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The purpose and content of «Light & Engineering» is to develop the science of light within the framework of ray, photometric concepts and the application of results for a comfortable light environment, as well as for visual and non-visual light technologies, including medicine. The light engineering science is a field of science and technology and its subject is the development of methods for generation and spatial redistribution of optical radiation, as well as its conversion to other forms of energy and use for various purposes.

The scope of journal includes articles in the following areas:

- Sources of light;
- Light field theory;
- Photometry, colorimetry and radiometry of optical radiation;
- Visual and non-visual effects of radiation on humans;
- Control and regulation devices for light sources;
- Light devices, their design and production technology;
- Light devices for the efficient distribution and transportation of the light energy: hollow light guides, optical fibers;
- Lighting and irradiation installations;
- Light signaling and light communication;
- Light remote sensing;
- Mathematical modelling of light devices and installations;
- Energy savings in light installation;
- Innovative light design solutions;
- Photobiology, including problems of using light in medicine;
- Disinfection of premises, drinking water and smell elimination by UV radiation technology;
- Light transfer in the ocean, space and other mediums;
- Light and engineering marketing;
- Legal providing and regulation of energy effective lighting;
- Light conversion to other forms of energy;
- Standardization in field of lighting;
- Light in art and architecture design;
- Education in field of light and engineering.

Journal "Light & Engineering" had been founded by Prof. Julian B. Aizenberg in 1993

LIGHT & ENGINEERING

СВЕТОТЕХНИКА

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Light & Engineering" is an international scientific Journal subscribed to by readers in many different countries. It is the English edition of the journal "Svetotekhnika" the oldest scientific publication in Russia, established in 1932.

Establishing the English edition "Light and Engineering" in 1993 allowed Russian illumination science to be presented the colleagues abroad. It attracted the attention of experts and a new generation of scientists from different countries to Russian domestic achievements in light and engineering science. It also introduced the results of international research and their industrial application on the Russian lighting market.

The scope of our publication is to present the most current results of fundamental research in the field of illumination science. This includes theoretical bases of light source development, physiological optics, lighting technology, photometry, colorimetry, radiometry and metrology, visual perception, health and hazard, energy efficiency, semiconductor sources of light and many others related directions. The journal also aims to cover the application illumination science in technology of light sources, lighting devices, lighting installations, control systems, standards, lighting art and design, and so on.

"Light & Engineering" is well known by its brand and design in the field of light and illumination. Each annual volume has six issues, with about 80–120 pages per issue. Each paper is reviewed by recognized world experts.

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TOPICS IMPORTANT FOR THE UP-TO-DATE INTERIOR LIGHTING PROFESSIONAL

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ABSTRACT

To avoid disappointments with LED lighting installations, detailed knowledge of the typical characteristics of the many different solid-state light sources is essential, while already long-available information on vision and colour seeing has to be combined with entirely new fundamental research on the relationship between lighting on the one hand and vision, performance, comfort, health and well-being on the other hand. Lighting has apart from visual effects also far-reaching non-visual biological effects. These effects influence the way our body "operates" and therefore, influence our health, well-being and alertness. Interior lighting installations today have to be designed so that they provide both suitable visual and non-visual biological effects, while adverse effects of lighting, like flicker, blue light hazard and disruption of the biological clock, are avoided.

LEDs offer the possibility to use them not only for lighting but also for data transmission. The use of LED lighting as a means for data communication is referred to as "light beyond illumination". Visible Light Communication (VLC), LiFi, and light itself used as sensor are part of this subject. The modern lighting professional has to get familiarised with these new technologies and applications.

The author of this article published in 2019 the book "Interior Lighting, fundamentals, technology and application" with Springer [1]. It discusses in 500 pages all topics important for the up-to-date interior lighting professional. The present overview article is entirely based on this book and follows the same chapter structure. Each chapter also describes, as an example, one or two crucial aspects in more detail.

