills and a limited time available for the development of MuuLUX the program itself have had been created in a cooperation of the author with a friend of his (Sándor /Althego/ Bágyi, from Budapest) who knew how to write programs with RS-232 communication necessities. The author was told about the basics via IRC (Internet Relay Chat) and have had begun to secure the required information, like the access codes for the RS232 interface of the measuring equipment.

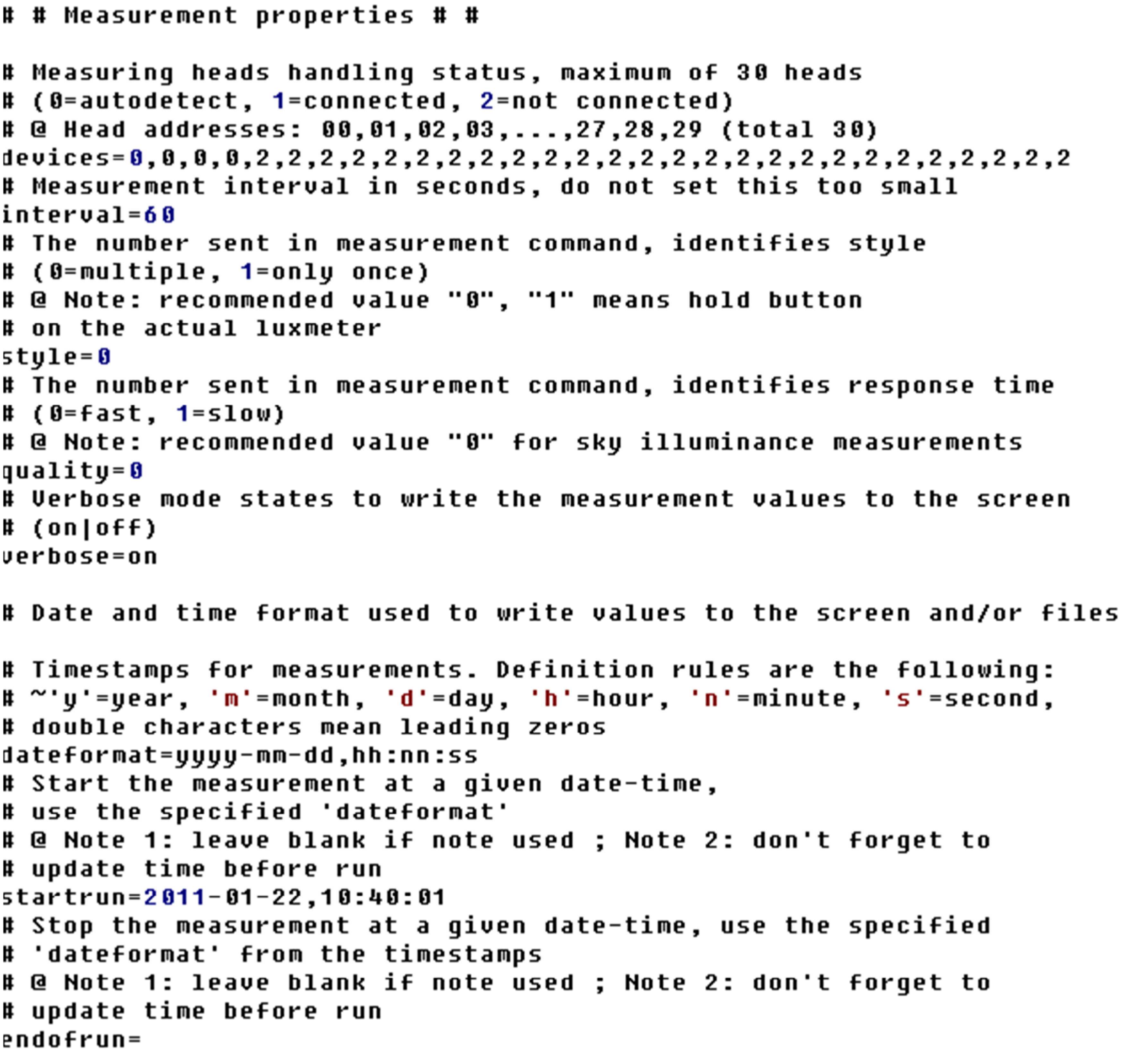
Because, the e-mail communication was most probably filtered-out by the spam rules of KONICA-MINOLTA Company a bit of reverse engineering had been done. It is a process similar to that of hacking, but fortunately, it did not handle about hacking or even about cracking, just about data flow monitoring via the serial port of the computer when the illuminance meter was connected to it. For this a software called SerialMon have had been installed on the computer of the author (it handled about a serial port monitor, free of charge). The essential data have had been obtained by subsequent measurements and connections done by EMlux, for different settings of the KONICA-MINOLTA T10 illuminance meter. The different settings do primarily refer to the addresses of the receptor heads (these are manually adjusted on the socket of the device).

The hexadecimal codes were determined within a day as well as the basic one. These values were then sent to Hungary, where they have had been implemented into the resulting software.

MuuLUX, at its current version still has its source written only in PASCAL. Has some minor bugs, but those does not really affect the capabilities of it. The software requires a configuration file to be set up correctly for it to run. The given file holds data about the serial port connection settings throughout which the illuminance meter is to be connected to the computer (serial port number, parity of the port, etc.), then about the monitoring process itself. Part of the configuration file is visible in fig. 42, while MuuLUX in action in fig. 43.

What are the advantages of MuuLUX?

- Continuous backup of measured data (after each 10th entry the values are saved to a text file);
- Easy to use (once the configuration file is created from the example file it can be run at any time);
- Repeated measurements can be done if needed for a limited time using MS Windows OS’s task scheduler (example: 60 measurements are to be done after each and every 5 minutes on each day for a week from 9:30). In this way the values obtained would be saved into separate files;
- It’s stable and has low hardware requirements (can be used on older personal computers with lower CPU frequencies just around 100 MHz and RAM of 16-32 MB’s);
- By using the correct libraries when ported it can be run also under U/L;



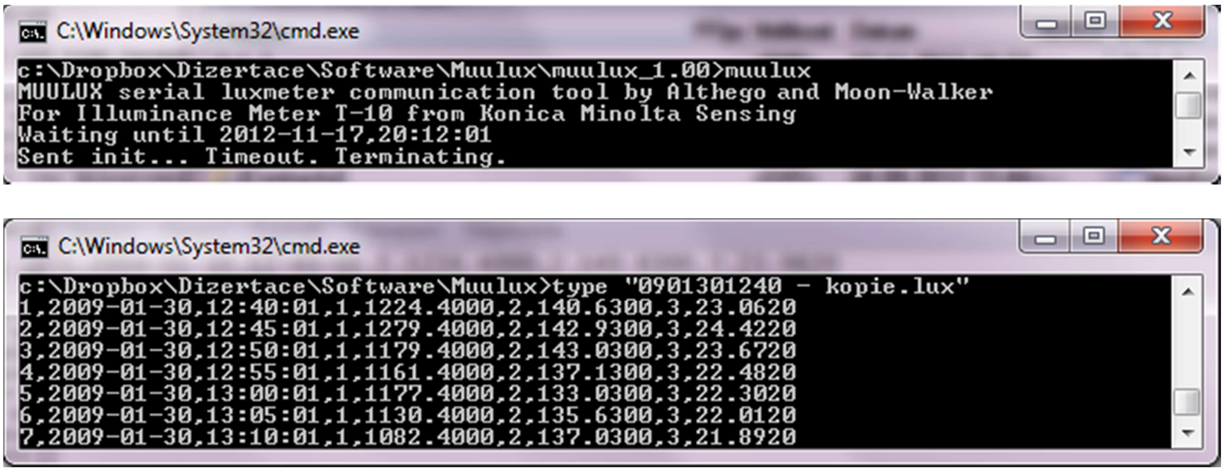
```
# # Measurement properties # #

# Measuring heads handling status, maximum of 30 heads
# (0=autodetect, 1=connected, 2=not connected)
# @ Head addresses: 00,01,02,03,...,27,28,29 (total 30)
devices=0,0,0,0,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2
# Measurement interval in seconds, do not set this too small
interval=60
# The number sent in measurement command, identifies style
# (0=multiple, 1=only once)
# @ Note: recommended value "0", "1" means hold button
# on the actual luxmeter
style=0
# The number sent in measurement command, identifies response time
# (0=fast, 1=slow)
# @ Note: recommended value "0" for sky illuminance measurements
quality=0
# Verbose mode states to write the measurement values to the screen
# (on|off)
verbose=on

# Date and time format used to write values to the screen and/or files

# Timestamps for measurements. Definition rules are the following:
# ~'y'=year, 'm'=month, 'd'=day, 'h'=hour, 'n'=minute, 's'=second,
# double characters mean leading zeros
dateformat=yyyy-mm-dd,hh:nn:ss
# Start the measurement at a given date-time,
# use the specified 'dateformat'
# @ Note 1: leave blank if note used ; Note 2: don't forget to
# update time before run
startrun=2011-01-22,10:40:01
# Stop the measurement at a given date-time, use the specified
# 'dateformat' from the timestamps
# @ Note 1: leave blank if note used ; Note 2: don't forget to
# update time before run
endofrun=
```

Fig. 42 *Part of the configuration file of MuuLUX [Author]*



```
c:\Dropbox\Dizertace\Software\Muulux\muulux_1.00>muulux
MUULUX serial luxmeter communication tool by Althego and Moon-Walker
For Illuminance Meter T-10 from Konica Minolta Sensing
Waiting until 2012-11-17,20:12:01
Sent init... Timeout. Terminating.
```

```
c:\Dropbox\Dizertace\Software\Muulux>type "0901301240 - kopie.lux"
1,2009-01-30,12:40:01,1,1224.4000,2,140.6300,3,23.0620
2,2009-01-30,12:45:01,1,1279.4000,2,142.9300,3,24.4220
3,2009-01-30,12:50:01,1,1179.4000,2,143.0300,3,23.6720
4,2009-01-30,12:55:01,1,1161.4000,2,137.1300,3,22.4820
5,2009-01-30,13:00:01,1,1177.4000,2,133.0300,3,22.3020
6,2009-01-30,13:05:01,1,1130.4000,2,135.6300,3,22.0120
7,2009-01-30,13:10:01,1,1082.4000,2,137.0300,3,21.8920
```

Fig. 43 *On the top MuuLUX run inside of MS Windows OS, on the bottom part of the result file written out [Author].*[8]

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[8] Althego is the nickname of Sándor Bágyi, Moon-Walker refers to the author.

6.2.3 The visual response of HOBO U12-012 data loggers

The HOBO U12-012 data loggers have had been partially purchased on the recommendation of our colleagues working at the Faculty of Architecture, University of Sheffield. There was however a problem with them from the beginning. Their response to any visual load was unclear. Therefore, these data had to be obtained throughout measurement alongside of the KONICA-MINOLTA T10 illuminance meter, done in “Laboratory No.2”. Three of the available detectors have had been put onto tripods then placed into a line in a distance of 1000*mm* away from the walls of the laboratories. Two sensors were located at the ends of the column and one in the middle.

The HOBO U12-012 had to go through a setup process before they could have had been placed. The reason behind this was, that the time and date settings had to be the same as they were on the computer running MuuLUX, therefore the applied data loggers were connected one after another to the same PC, through OnsetComp © a software for manipulation them. After the initial setup, the HOBO U12-012 data loggers have had been moved next to the measuring heads of the T10 illuminance meters on separate tripods and the measuring process had begun.

The results regarding this comparison are shown in the following figures.

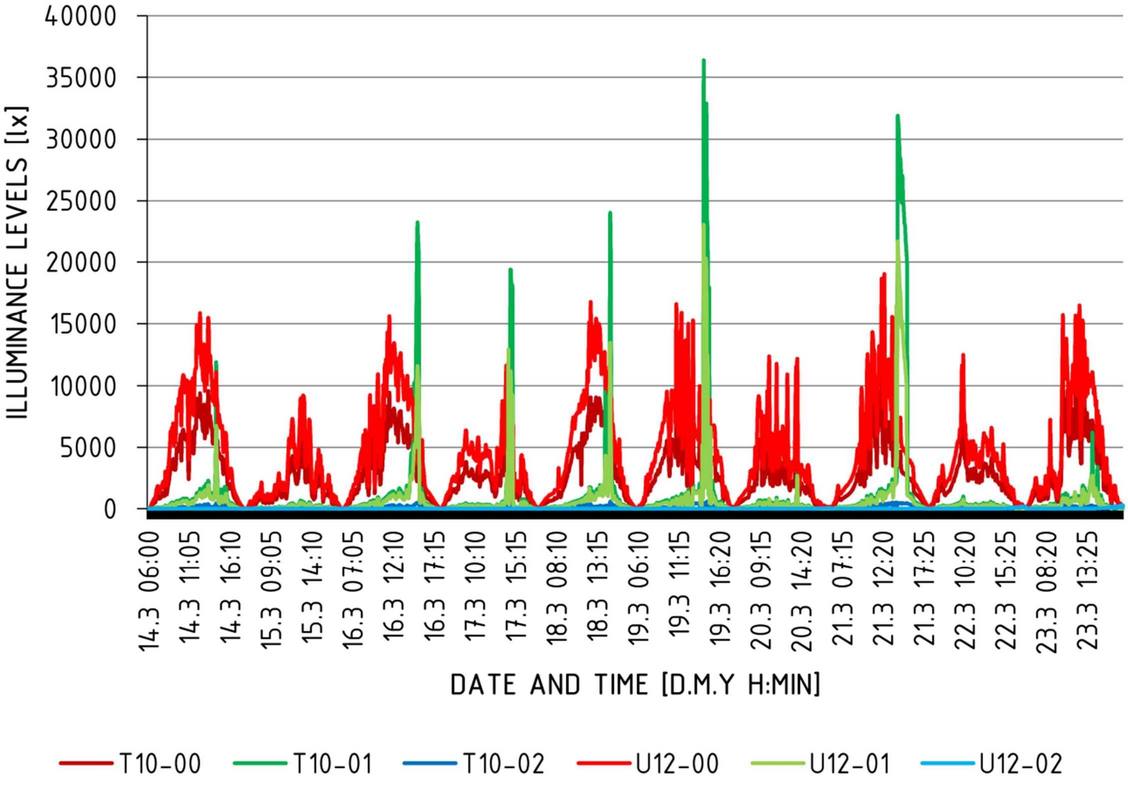


Fig. 44 *10 day data collection in “Laboratory No.2”*

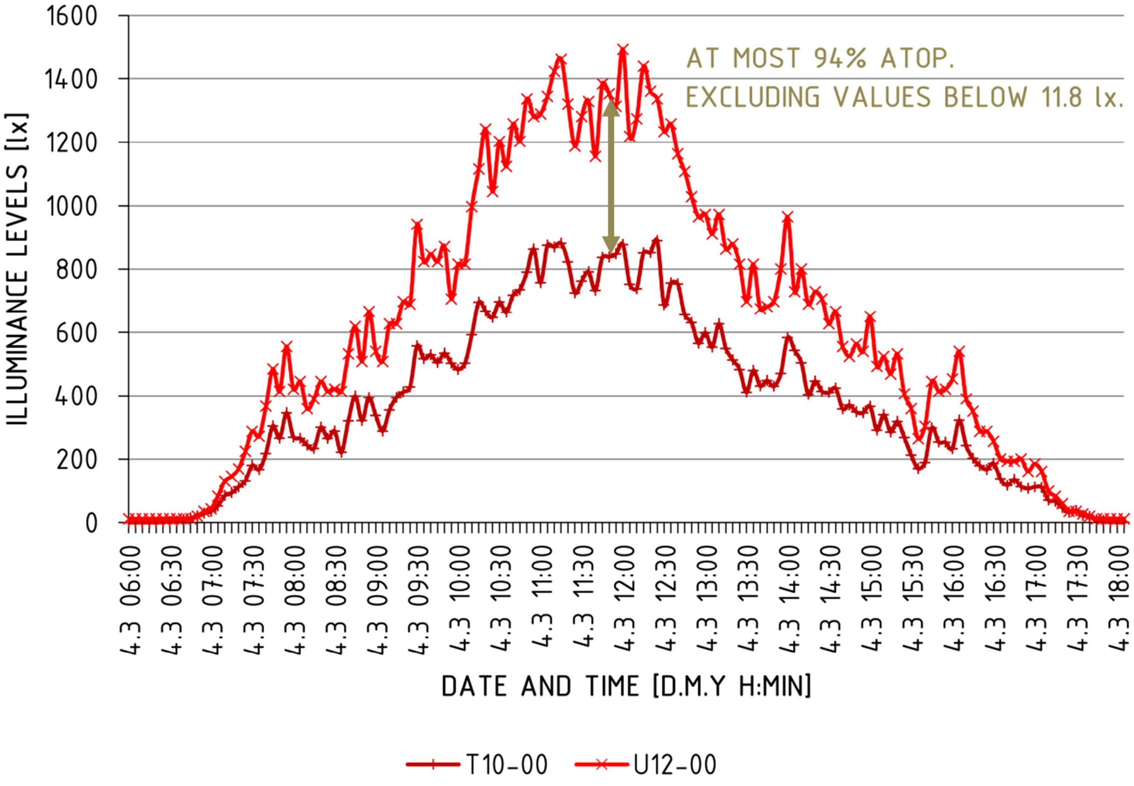


Fig. 45 *Illuminance levels at point A under overcast sky conditions.*

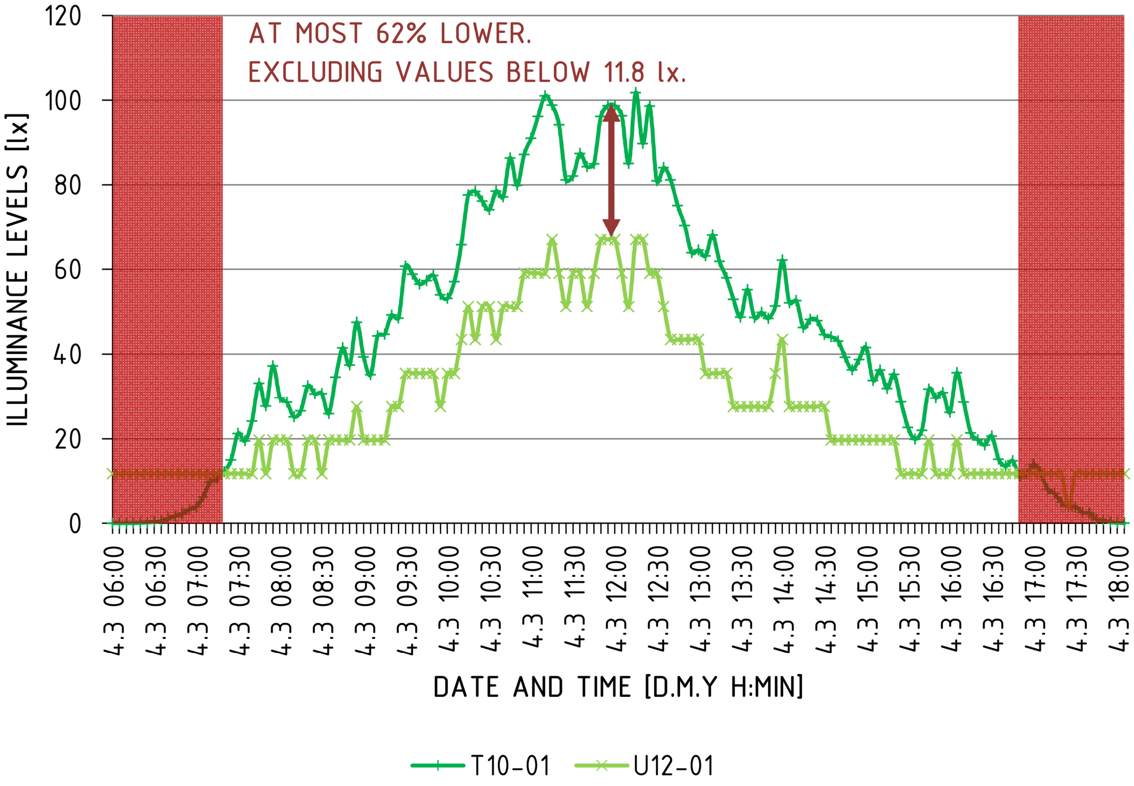


Fig. 46 *Illuminance levels at point B under overcast sky conditions.*

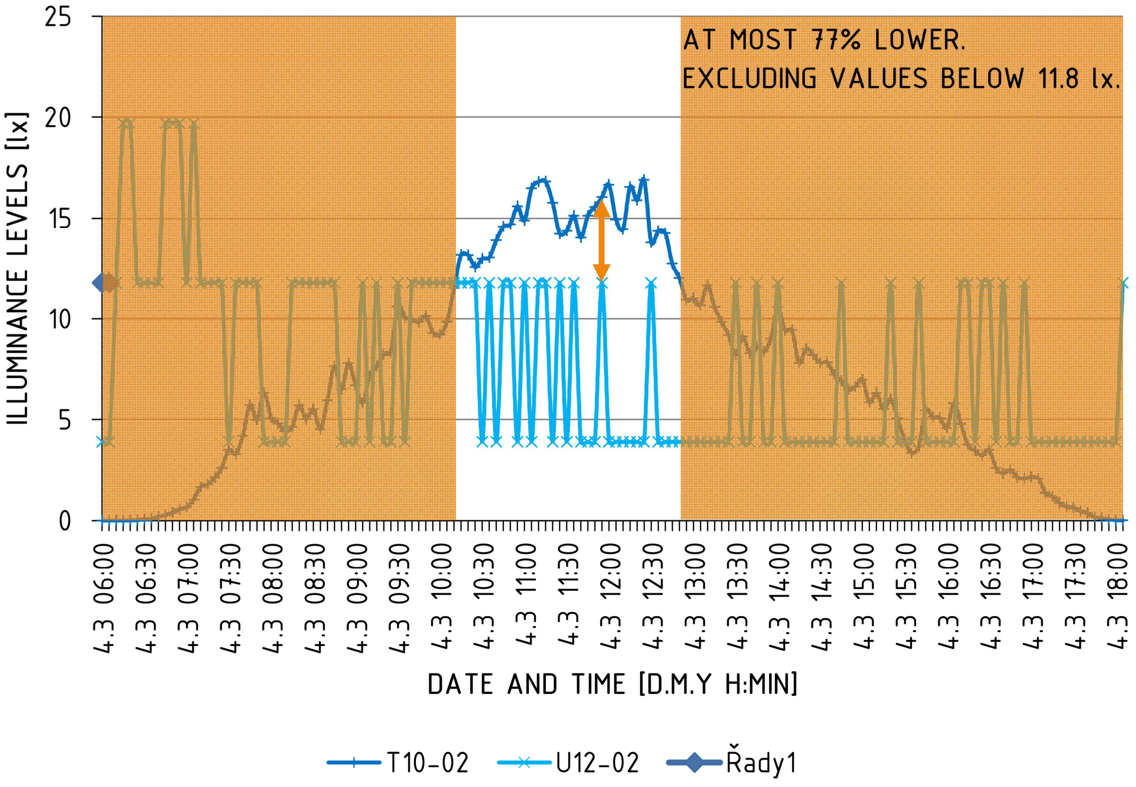


Fig. 47 *Illuminance levels at point C under overcast sky conditions.*

The previously shown figures do tell us, that the error rate of the HOBO U12-012 data loggers with means to measure illuminance levels is shockingly huge.

The HOBO U12-012 data logger’s lowest threshold is at 3.2 or 11.8 luxes. This means, that these types of measuring apparatuses cannot be used for high quality measurements of light sources with low intensities.

Another of the findings was that the response time of the photo-sensor in the HOBO U12-012 loggers is low at low levels of incident light. This can be seen in fig. 46. While the KONICA-MINOLTA illuminance meter had measured different values and the resulting chart is zigzag like, the data logger did obtain a constant value at a 5-minute cycle and thus the dynamic effect of daylight did not appear (9:30 to 9:50 or 14:30 to circa 15:20).

The results had begun to look alike only at higher values, though taking into account the difference between the values achieved by the HOBO U12 and KONICA-MINOLTA T-10 illuminance meters, it can be stated that something is amiss. The HOBO’s did measure with up to 94% higher illuminance levels in case of values exceeding 100 lux’s on the T-10’s, and about 62% less while looking at values below 100*lx*.

The same can be also seen in the figures representing an intermediate sky, below.

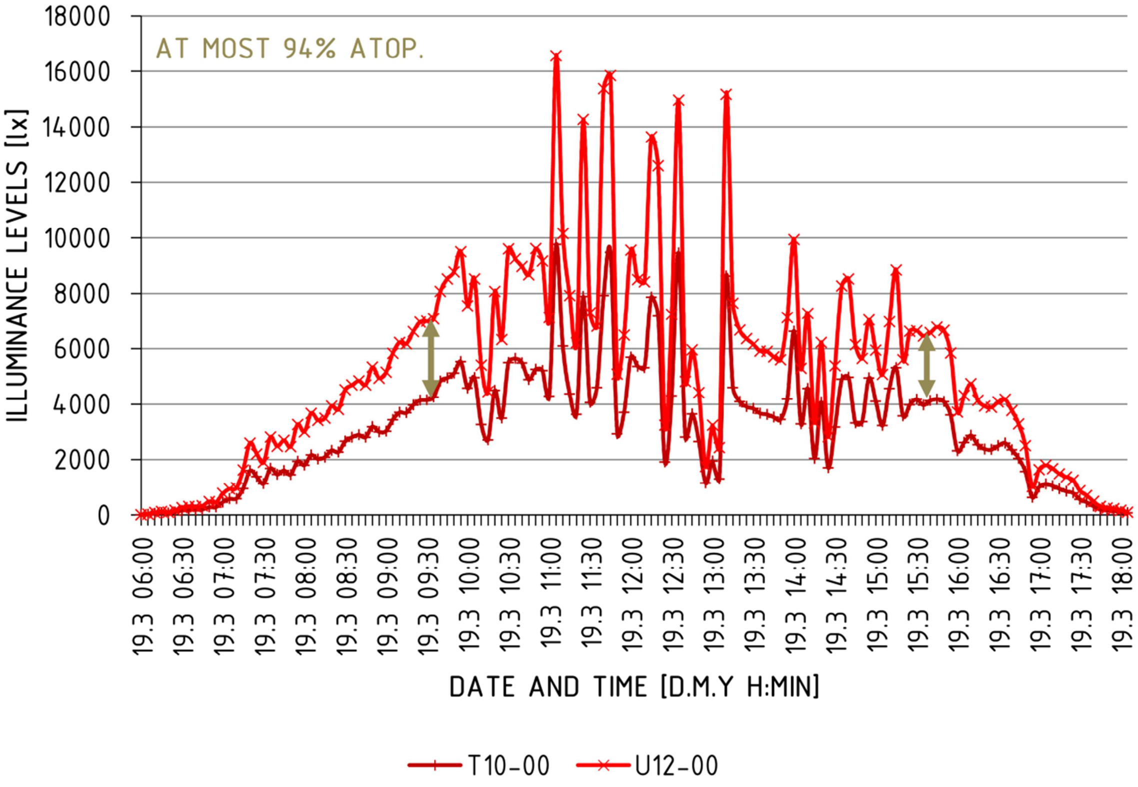


Fig. 48 *Illuminance levels at position A under intermediate dynamic sky conditions.*