Keywords: interior lighting, human-centric lighting, lighting and health, lighting and age, visual performance, visual satisfaction, therapeutic effects of lighting, hazardous effects of lighting, LEDs, interior lighting design

1. FUNDAMENTALS

1.1. Visual Mechanism

A visual sensation is the result of processes in the eye and brain. Light entering the eye is projected on the back of the inner part of the eye, the retina. The retina contains photoreceptor cells: cones and rods. Photopigments in these receptor cells absorb light, resulting in a chemical-electrical signal, which travels down a nerve into the visual cortex part of the brain where the visual sensation is invoked. A small area of the retina around the axis of the eye, the fovea, only contains cone cells. The other, peripheral, areas have few cone and many rod cells. The cone cells in the fovea have a one-to-one nerve connection to the brain. Rod photoreceptor cells are located in the periphery of the retina. Many of them converge on a single ganglion cell. Consequently, foveal vision is sharp and peripheral vision is not sharp.

The set of rods converging on the same ganglion, called the receptive field of that cell (Fig. 1), are processed through an opponent mechanism. Ganglion cells compare signals arriving from an inner circular area of the receptive field with signals arriving from the outer circular area (the surrounds) of the same receptive field. The centre-surround opponent processing by the retinal ganglion cells enables detection of light-dark transitions and thus edge detection of bright objects.

Fig. 2 -left illustrates this by showing how a bright circular object (or light source) of uniform luminance interacts with a group of receptive fields of neighbouring ganglion cells. Only the cells indicated in red are excited. This means that only the edges of the uniform bright area forward information into the brain. From the uniform parts of the light source, no information is forwarded to the brain so that the brain is less engaged. A multitude of smaller bright objects of light sources (Fig. 2 -right, like, for example, matrix LED luminaires) excites more ganglion cells by the larger number of edges and consequently engages the brain more, which, in turn, may be the reason for a higher degree of discomfort glare of LED-matrix luminaires. This phenomenon is now used to develop an entirely new fundamental basis for discomfort glare prediction. Preliminary results show promising results [2, 3, 4, 5].

Colour vision is possible because there are three types of cones, one with sensitivity for reddish, one for greenish and one for bluish light. A colour opponent mechanism processes their signals. This procession does not take place in the ganglion cells of the retina but in ganglion cells located at a kind of substation in the central part of the brain. It is called

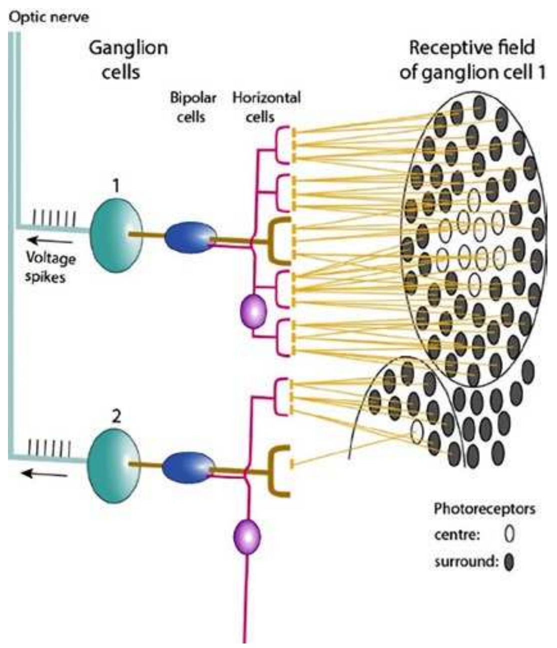

Fig. 1. Receptive fields of two ganglion cells

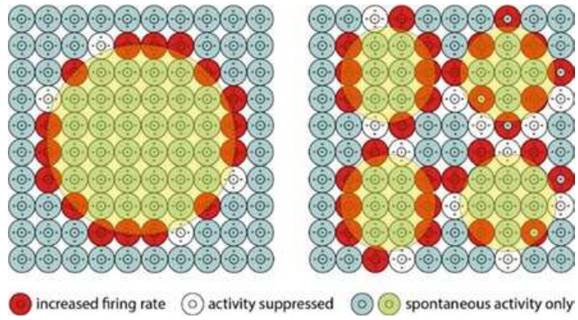

Fig. 2. Edge detection of a light source: the light source with a uniform luminance (left) excites fewer ganglion cells than the source with non-uniform luminance (right)

the lateral geniculate nucleus (LGN). This opponent colour mechanism with an opponent yellow-blue, green-red and white-black channel determines to a large extent how we perceive colours. Since we have just one type of rod cell, colour vision with rods is impossible.