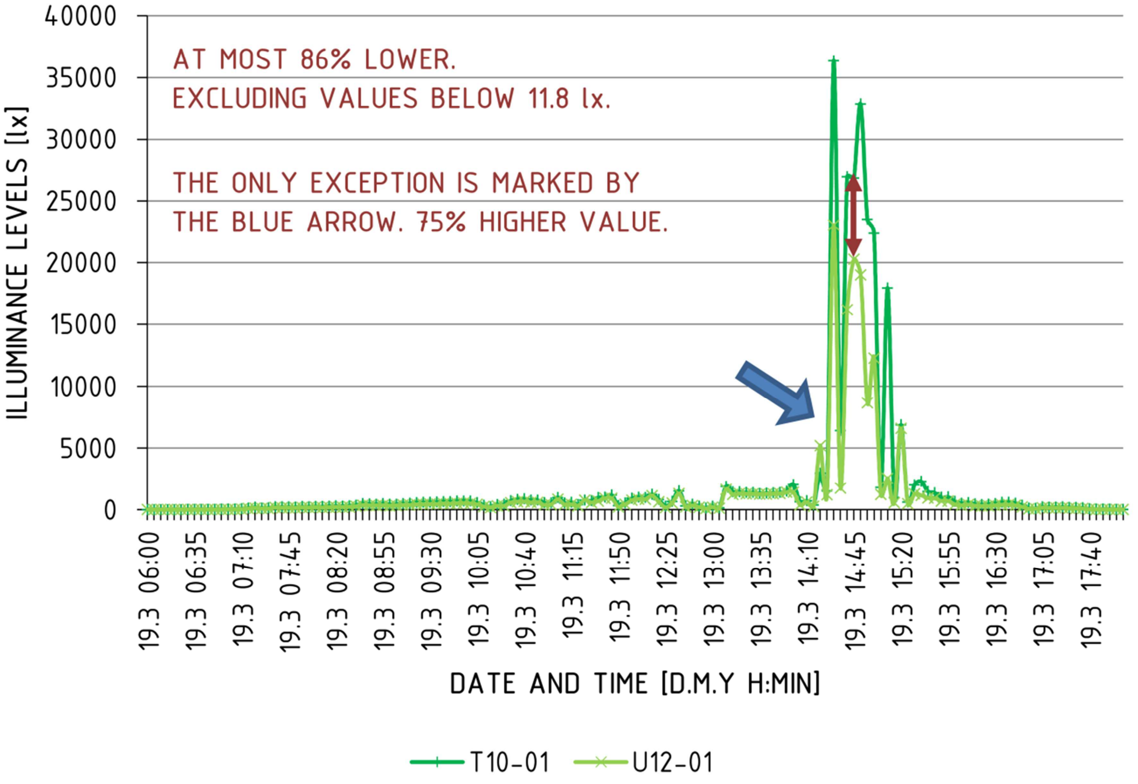


Fig. 49 *Illuminance levels at position B under intermediate dynamic sky conditions.*

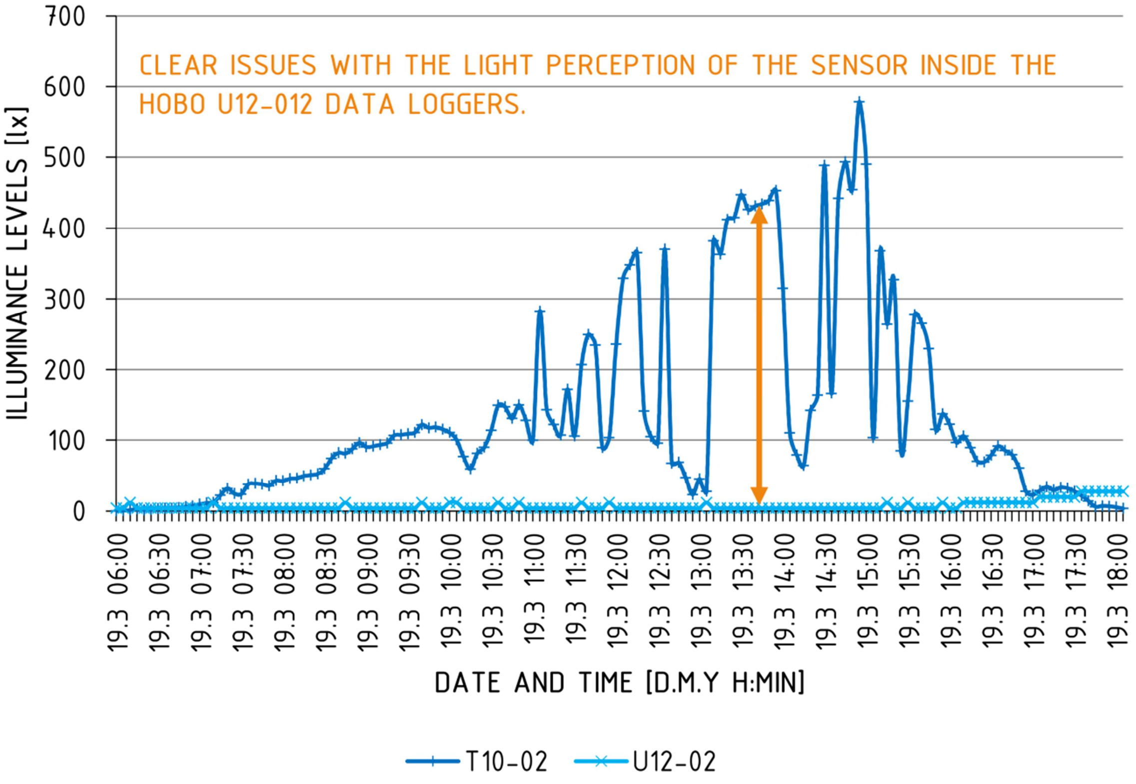


Fig. 50 *Illuminance levels at position C under intermediate dynamic sky conditions*

Under intermediate sky conditions, the graphs do show a slightly different view. The HOBO U12-012 closest to the roof window did have approximately the same graph plot than the T-10's receptor head, but the values obtained by them were higher. This by itself is similar to the results obtained under overcast sky conditions.

In the middle of the room, due to a different solid angle under which the light reaches the illuminance meter the table turns by 180°. The biggest values, except for one case, have had been shown by the KONICA-MINOLTA manufactured measuring equipment, which is valid also for the darkest part of the room too, the position furthest away from the windows.

If a closer look would be taken at the results, then a special occurrence happens, caused by the ineffective cosine correction of the HOBO U12 data loggers, and thus they are influenced less by the luminous flux arriving at a different angle then those closest to the apparatuses surface normal.

6.2.4 Sky luminance verification and global horizontal illumination determination

Sky luminance measurements took place repeatedly over the first period of measurements done inside the two laboratories, in the loft of building D of the faculty. The monitoring process depended on two factors, continuously:

- Visual verification of sky and weather: by looking at the sky it was possible to tell, whether it handled about a CIE standard overcast sky or not;
- And by teaching and other activities ot the author.

To obtain the suitable data the determination of sky luminance values have had to be in accordance with the monitoring process inside the laboratories. The computers' hardware clock running MuuLUX, thus connected to the KONICA-MINOLTA T10 illuminance meter was set to be in agreement with the watch of the author.

The luminance values have had been determined at several locations of the sky, but only under those azimuthal angles from which the sky elements could influence the daylighting the most. Therefore the sky elements at which the luminance values were measured, had to have an azimuthal angle of 45°, if taking into consideration of the roof windows glazing surface normal in plan.

Because of the slower response time of the luminance meter, the measurements had to be timed perfectly with a time difference of 3 seconds. The first value was taken already six seconds before the minute got full. The next values were then taken after three seconds. Although such measurements took place about ten times within three months, the only day in case of which the verification finally turned out to be positive was on 17th of March 2009. These data together with the evaluation is part of tab. 29.

Tab. 29 *The obtained sky luminance values and their evaluation*

Time	**17.3.09 12:05**			**17.3.09 12:10**			**17.3.09 12:15**			**17.3.09 12:20**		
Sky elem. pos.	**Sky luminances [cd/m2] and their verification [-]**											
	L	**Ver.**		***L***	**Ver.**		***L***	**Ver.**		***L***	**Ver.**	
Zenith	8044	1.00	-	7380	1.00	-	7369	1.00	-	6487	1.00	-
45.1	6100	0.76	**OK**	5050	0.68	**BAD**	5150	0.70	**OK**	4764	0.73	**OK**
15.1	4640	0.58	**OK**	3770	0.51	**OK**	4149	0.56	**OK**	3925	0.61	**BAD**
45.2	6056	0.75	**OK**	5235	0.71	**OK**	5211	0.71	**OK**	4802	0.74	**OK**
15.2	4674	0.58	**OK**	3815	0.52	**OK**	4100	0.56	**OK**	3853	0.59	**OK**
E_e [lx]	**19655**			isn't evaluated			**18006**			isn't determined		

6.2.5 RADIANCE and WDLS models

Daylighting simulations, at least the models input to daylighting simulations are often simplified. The degree of simplification depends on the actual evaluation method, from graphical methods up to computer simulations made in rendering software like « RADIANCE » visualization software package, which made it possible to imply the ray-tracing algorithm also to daylighting calculations at a higher rate.

This software allows the engineering community to change the basic surface material descriptions from a simple models which is thought as a perfectly diffuse “Lambertian” one up to high grade ones, adding certain roughness, specularity to them and if needed even textures.

Another advantage of these more advanced packages is that the scene can have a higher detail, including complex objects like surfaces of revolutions.

The following figures do demonstrate the model details for which the results are being represented in the following chapter as parts of the results.

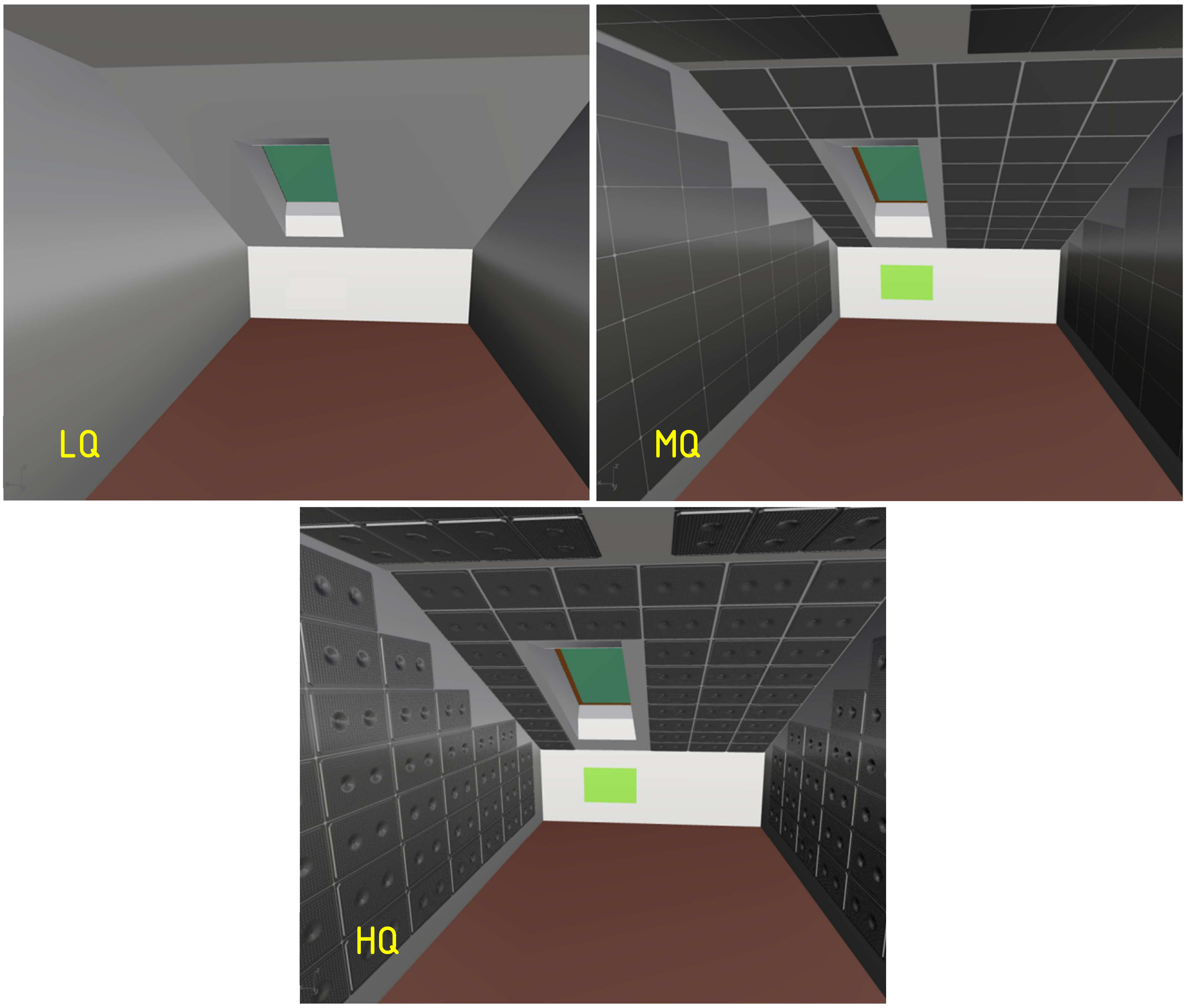
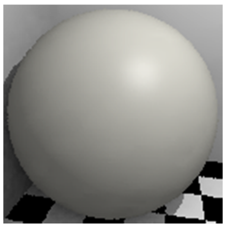


Fig. 51 *The used quality details for the models*
/LQ – Low quality, MQ – Middle Quality, HQ – High Quality/ [Author].

Altogether three different model details have had been used within the assessment.

- Low quality model – in this particular case the surfaces are present by their averaged surface reflectance values obtained by calculations. The complex window is input as a single sheet of glass the light transmittance of which was determined earlier with measurements. Hence, it has to be modified with the ratio of the areas of the transparent parts of the windows and that of the overall area of the daylighting system, only. These data are used in each of the computer aided design tools involved within the evaluation process of the thesis and also while doing the calculations via the only numerical approach. The calculations within «WDLS v3.1 » and « WDLS v4.1 » have had been provided for all of the available choices built into them, from multiple reflections until empiric methods. The innovated Daniljuk's methodology had been improved with the BRS technique, since Daniljuk's concept cannot be used for the determination of the internally reflected component of the daylight factor. The BRS type equations for the determination of the minimal and average values of the internally reflected components of the daylight factor were chosen above Krochmann-Kittler's theory because the later includes reflections coming from the terrain, too, nonetheless in case of the laboratories, because of the roof windows angle these can be neglected;

- Middle quality models – It handles about a more detailed description of the same model, in both « RADIANCE » and « WDLS ». The more detailed refers to the description of the PCM based panels mounted all over the surfaces of the given room, on top of the rooms and ceilings, but it is not just about the alumina panels. The door wing and the doorframe have had been described separately, too. Moreover in « RADIANCE » the window description is already separated into the frame and the glazing, though it handles about plane elements only;
- High quality models – have had been input only into « RADIANCE » because of the lack of possibilities in other evaluating methods. These models have almost everything modelled out just as it could be seen in reality inside of the laboratory. The window frame does already have 3 dimensions. Instead of one glass pane, there are two with a total light transmittance equal to the measured value. The PCM panels are the closest to reality, not just with their geometry, but with their material descriptions too, which have had been based upon plastic (eq. 60) and metal (eq. 61). Fig. 52 and fig. 53 do view the alumina panels in real life, and in the scene, also. The high quality model consists from 7164 elementary surfaces after being exported to a radfile.

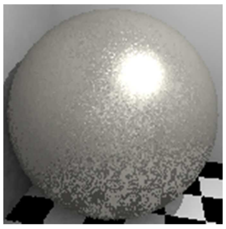


void plastic PCM_FULL_PLASTIC

0

0

5 0.390 0.385 0.349 0.025 0.200 (60)



void metal PCM_FULL_METAL

0

0

5 0.410 0.400 0.363 0.500 0.200 (61)

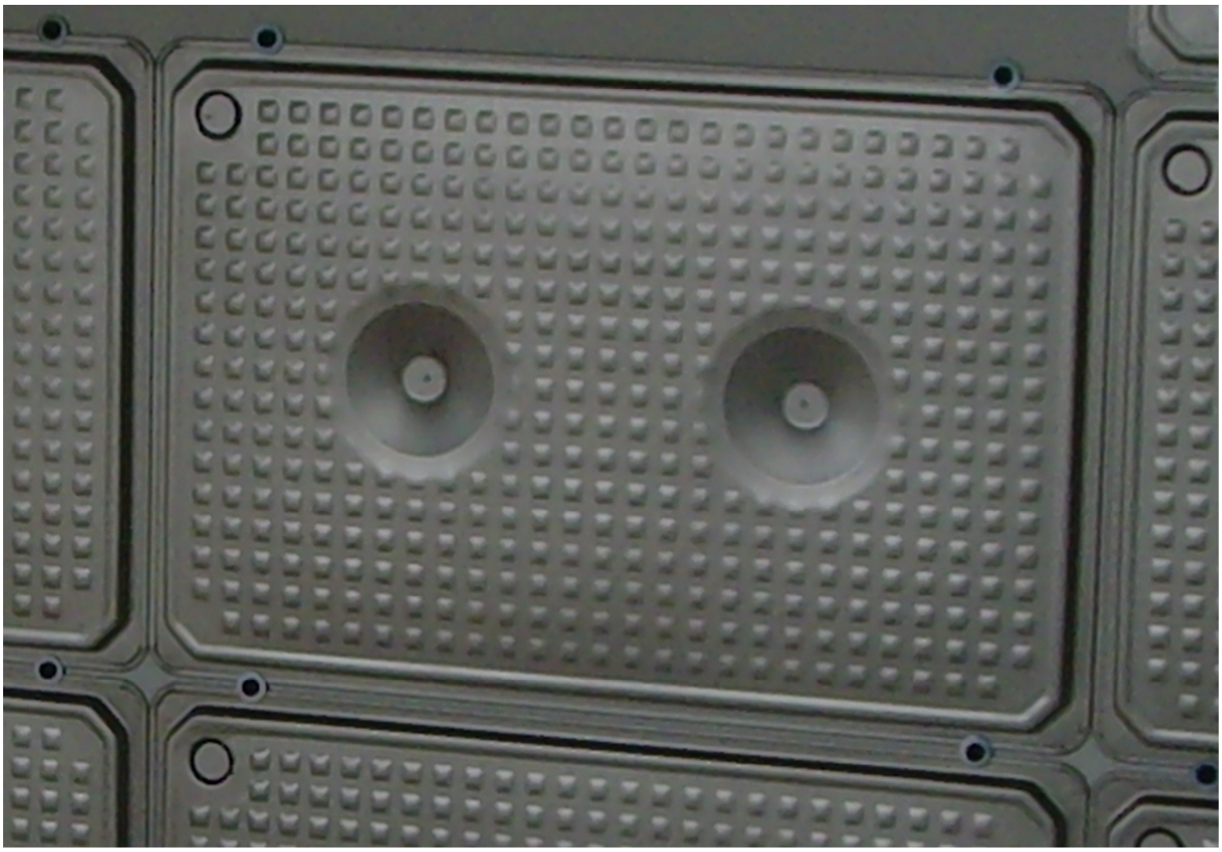


***Fig. 52** A closer view to the installed PCM panel [Ing. David Bečkovský, Ph.D.].*

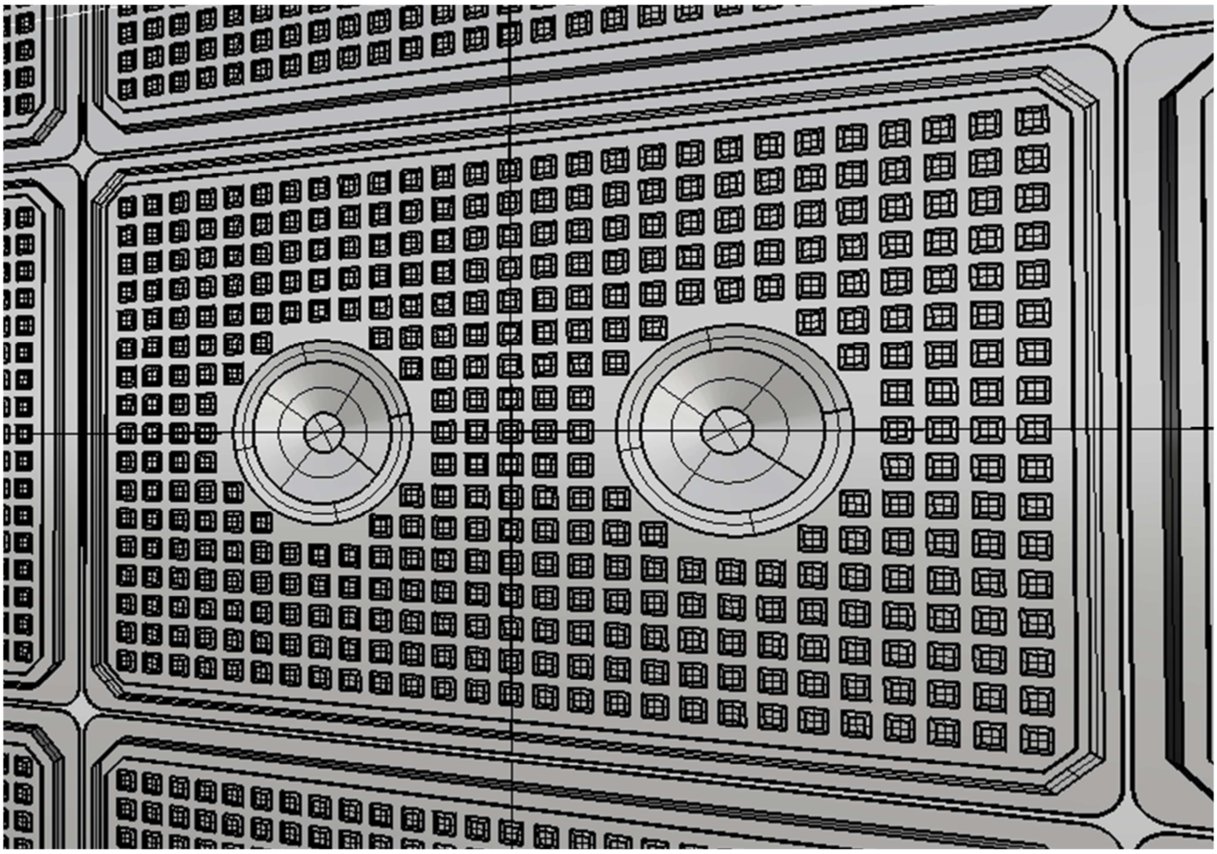


***Fig. 53** A closer look at the full detail model of the same PCM panel [Author].*

6.2.6 Results of simulations and calculations done for Laboratory No.2

Tab. 30 *Daylight factor value comparison for Laboratory No.2 at 12:05 on 17.3.09*

Evaluation method	**Determined DF levels [%]** **Deviation to reference values [%]**			Δ ***min*** Δ ***max*** **[%/%]**
	A	**B**	**C**	
Measured data:	**13.51**	**1.69**	**0.28**	**- / -**
RADIANCE: *Ray-tracing, LQ*	14.00 3.63	1.40 -17.16	0.14 -50.00	**-50.0** **3.6**
RADIANCE: *Ray-tracing, MQ*	14.76 9.25	1.53 -9.47	0.17 -39.29	**-39.3** **9.3**
RADIANCE: *Ray-tracing, HQ-P* a)	14.67 8.59	1.44 -14.79	0.14 -50.00	**-50.0** **8.6**
RADIANCE: *Ray-tracing, HQ-M* b)	14.73 9.03	1.43 -15.38	0.16 -42.86	**-42.9** **9.0**
WDLS 3.1: *Multiple refl., LQ*	14.43 6.81	1.61 -4.73	0.21 -25.00	**-25.0** **6.8**
WDLS 3.1: *Kroch.-Kittler, LQ*	14.14 4.66	1.68 -0.59	0.37 32.14	**-0.6** **32.1**
WDLS 3.1: *Kroch.-Kittler, MQ*	14.32 6.00	1.83 8.28	0.48 71.43	**6.0** **71.4**
WDLS 3.1: *BRS, LQ*	13.89 2.81	1.49 -11.83	0.24 -14.29	**-14.3** **2.8**
WDLS 3.1: *BRS, MQ*	13.96 3.33	1.56 -7.69	0.32 14.29	**-7.7** **14.3**
WDLS 4.1: *Multiple refl., LQ*	15.60 15.47	1.80 6.51	0.30 7.14	**6.5** **15.5**
WDLS 4.1: *Multiple refl., MQ*	16.50 22.13	2.70 59.76	0.90 221.43	**22.1** **221.4**
WDLS 4.1: *Lum. ratio, LQ*	15.60 15.47	1.80 6.51	0.30 7.14	**6.5** **15.5**
WDLS 4.1: *Lum. ratio, MQ*	16.50 22.13	2.60 53.85	0.80 185.71	**22.1** **185.7**
Numerical: *Mod. Daniljuk*	13.70 1.41	1.48 -12.43	0.22 -21.43	**-21.4** **1.4**

a) The material description of the PCM based alumina panels was based on the properties of plastics

b) The material description of the PCM based alumina panels was based on the properties of metals

***Tab. 31** Daylight factor value comparison for Laboratory No.2 at 12:15 on 17.3.09*

Evaluation method	**Determined DF levels [%]** **Deviation to reference values [%]**			***Δ min*** ***Δ max*** **[%/%]**
	A	**B**	**C**	
Measured data:	**13.45**	**1.62**	**0.28**	**- / -**
RADIANCE: *Ray-tracing, LQ*	14.00 4.09	1.40 -13.58	0.14 -50.00	**-50.0** **4.1**
RADIANCE: *Ray-tracing, MQ*	14.76 9.74	1.53 -5.56	0.17 -39.29	**-39.3** **9.7**
RADIANCE: *Ray-tracing, HQ-P* [a]	14.67 9.07	1.44 -11.11	0.14 -50.00	**-50.0** **9.1**
RADIANCE: *Ray-tracing, HQ-M* [b]	14.73 9.52	1.43 -11.73	0.16 -42.86	**-42.9** **9.5**
WDLS 3.1: *Multiple refl., LQ*	14.43 7.29	1.61 -0.62	0.21 -25.00	**-25.0** **7.3**
WDLS 3.1: *Kroch.-Kittler, LQ*	14.14 5.13	1.68 3.70	0.37 32.14	**3.7** **32.1**
WDLS 3.1: *Kroch.-Kittler, MQ*	14.32 6.47	1.83 12.96	0.48 71.43	**6.5** **71.4**
WDLS 3.1: *BRS, LQ*	13.89 3.27	1.49 -8.02	0.24 -14.29	**-14.3** **3.3**
WDLS 3.1: *BRS, MQ*	13.96 3.79	1.56 -3.70	0.32 14.29	**-3.7** **14.3**
WDLS 4.1: *Multiple refl., LQ*	15.60 15.99	1.80 11.11	0.30 7.14	**7.1** **16.0**
WDLS 4.1: *Multiple refl., MQ*	16.50 22.68	2.70 66.67	0.90 221.43	**22.7** **221.4**
WDLS 4.1: *Lum. ratio, LQ*	15.60 15.99	1.80 11.11	0.30 7.14	**7.1** **16.0**
WDLS 4.1: *Lum. ratio, MQ*	16.50 22.68	2.60 60.49	0.80 185.71	**22.7** **185.7**
Numerical: *Mod. Daniljuk*	13.70 1.86	1.48 -8.64	0.22 -21.43	**-21.4** **1.9**

[a] The material description of the PCM based alumina panels was based on the properties of plastics
[b] The material description of the PCM based alumina panels was based on the properties of metals

In the tables with the measured, calculated and simulated values for the illuminance meters sensors at position A, B and C do display two sets of comparisons. Tab. 30 stands for measurements done on 17th of March 2009 at

12:05. On the other hand, tab. 31 includes the data for measurements done on the same day, but 10 minutes later.

By taking a closer look at the calculated and measured data, it can be seen, that most of the daylight factor values which were obtained by « RADIANCE », « WDLS » (only version 3.1) and the combined innovated Daniljuk's methodology with the BRS approach for point A at (12:05 and 12:15), which is below the window, does have a relatively high accuracy. The main difference between the data sets is only up to 10%. Only « WDLS v4.1 » did have a higher error rate, exceeding that of 15% when choosing either of the available settings for the determination of the externally reflected component of daylight factor (i.e. luminance ratio between the sky and the barrier, or multiple reflections) at the lowest model detail. In case of a higher model detail, referred to as "MQ (middle quality)" the difference had increased to 22%, which was already too high.

For position B, « RADIANCE », more specifically the ~rtrace~ returned a value with a difference between -9 and -17.2%, when looking at the monitored data at 12:05 and a difference between -5 and -14% for data valid for the time of 12:15. The difference between the time sets is caused by the slightly different daylight factor levels attained for both times by measurements. This difference is visible on the rest of the researched approaches too. The numerical approach turned out to have a difference of -12.43% and -8.64%. So far, « WDLS v3.1 » had given the most correct predictions of daylight factor levels inside "Laboratory No.2".

For location C, the variability of the difference varied quite a lot. While radiance was estimating lower values of daylight factor levels, and its predictions were off with roughly 50%, the other approaches, except for the numerical one, had the same issue depending on the know-hows' of setup of « WDLS v3.1 and v4.1 ». The results of « WDLS v3.1 » at *low quality* model detail were off within the interval of -14% up to +32%. The bigger resulting values have had been obtained by Krochmann-Kittler's approach for the determination of the internally reflected component, which by guessing included some reflections coming from the terrain. For *middle quality* model detail the difference was changing between -3.7% and +12.96%. Unfortunately « WDLS v3.1 » wasn't able to finish the simulation process while set to multiple reflections (the author tried to run it on 10 different computers, but the toll of 1900+ elementary planes had taken its price and the computers froze down resulting in a hard reset). In «WDLS v4.1», the results were in a close range to the original measured ones only when the input was of low quality model detail. At middle detail, the values were unreasonably high, but these are to be seen in the tables above.

A comprehensive comparison as part of the following pictures shows results from both « RADIANCE » and « WDLS v4.1 » in low, medium and high detail. The figures coming from « RADIANCE » does have a specialty, that is, that they do display the luminance distribution over the surfaces. In case of «WDLS», the amount of light falling onto the surfaces is distinguishable too, but the values do display the illuminance values incident to a point over the surfaces.

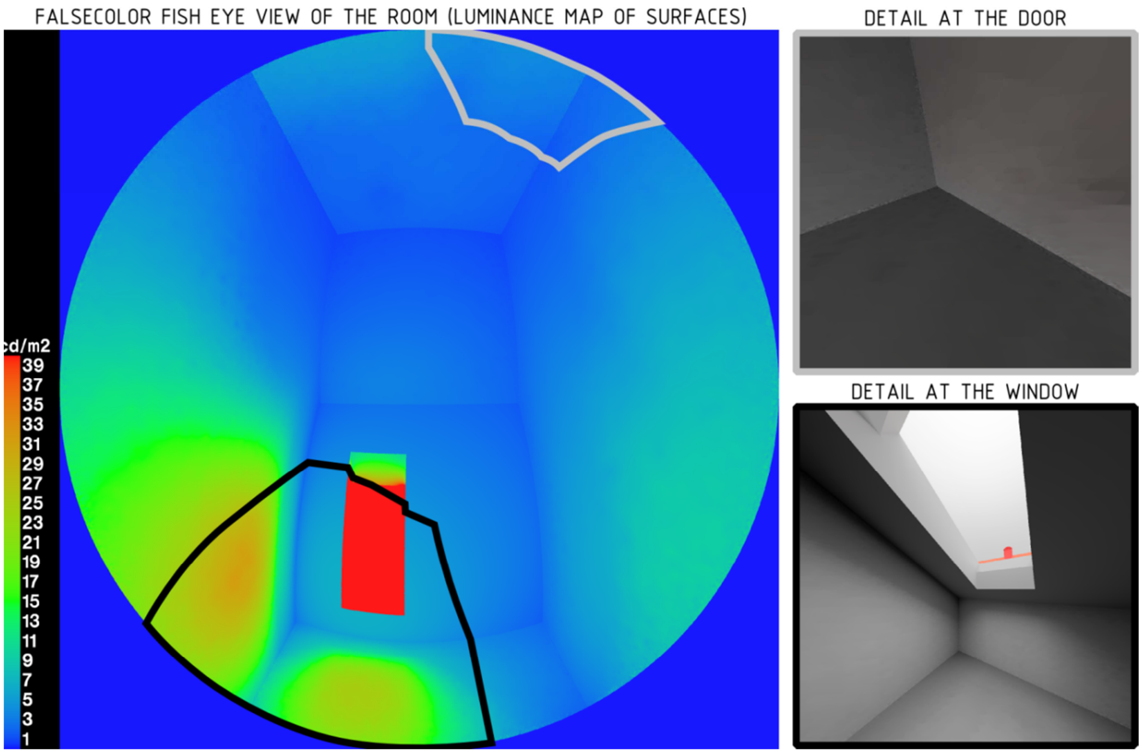


Fig. ***54*** *Luminance values on the surfaces and detail views at low quality, from ~rpict~ and ~falsecolor~ <–aa 0.05 –ab 4 –ad 2048 –as 512 –ar 1024>*

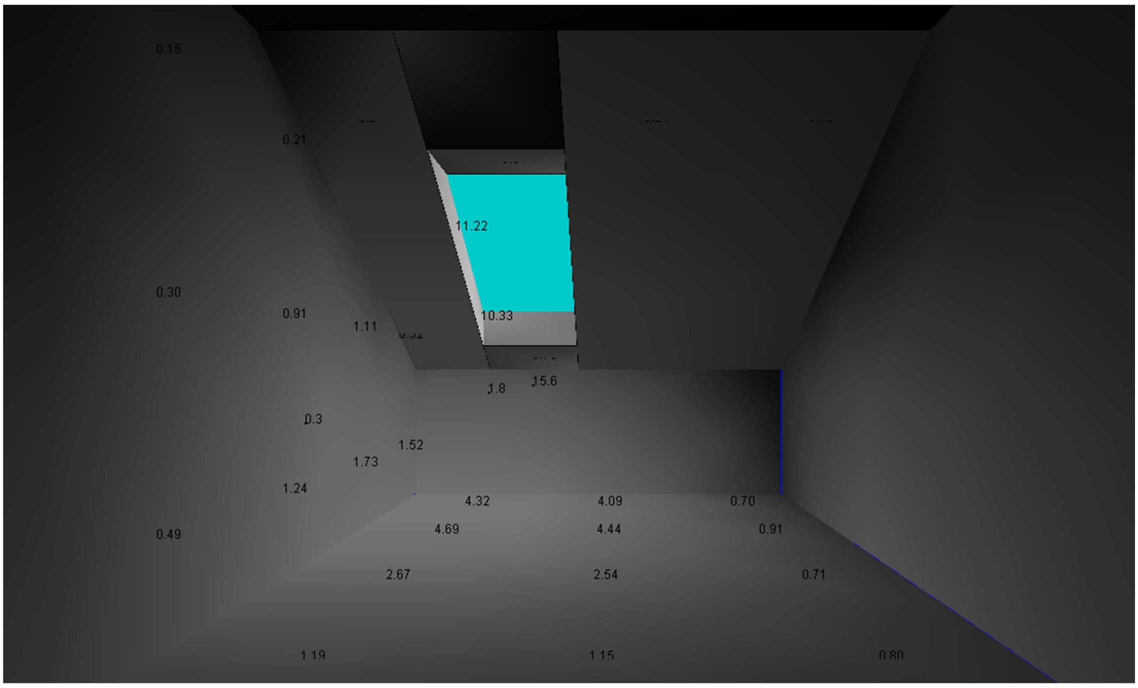


Fig. 55 *A view to the room from the position of the door, from WDLS v4.1 in LQ.*

Notice the aberration between the luminance distributions in low and middle qualities near the floor. The picture with « WDLS » as a source is darker compared to the previous, but at the same time brighter at the glazing.

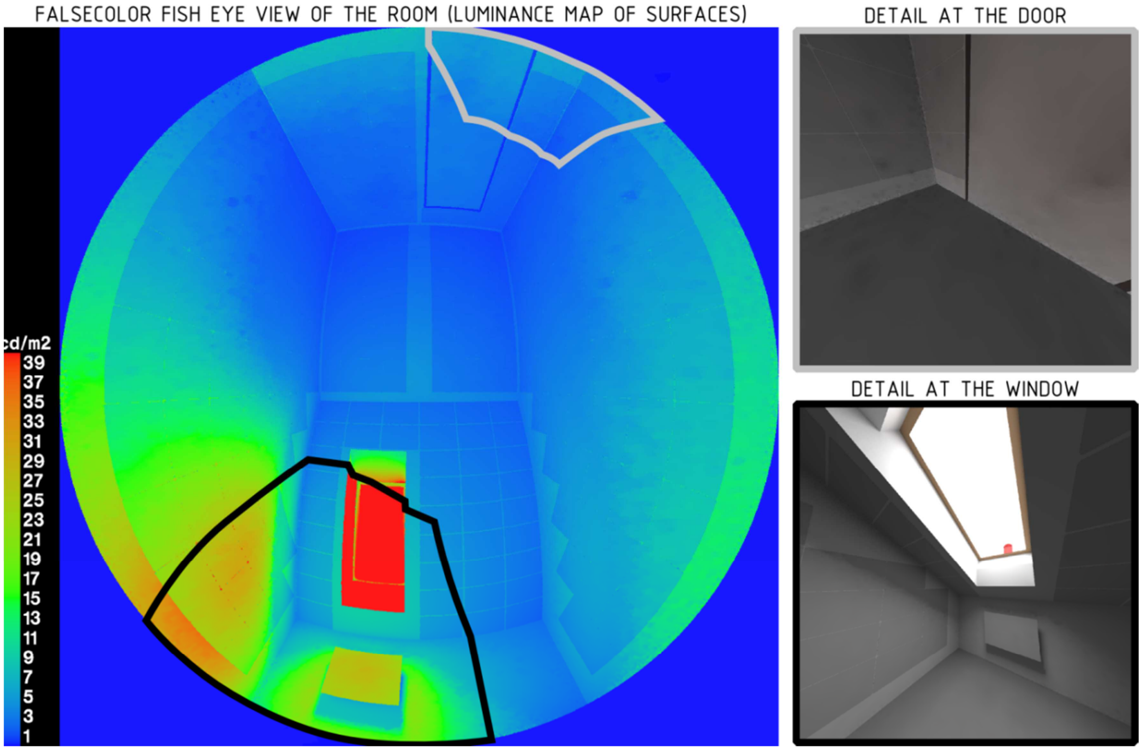


Fig. 56 *Luminance values on the surfaces and detail views at middle quality, from ~rpict~ and ~falsecolor~ <–aa 0.05 –ab 4 –ad 2048 –as 512 –ar 1024>*

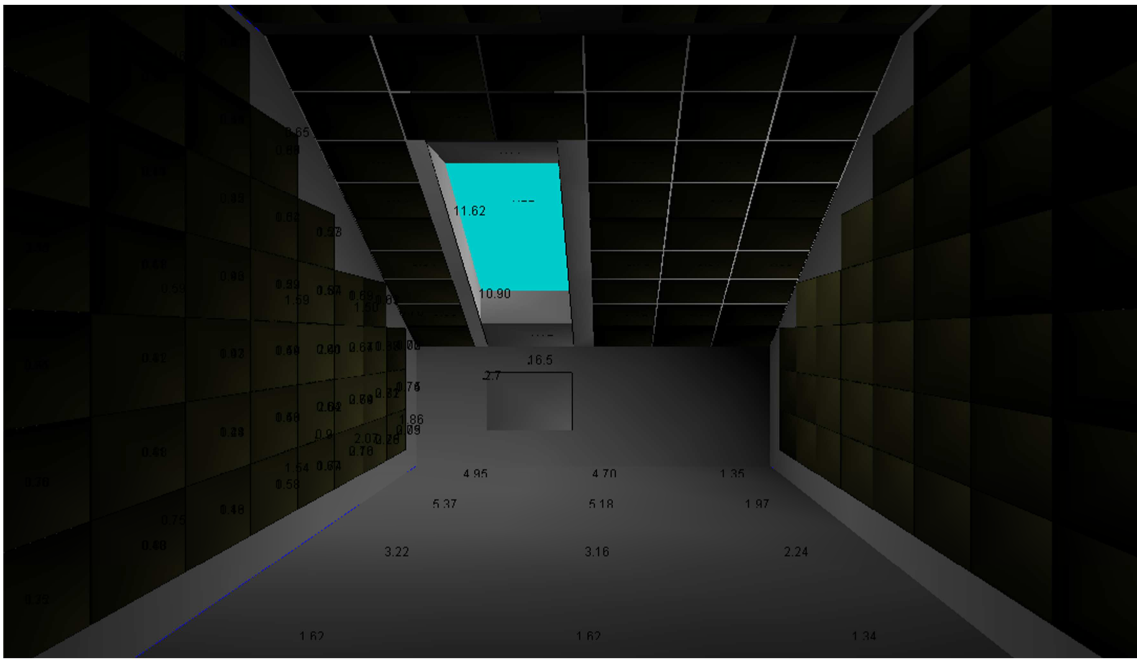


Fig. 57 *A view to the room from the position of the door, from WDLS v4.1 in MQ.*

At full quality, the biggest diversity is visible on the surface of the PCM panels. While plastic, the luminance distribution is continuous, while described as a metal there are some jitters, caused by the roughness specified.

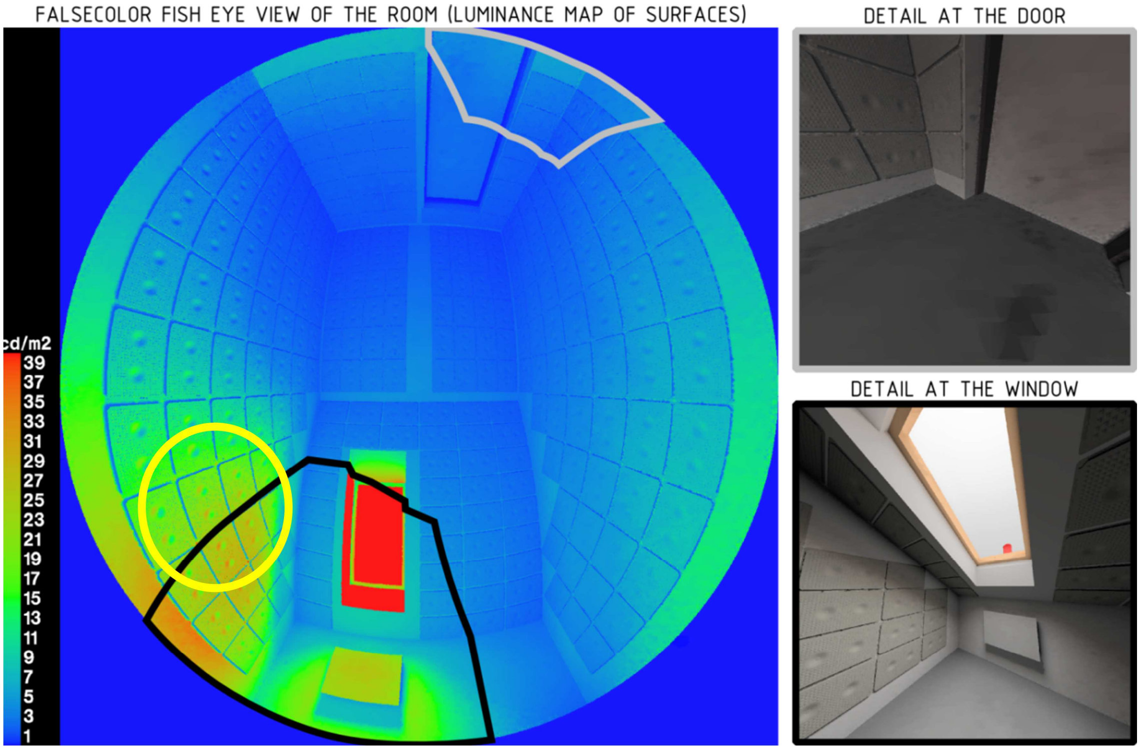


Fig. 58 *Luminance values on the surfaces and detail views at high qual. – plastic mat. ~rpict~ and ~falsecolor~ < –aa 0.05 –ab 4 –ad 2048 –as 512 –ar 1024>*

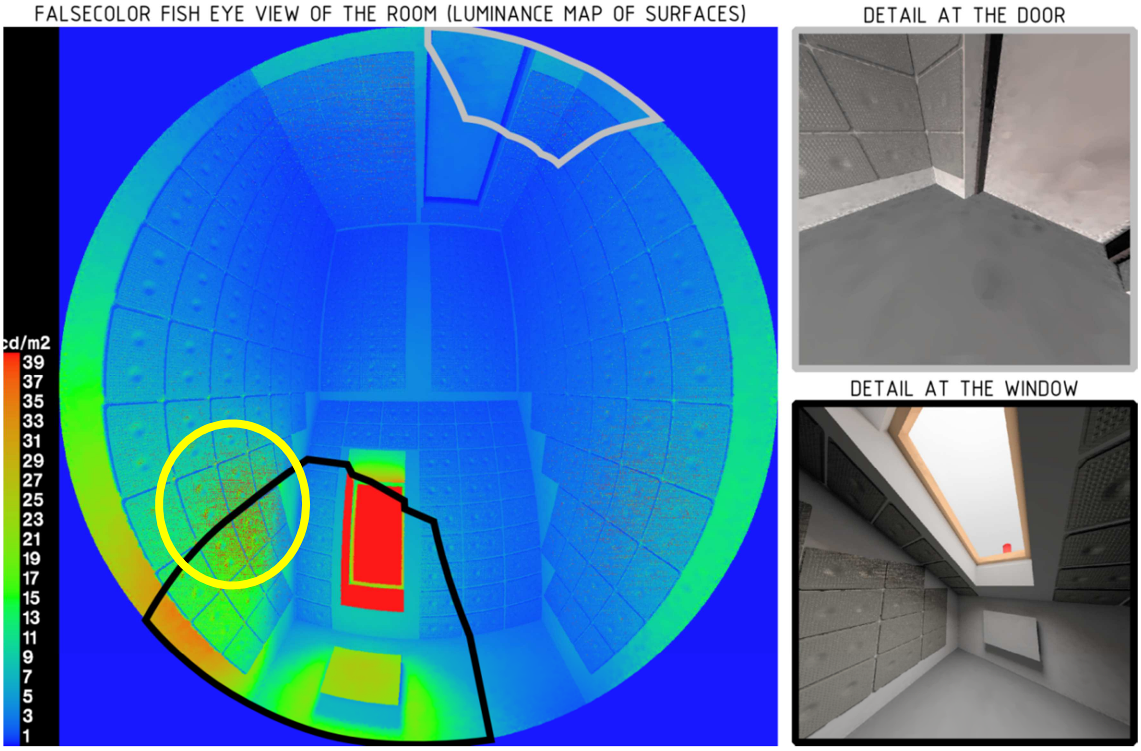


Fig. 59 *Luminance values on the surfaces and detail views at high qual. – metal mat. ~rpict~ and ~falsecolor~ <–aa 0.05 –ab 4 –ad 2048 –as 512 –ar 1024>*

7 CONCLUSIONS OF THE WORK

- **Conclusions to the results**
- **Contributions for the profession**
- **Visions**

7.1 CONCLUSIONS TO THE RESULTS

The discussed thesis, deals with several aspects of daylighting design, from CIE test cases until calculations done by hand via luminance measurements of the sky and computer simulations done with the aim to determine the quality of evaluation methods. Accordingly, the conclusion does discuss each issue separately:

- CIE test cases;
- Sky luminance and illuminance measurements;
- Computations in RADIANCE and WDLS;
- And for numerical analysis.

7.1.1 Conclusions to the validation of design methods against CIE test cases

CIE test cases for the validation of the accuracy of computer simulation software for lighting were introduced in 2006. The standard itself implements some ideas, which were described earlier by F. Maamari. However, after the implementation a number of mistakes became apparent within it, more specifically in the appendices of the standard including the reference data for the test cases used to assess the quality of software used for daylighting simulations. Some of these errors have had been already pointed out in the previous chapter of the thesis, some not. Nevertheless, because of these mistakes some laboratories do tend to test the software sent to them only for a few of the reference cases and leaving out the rest or testing it for against other values, like it was done in case of the already mentioned “Velux Daylight Visualizer in version 2” [6].

To cite the authors of the report, from the test report itself:

“The authors of the current study believe the analytical reference given in the original CIE document is erroneous for test case 5.13 and 5.14. The Chief of project of CIE 171:2006 document (Fawaz Maamari) has been contacted and acknowledged the analytical reference for Test Case 5.13 and 5.14 is certainly erroneous, and explained the CIE will emit an errata. We invite the reader to refer to section ‘Proposition of alternative …”[9]

Although the authors of the test report did turn out to propose a few changes for the evaluation process, the standard was still left untouched. That is why « RADIANCE », « WDLS » and the numerical approach have had been tested against all of discussed test case scenarios inside the thesis.

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[9] This test report can be downloaded from the internet, free of charge.

7.1.2 Sky luminance measurement

The sky luminance measurement enclosed in the thesis is valid for 17th of March 2009, only. Despite the fact that it handled about a CIE Overcast Sky verified with the expressions published by R. Kittler in 1983, in reality while comparing the simulated and calculated values to the ones obtained over the working plane of "Laboratory No.2" by consecutive measurements, it made it clear that a small inaccuracy had planted its roots into the validation process. This error is something, which can but at the same time cannot be called as a mistake, because the values were compared to only simulations and numerical evaluations, but let us review the issues regarding it.

At first, the luminance gradation ratio of 1:3 of a CIE Overcast Sky from the horizon to the zenith the interval of <0.3, 0.6> used for the verification of the sky elements luminance ratio at 15° angle above the horizon allows quite a considerable play. The values entailed in table 29 did just-just meet the highest value, therefore the luminance gradation of the sky was influenced most probably by a slight turbidity of the atmosphere. Hence, the daylight levels were also higher than anticipated in the back of the room. By taking into consideration the year when R. Kittler‘s work have had been published and how the measuring apparatuses and approaches did change over the time, maybe, it could be revised.

For second, the luminance measurements over the sky, done by the author of the thesis, were bound by a small error rate themselves, caused by the fact that the values were obtained in a sequence of 3*s*. The time difference between the first and the last shot taken by the luminance meter was 12*s*. By considering the dynamic properties of the sky, even under the given circumstances it would be unthinkable that such a change could occur under such a short time under an overcast sky. However, the errata of the measurements could be cured by an apparatus made up from illuminance meters (fig. 60).

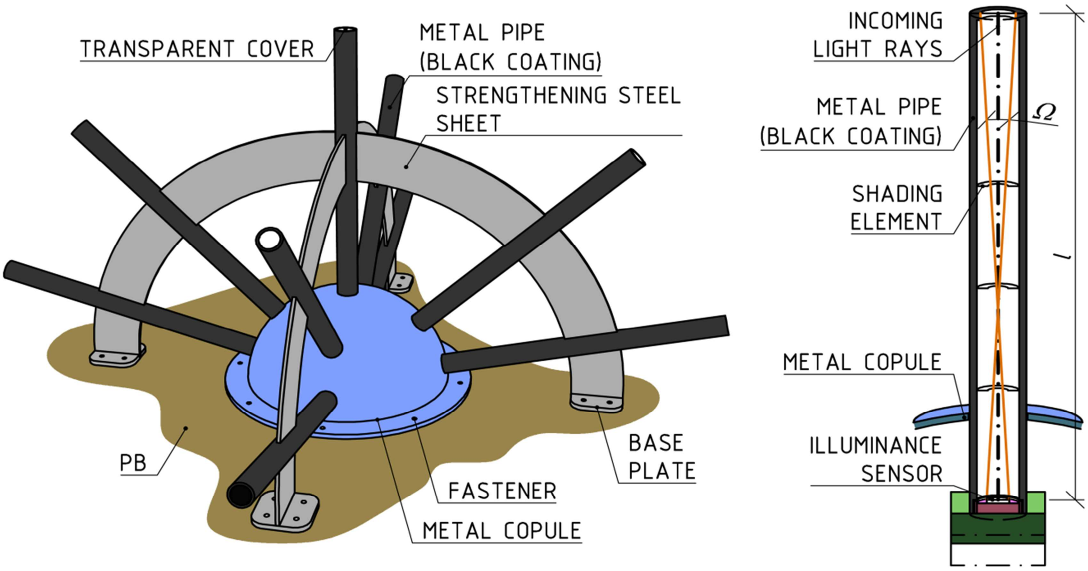


Fig. 60 *A device measuring the luminance values of sky elements at 9 positions.*

The question is, whether a research focused on the availability of a CIE Overcast Sky in the age of global and diffuse sky illuminance measurements is still actual or not.

7.1.3 Computer simulations

WDLS

The findings regarding this computer aided design tool are full of contradictions especially in version 4.1, which as a commercial tool written in the Czech Republic for the Czech engineering community would be thought as one of the best, unfortunately that is not the case.

By looking at « WDLS v3.1 », it is possible to see a slight resemblance between the retrieved values and those of CIE reference cases for most of the evaluated points under for different approaches. The determined data with the help of it, do have a relatively small error rate at low values, which is for the best, whereas are smaller when glazing is applied to the openings. Yet, by taking a good look at « WDLS of v4.1 », some major flaws are visible. One of these flaws is that the sill must have a thickness other than that of 0*mm*. In reality however, it is not a mistake of the program and the algorithm inside of it, but that of the CIE test cases and the authors of these reference models by not taking into account concreteness, like structures. Nevertheless, as it have had come to this, it must be mentioned that « WDLS » cannot handle a wall thickness of 0mm. The output is determined with a huge error rate, particularly when a vertical working plane is validated. Nonetheless, under real-life conditions such a thing cannot happen, maybe if evaluating the daylight factor levels in a point on the façade of the building.

Another of its flaws can be seen within the comparison of results obtained for “Laboratory No.2”. In « WDLS v3.1 », a user can choose from three available concepts, which can be used for the determination of the daylight factor over the working plane. While researching the differences for the CIE reference cases, it had not really matter, which of these options was used, as to each and every of them influences the internally reflected component of the daylight factor only. This on the other hand is not valid when the assessment revolves around real measured data. The simulations involving averaged surface reflectance values and lower detail of the scene were closer or smaller to the data attained for the working plane of the laboratory than the models with higher details. But the results alternated more by the model detail in « WDLS v4.1 » than in « WDLS v3.1 » and were even higher than the reference values at every time, furthermore the lowest values attained for the least illuminated point “C” did turn out to have a non-realistic value.

In overall « WDLS v4.1 » is non-reliable software the application of which is not recommended for expertise activities. Engineers should rather fall back to the older version of the given software.

Radiance

The simulations in « RADIANCE », although they've had been done for a large number of combinations of ambient parameters, were still validated against CIE test case scenarios with an allowed maximum deviation from the base values equal to 10%. This means that in case of a reference value, which would have had a number a 1%, the ray-tracing process had to return a number between 0.9 and 1.1%. However, only the horizontal working plane was checked this way because of the modified sky description generation where the ground reflectance was manually set to 0- and the missing lower hemisphere resulted in a loss of the externally reflected component of daylight factor (described in chapter 6.1.3).

Once the results have had been checked by a program written by the author, it was clear, which ambient value combinations were able to predict a similar output to those given within the CIE 171/2006. For each of the CIE reference models 343 ambient parameter combinations were created, which do result in 343 result files.

By looking only at the test cases, which do check the quality of the given methodology for the determination of the sky components only, then CIE test cases II.8 up to II.11 must be examined in more detail, in spite of that these have had been already partially presented in chapter 6 of the thesis. By increasing the ambient parameters, « RADIANCE » is freely applicable for daylighting design of buildings. Interesting results have been achieved already by the following combination of ray-tracing parameters: –ad 512 –as 16 –ar 32 –aa 0.01 –ab 1. This however, cannot be taken as granted, because at the exact same time the following parameters have had failed the evaluation: –ad 1024 –as 1024 –ar 64 –aa 0.01 –ab 1.

By adding all of this together, « RADIANCE » is a great tool when viewing the sky only, with a high value of ambient density.

In cases II.12 and II.13 except for a few occasions, the results were within a reasonable boundary. Those exceptions can be connected to the issues regarding the quality of CIE data sets.

When looking at the quality of « RADIANCE » package with a viewpoint to real measurements, the values do fluctuate depending on the model detail the values though were almost every time lower, thus it has a great safety factor.

In overall « RADIANCE » package is to be recommended for use in case of expertise activities connected to daylighting design.

7.1.4 Hand made daylighting design

The innovated Daniljuk's methodology did give the most unexpected results. Globally it gave one of the best deviations compared to those of computer simulations, with a steady flow. When the value needed to be lower, it was determined as smaller. The errata, hence was also the lowest.

In overall Daniljuk's approach should be used and innovated in the future too, alongside « RADIANCE » or « WDLS v. 3.1 ».

7.2 CONTRIBUTIONS FOR THE PROFESSION

The findings of the dissertation as part of the conclusion mainly for the profession can influence the field of research as well as the daylighting design of buildings. These may be categorized into the following categories:

- Measurement of daylighting;
- Daylighting design of indoor spaces with computer based tools;

7.2.1 Quality of measuring equipment

Nowadays more and more companies do manufacture measuring apparatuses for different fields. Sometimes these firms do combine several products into one tool only so that they could sell it better and thus achieve a higher cash flow, resulting in a higher profit. Such a product is also the HOBO U12-012 data-logger used within the solution of the dissertation, peculiarly for daylighting measurement next to the specialized product of KONICA-MINOLTA.

As it was found out that the quality of the sensor built-in to the data logger can’t be necessarily used for the measurement of illuminance levels over the working plane or anywhere inside and outside of the building, because it has an huge transgression in comparison to the values retrieved by the KONICA-MINOLTA T10 illuminance meter. The error was around ±90% (roughly), sometimes bigger, sometime smaller.

When the devices have had been bought from ONSET company, who had advertised the product as an illuminance meter among others, nevertheless, it is also true that the manufacturer had not published the spectral response of the data-loggers and they were not even asked to provide them before issuing the order. Only after the evaluation of the results and a bit of communication with the manufacturer it became clear, that the product do have some issues and what’s worst of all a response to optical radiation which isn’t even close to the *V(λ)* curve for photopic vision (see. fig. 61).

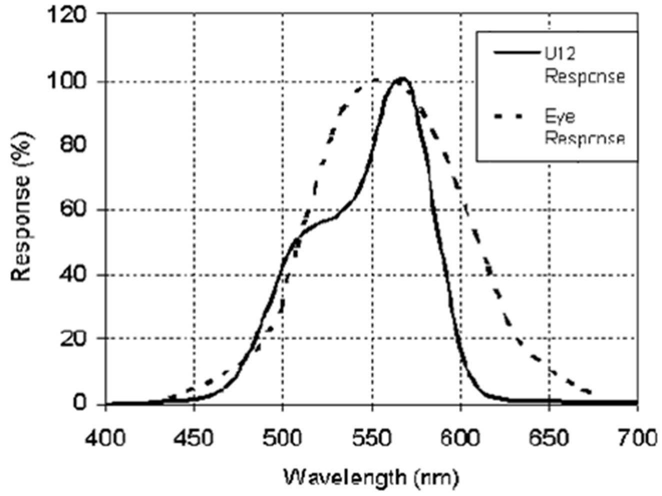


Fig. 61 *The light wavelength response of HOBO U12 data-loggers [58].*

So if ONSET did know about these problems earlier, why didn't they apply a colorimetric correction to the data-logger. Also, why didn't they use a cosine correction for the sensor, whereas it is evident now, that the directional capabilities of the data-logger are as low as that of visual response. At the current, the data-logger U12-012 is an unfinished product sold for relative measurements of light, though a question arises: can this product be clearly used for relative measurements? By placing them in a distance of 1m the user cannot even be sure that the obtained data is comparable. Nonetheless, it handles about a great tool for measuring relative humidity and temperature.

Therefore, a user should always ask for the required data sheets before issuing out an order for machineries or equipment's.

7.2.2 Daylighting design of building

Existing older computer programs in the field of daylighting and artificial lighting are often based on a combined graphical/numerical evaluation method, such as the diagrams of Daniljuk or the protractors' of Kittler. A representative of these is also « WDLS ». Although in case of « WDLS » newer versions do arise from time to time, it still utilizes the same old algorithm in place of the newer ones like radiosity or ray-tracing and so go with the flow of the technologies available in the 21st century.

In « WDLS », the user is limited to the set-up process available in the given version, used. On the other hand, software like « RADIANCE » or POV-Ray, do allow the user to define the parameters influencing the result from the worst to the better, but not just the result but also the time needed for the computational process.

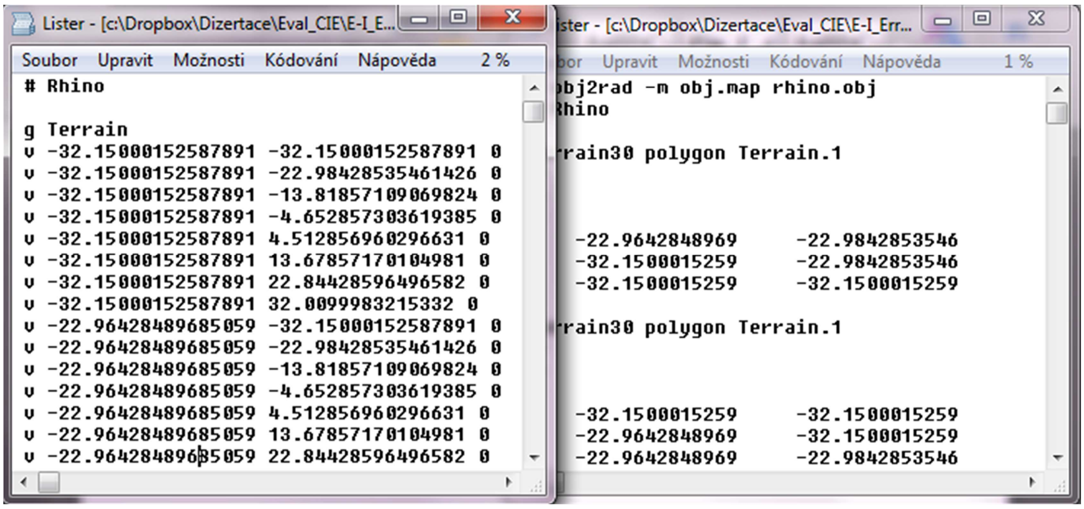
At the concurrent time, it could be said that the latest version of « WDLS » should not be used for daylighting design process at all.

The author himself began to use « RADIANCE » after the assessment as to « RADIANCE » did turn out to have a great prediction of final daylight factor levels. Some of the results are presented within the thesis. If a person has prerequisites for programming then can create plugins like the Diva for Rhino. The latest version of this tool costs $470 [59], which in contrast to « WDLS » as a separate tool, did focus on the integration into Rhino 3D modelling software and on the utilization of free tools applicable within other fields of building physics too, not just in daylighting. Older versions of the tool are free to download. Then again, the author must inform the community about the issues connected to it.

Diva for Rhino uses the Rhino 3D's internal plugin to save the model into a WaveFront file format (having an extension of *.obj). This is then turned into a RADIANCE file (radfile) by a specialized internal component of « RADIANCE », called as obj2rad. The problem arises when the model is exported for Rhino into WaveFront. This is visible in the inconsistency of the exported surfaces. The plugin creates the meshes exported on top of the original ones, not inside of them. Thus, the edges of surfaces are moved in the direction of their surface normal a bit, causing a discrepancy, throughout which the elementary planes are not going to be connected. Like this, some particles observed via backward ray-tracing could reach the light source directly without any reflections, and can influence the results in the worst.

As a solution to this problem, instead of Diva for Rhino a user can use a different plugin written for a different program, namely, for Google SketchUp. The plugin is called ~SU2RAD~ (short for SketchUp to RADIANCE). Once a model is saved into *.skp file format it can be used in SketchUp itself to export the model into a radfile. The given script should be able to run the ~rpict~ process too, but not the ray-tracing ~rtrace~ one required for the illumination calculations to take place. SU2RAD is free of charge, and does not require Diva for Rhino. Another of its advantages is that SketchUp can be used in connection with AutoCAD, too. Therefore, the costs do fall rapidly.

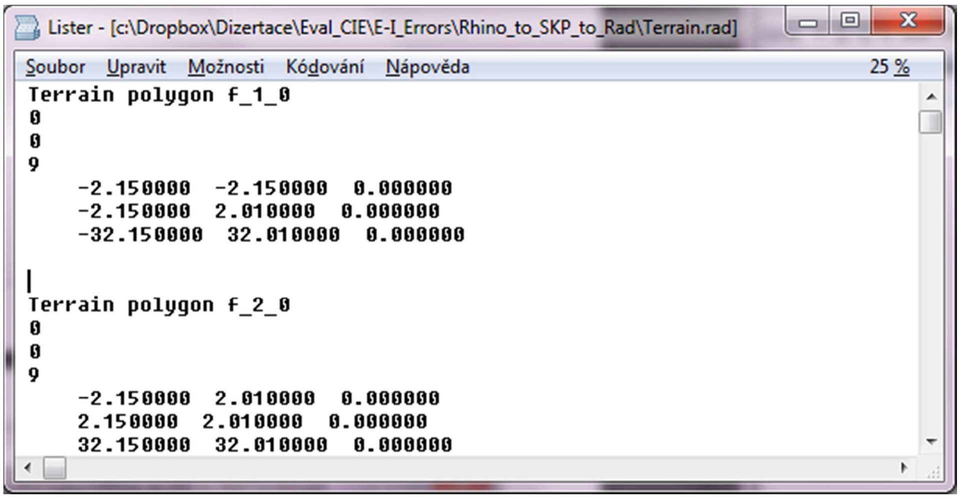
A comparison of the models exported via Diva for Rhino and SU2RAD is visible below.



```
# Rhino

g Terrain
v -32.15000152587891 -32.15000152587891 0
v -32.15000152587891 -22.98428535461426 0
v -32.15000152587891 -13.81857109069824 0
v -32.15000152587891 -4.652857303619385 0
v -32.15000152587891 4.512856960296631 0
v -32.15000152587891 13.67857170104981 0
v -32.15000152587891 22.84428596496582 0
v -32.15000152587891 32.0099983215332 0
v -22.96428489685059 -32.15000152587891 0
v -22.96428489685059 -22.98428535461426 0
v -22.96428489685059 -13.81857109069824 0
v -22.96428489685059 -4.652857303619385 0
v -22.96428489685059 4.512856960296631 0
v -22.96428489685059 13.67857170104981 0
v -22.96428489685059 22.84428596496582 0
```

```
bj2rad -m obj.map rhino.obj
hino

rain30 polygon Terrain.1



 -22.9642848969     -22.9842853546
 -32.1500015259     -22.9842853546
 -32.1500015259     -32.1500015259

rain30 polygon Terrain.1



 -32.1500015259     -32.1500015259
 -22.9642848969     -32.1500015259
 -22.9642848969     -22.9842853546
```

Fig. 62 *Rhino to Wavefront (on the left) and Wavefront to RADIANCE (on the right)*



```
Terrain polygon f_1_0
0
0
9
    -2.150000  -2.150000  0.000000
    -2.150000  2.010000  0.000000
    -32.150000  32.010000  0.000000


Terrain polygon f_2_0
0
0
9
    -2.150000  2.010000  0.000000
    2.150000  2.010000  0.000000
    32.150000  32.010000  0.000000
```

Fig. 63 *The same model exported to RADIANCE vie SketchUp.*

Notice the decimal numbers regarding the edges.

Another great tool available for the daylighting design of buildings, tested by the author, is VELUX Daylight Visualizer (VDI for short). It handles about a ray-tracing application with results and renderings similar to those one can get from « RADIANCE ». The main difference, however lies in the sky definitions included in VDI, as to it can simulate all 15 types of skies for every day and time of a year. It is free of cost and the output is clearly readable.

Then are the most widely developed software's of today, the DIALux and RELUX. Both of them focused primarily onto luminary design. The only flaw of DIALux is, that the peripheral walls must to have a thickness of 300mm. In DIALux Evo this issue was however already solved. RELUX on the other hand is complicated to use if a daylighting evaluation of an indoor space is required. Both DIALux and RELUX are based on the already discussed ray-tracing algorithm, but the ray-tracing parameters are chosen by the software itself.

7.3 VISIONS

There may be many visions for further development in the field of daylighting, from further research on the efficiency of tubular light guide systems until research done on very new systems that could be equal or better than the windows, which are used now the most. In the following years, the author would like to focus his attention onto the indirect methods of daylighting, more specifically on daylighting with the help of Fresnel lenses and optic fibres.

Furthermore, he sees a possibility in the evolution daylighting evaluation in case of contrast comparison and glare design, as to the newer and newer technologies and computer aids do respond to the needs of the applicants, therefore it may possible to visualize these effects in no time.

During the solution of the given dissertation and the expertise activity the author was and is still involved in, he had met several problems in the field of daylighting and insolation of buildings, which could be solved by scientific and research activities. Some of these are:

- Optimize the solution of insolation determination;
- Daylighting of in-accessible spaces in buildings by passive and active methods of daylighting system;
- Optimization of integral lighting design of buildings;
- Etc.

7.3.1 Optimize the solution of insolation determination

The insolation time of living spaces, can be determined with the help of three available diagrams (methods):

- The shading diagram (the simplest);
- The orthogonal diagram (advanced);
- And the stereographic diagram (most complicated).

Each and every of these methods is however based on the same latitude, which is equal to 50° for the Czech Republic, resulting in the same base graphical element.

The set-up and application of these diagrams then is dependent on the longitude of the given location in the form of the meridian convergence coefficient, an angle that rotates the north within the diagram clockwise, so that the real direction of the north could be taken into account.

However, is this approach correct? Would not it be better to divide-up the country into zones and create separate diagrams for them?

Another disadvantage of the current insolation calculation is how the sunrays influencing the insolation are taken into account. The standard

ČSN 73 0581:2009 states, that the angle between the sunrays and the glazing must have at least 25°.

Why exactly 25°? Would not it be more appropriate to take into account the thickness of external walls, with regard to the width of the opening?

7.3.2 Daylighting of in-accessible spaces in buildings by passive and active methods of daylighting systems

Architects and civil engineers do often have problems daylighting, while designing building objects of administrative type on huge plots in case of which they aren't able to locate the indoor spaces near the envelope, or just because some rooms are going to have a huge depth as a result of the dimensions of the building itself. In the Government Decree 361/2007 coll. It is on the other hand stated that a working space can be illuminated with luminaries only if it handles about a room located underground, or in the centre of a building (though the officials doesn't like this solution). Nevertheless, most of the builders are against the usage of indirect systems, against light guides because of their overall efficiency and their interference to the structures.

However, there are other aspects too, like the utilization of optic fibres, transparent concrete or even Fresnel lenses, etc.

Into the future, the author would like to map a few of these available elements.

7.3.3 Optimization of integral lighting design

Daylighting moreover integral lighting design is a task, which does not care about the optimization of uniformity of light just to meet the requirements for the daylight factor of natural light. However, if the integral lighting including that of the luminaries should be designed correctly in two steps from the beginning, then it would require the evaluation to take into account glare too in the proximity of windows and openings.

Natural light, especially under different sky types than that of the overcast sky can influence the wellbeing of humans when they want to take a closer look at something or someone located under the daylighting systems, hence often these objects can be seen only as dark faces with a bright silhouette. This effect can be casually corrected by moving closer to the object or person from the depth of the room, as to the eyes of a person do adopt in an instant to the changing amount of light, or could be counterbalanced by spotlights pointing in the direction of the transparent elements dividing the exterior from the interior.

Into the future at least the author thinks so, it could handle about a useful theme for scientific and research activities.

7.3.4 Upgrading MuuLUX

The first and so far the latest version of MuuLUX software have had been created under time pressure in PASCAL programming language. Hence, it does have some limitations, may they be connected to the available operations, GUI (graphical user interface) creation possibilities or simply to the libraries throughout which the software could create a connection to the KONICA-MINOLTA T10 illuminance meter via the serial port of a computer. In addition, the computer industry does not solely rely on 16 and 32-bit applications anymore, furthermore as time moves on it is even harder to find and operating system, which could host such software any more, though MuuLUX requires only a terminal.

MuuLUX in its current version with the configuration file cannot be launched by anyone. The person, who would like to use it, needs to know the working scheme of the actual illuminance meter itself, therefore the usage of MuuLUX is recommended primarily to researchers, only.

Nevertheless, the newer versions of MuuLUX with a bit of luck could be written in C++ or JAVA programming language, which do allow the implementation of GUI, tooltips, help files, advanced result exporting features while it could be run on most of current OS's.

Another aim regarding the new MuuLUX would be its compatibility with the newest illuminance meter from KONICA-MINOLTA, namely with the model T10A, sold approximately from 2011.

7.3.5 Creation of an application for daylighting calculations

Nowadays there exists only a handful of computer simulation software created for the daylighting and integral lighting design of interiors, which could be used without any limitations. Just taking into account the three most widely used applications in the Czech Republic: the Den-DQL, WAL and WDLS/WILS. The previously mentioned software are old (some of them are not sold anymore), or are anything but user friendly at all (and we are not even talking about the graphical user interface).

In an international scale one would say that Autodesk's Ecotect has some cool features regarding the daylighting design of indoor and outdoor spaces with the help of daylight factor and daylight autonomy values, or that DIALux and Relux are nice even if they are primarily written for artificial lighting design. Another person could say, that the best program available is called AGI32 or …

But, is it really so?

An aim of mine into the future is to develop of a computer simulation tool working on several theories at the same time, having an easy to use interface and 3D scene import feature from peculiar file formats (*.DWG, *.DXF, and so on) without deteriorating the shapes of objects within the model. The output and results coming from the software should be convenient to use, understandable and reproducible.

A possibility for this would be the creation of a front-end to RADIANCE only, similar to that of Diva for Rhino, but having features needed for daylighting design only.

8 LITERATURE REFERENCE

- **List of books and thesis’s**
- **List of papers in conferences and journals**
- **List of laws and standards**
- **Other references**

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9 SYMBOLS AND LISTS

- **List of symbols and shortcuts**
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9.1 LIST OF SYMBOLS AND SHORTCUTS

9.1.1 Latin alphabet

Symbol	Unit	Description
A	$[\mathrm{m}^2]$	Is the area of the projected cross-section of the light corpuscle influencing a surface
a,b	-	Luminance gradation parameters
$B\,(x,t)$	-	Immediate deviation of magnetic waves
c,d,e	-	Scattering indicatrix parameters of CIE standard skies
c_0	$[\mathrm{m}\cdot\mathrm{s}^{-1}]$	Velocity of light in vacuum
c_i	$[\mathrm{m}\cdot\mathrm{s}^{-1}]$	Speed of light passing through a material
$C\,(x,t)$	-	Immediate deviation of electric waves
C_m	-	Amplitude of the deviation of electric waves
DF	[-] or [%]	Daylight factor
DF_e	[-] or [%]	Externally reflected component of daylight factor
DF_i	[-] or [%]	Internally reflected component of daylight factor
DF_m	[-] or [%]	Mean value of daylight factor determined over the working plane
DF_{max}	[-] or [%]	Maximal value of daylight factor determined over the working plane
DF_{min}	[-] or [%]	Minimal value of daylight factor determined over the working plane
DF_s	[-] or [%]	Sky component of daylight factor
dQ_e	[J]	Maximal radiant energy
e_P	[eV]	Energy of photons
E_e	[lx]	Illuminance under an unobstructed CIE standard sky
E_i	[lx]	Illuminance indecent to a point on the working plane
$E_{ref,i}$	[lx]	Illuminance indecent to the reference surface
E_v	[lx]	Illuminance
$E_{w,m}$	[lx]	Mean value of illuminance determined over the working plane
$E_{w,min}$	[lx]	Minimal value of illuminance achieved over the working plane
f	[Hz]	Frequency of oscillation
$f(Z_s)$	-	Scattering indicatrix function of the sky at the zenith
$f(\chi)$	-	Scattering indicatrix function of the sky at an arbitrary point
f_P	[m]	Frequency of a photons adequate radiation
H_P	$[\mathrm{eV}\cdot\mathrm{s}]$	Planck's constant
I_v	[cd]	Luminous intensity
K_m	[-]	Luminous efficiency of electromagnetic radiation

Symbol	Unit	Description
L_{15}	[cd·m^{-2}]	Sky luminance of sky at an angle of 15° above the horizon
L_{45}	[cd·m^{-2}]	Sky luminance of sky at an angle of 45° above the horizon
L_a	[cd·m^{-2}]	Sky luminance at an arbitrary point
L_A	[cd·m^{-2}]	Average sky luminance
L_{ref}	[cd·m^{-2}]	Luminance on the reference surface
$L_{ref,i}$	[cd·m^{-2}]	Luminance on the reference surface
L_{surf}	[cd·m^{-2}]	Luminance on the base surfaces
L_v	[cd·m^{-2}]	Luminance of an arbitrary area on a surface
L_Z	[cd·m^{-2}]	Sky luminance at zenith position
L_γ	[cd·m^{-2}]	Sky luminance at an angle of γ above the horizon
M_e	[W·m^{-2}/μm]	Stefan-Boltzmann law
$M_{e,\lambda}(\lambda,T)$	[W·m^{-2}/μm]	Spectral radiant exitance of materials
M_v	[lm·m^{-2}]	Luminous emittance of a surface
N	[-]	Number of iterations
q	[-]	Luminance gradation fator required by Daniljuk's metholody
t,T	[s]	time
t_n	[-]	Light transmissivity of glazing, necessary data for RADIANCE simulations
T_n	[-]	Light transmittance of glazing
UAL	[-]	Uniformity of artificial light indecent to the working plane
UDL	[-]	Uniformity of daylight indecent to the working plane
v	[m·s^{-1}]	Phase velocity of motion
$V(\lambda)$	[-]	Relative luminous efficiency of photopic vision
x_E	[m]	Displacement of current
Z	[rad]	Angular distance between the sky element and the zenith
Z_S	[rad]	Angular distance between the Sun and the zenith

9.1.2 Greek alphabet

Symbol	Unit	Description
α	[rad]	Azimuth of the sky element
α_v	[-]	Light absorption of matters
α_i	[°] or [rad]	Angles required by Daniljuk's methodology for the determination of the sky and externally reflected components. Its value can be determined numerically or graphically from the plan of the building.
α_S	[rad]	Azimuth of the Sun
β_1 , β_2	[°] or [rad]	Angles required by Daniljuk's methodology for the determination of the sky and externally reflected components. Its value can be determined numerically or graphically from the section of the building.
γ	[rad]	Elevation angle of sky element
γ_s	[rad]	Elevation angle of Sun
Δ_{max}	[%]	The biggest higher deviation
Δ_{min}	[%]	The biggest lower deviation
ε	$[F \cdot m^{-1}]$	Permittivity of environment
ε_0	$[F \cdot m^{-1}]$	Permittivity of vacuum environment
η_0	[-]	Index of refrection of light in vacuum
η_i	[-]	Index of refrection of light in a material
θ	[K]	Temperature of matters
Θ	[rad]	The angle enclosed between the direction of the lights spreading and the surfaces normal it's falling onto
λ	[m]	Wavelength of motion / radiation
λ_{BBody}	[m]	Wavelength of radiation emitted by a black body
μ	$[H \cdot m^{-1}]$	Permeability of environment
μ_0	$[H \cdot m^{-1}]$	Permeability of vacuum environment
ρ_{blue}	[-]	Light reflectance value of surfaces in the blue colours spectrum
ρ_{green}	[-]	Light reflectance value of surfaces in the green colours spectrum
ρ_{red}	[-]	Light reflectance value of surfaces in the red colours spectrum
$\rho_{ref,m}$	[-]	Mean light reflectance of the reference surface (etalon)
ρ_v	[-]	Light reflectance of matters
ρ_d	[-]	Light reflectance value of Lambertian surfaces
ς	[rad]	beginning phase angle
τ_0	[-]	Correction coefficient representing the area of glazing inside openings

Symbol	**Unit**	**Description**
$\tau_{0,\psi}$	[-]	A coeffient representing the light transmittance losses of glazing in overall
τ_{loss}	[-]	Light transmittance losses of openings
$\tau_{m,ext}$	[-]	Maintenance factor of glazing reprezenting the exterior
$\tau_{m,int}$	[-]	Maintenance factor of glazing reprezenting the interior
$\tau_{s,nor}$	[-]	Light transmittance of glazing under an angle parallel to the glazings surface normal vector
τ_{v}	[-]	Light transmittance of matters
$\varphi(Z)$	-	is the luminance gradation function
Φ_{e}	[W]	Radiant flux
$\Phi_{e,\lambda}$	[W]	Luminous flux for wavelength λ
Φ_{v}	[lm]	Luminous flux
$\Phi_{v,\alpha}$	[lm]	Absorbed component of indecent luminous flux
$\Phi_{v,\rho}$	[lm]	Reflected component of indecent luminous flux
$\Phi_{v,\tau}$	[lm]	Transmitted component of indecent luminous flux
χ	[rad]	Angular distance between the sky element and the Sun
ω	[rad·s^{-1}]	Angular frequency of motion
Ω	[sr]	Solid angle under which light is emitted into space

9.1.3 Shotcuts

Shortcut	Description
-aa, -ab, -ar, -as, -ad, -av, -aw	Ambient parameters required by RADIANCE
CFL	Compact fluorescent lamp
CIE	Commission Internationale de l'Eclairage
ČSN	Czech national standard
-g	Ground reflectance used by Gensky while sky generation
I/O	Input-output software
IR	Infrared radiation
LED	Light emitting diode
LNBL	Lawrence Berkeley National Laboratory
LW	Long wavelength
MinGW *CYGWIN*	Crosscompilers for U/L based applications onto MS Windows OS
MS Win	MS Windows Operating System
MW	Middle wavelenght
NASA	National Aeronautics and Space Administration
OPT5	Optics 5 software developed by LNBL
rough.	Roughness of surfaces
SI	Le Système International d'Unités
spec	Specularity
SW	Short wavelength
-u	A boolean switch turning on/off the Monte Carlo sampling within ray-tracing
U/L	UNIX/ LINUX Operation system
UV	ultraviolet radiation
VDI	Velux Daylight Visualizer
VSG	A type of safety glazing
WDLS	Windows Day Lighting System, a software widely used in the Czech Republic for daylighting design by the engineering community
WP	Working plane
X11	X window system of UNIX/LINUX based operation systems

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10 APPENDICES

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A3 The source code of MuuLUX software
A4 The RADIANCE models of CIE Test Cases
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