Cones are mainly active at lighting levels larger than some 5 cd/m^2. Vision is then referred to as photopic. The spectral eye sensitivity curve *V(λ)* defined for photopic vision is the basis for all photometric units.

1.2. Colour

Solid-state light sources offer far more possibilities to engineer lamp spectra to suit different colour quality requirements than gas discharge lamps did. Accurate lamp colour specification based on perceived colour has therefore received renewed attention. This concerns in the first place the specification of different types of white light sources. Coloured LEDs are more and more used in interior spaces so that also an accurate specification of coloured light sources is needed.

The number "three" plays an essential role in colour vision. Examples are the three types of cones and the three-channel opponent colour vision system described in the previous section. Principally, all colours that can be produced by three primary colours can only be presented in a three-dimensional space. A simplification towards a two-dimensional plane presentation is possible by neglecting the effect of differences in brightness of the colour stimulus and concentrating on hue and saturation of the colour sensation only. With the two coordinates x and y, used in a rectangular coordinating system, the CIE1931 *x-y* chromaticity diagram (the well-known "CIE colour triangle") is constructed.

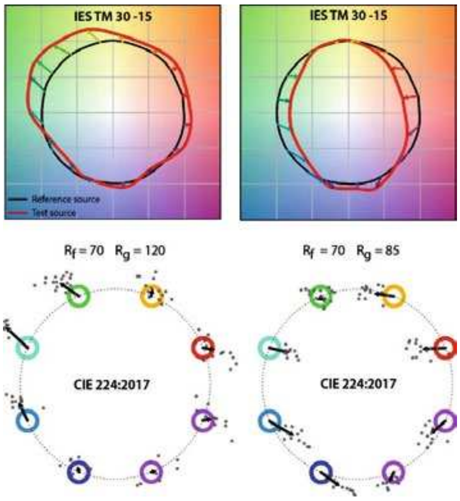

Fig. 3. IES TM 30–15 (top) and CIE224:2017 (bottom) [11] colour vector graphics visualising colour shifts as obtained with the same two light sources relative to their reference sources

Correlated colour temperatures of light sources, as a characterisation of the tint of whiteness, are easily obtained from the *x–y* chromaticity coordinates. MacAdam ellipses, in a more uniform *u′–v′* chromaticity diagram, are the basis for the binning process in the LED manufacturing process. More uniform means that an equal distance in the *u′–v′* diagram represents better a same perceived colour difference.

A wealth of new research on colour science is available as a basis to replace some colour concepts that have been developed between the 1930s and 1960s. New uniform three-dimensional colour spaces have been introduced. The CIECAM02-UCS colour space is proposed in report TM-30 of the IES of North America [6] as a basis for a novel two-metric colour-rendering system with a fidelity index R_f and a gamut index R_g. Many studies have shown that there exists a relatively good correlation between R_f and the CIE colour rendering index R_a, [7, 8, 9, 10]. However, with the possibility of engineering LEDs that emit light with small spectrum lines at specific wavelengths (for example with the use of quantum dots), the colour fidelity index R_f method is more "future-proof" than the old R_a method. The second metric, gamut index R_g of the two-metric system, is a measure of colour saturation. In some applications, a light source that shifts a particular colour or colours in a specific direction, for example towards more saturation and thus to more colourful colours, may make the visual scene more pleasant. If the gamut index is larger than 100, the colour shift is generally towards more saturation and if smaller than 100 towards less saturation. Colour vector graphics visualise the colour properties of light sources. They represent an indispensable new tool for the lighting designer in the LED era. The top of Fig. 3 shows the vector graphic diagrams proposed by IES-TM-30 [6] for two different light sources with the same fidelity index but with different gamut index. The colour shift is indicated by an arrow (the vector) relative to the black circle, which represents the reference source (no colour shift). The ends of the vectors are interconnected by the red line so that both the size and direction of colour shift in each part of the diagram are visualised. Where the line lies outside the circle of the reference source, saturation increases, and where the line is inside the circle, saturation decreases. So, the light source represented on the left of Fig. 4 (top) saturates green-yellow colours strongly and red-orange colours a little. On average, this light source results in strong saturation which is also clear from its high gamut index (R_g = 120). The light source on the right (top) results in strong desaturation of a large part of the colours (R_g = 85). In CIE publication [11] developed an alternative graph for visualising colour shifts (Fig. 3 bottom) that contains

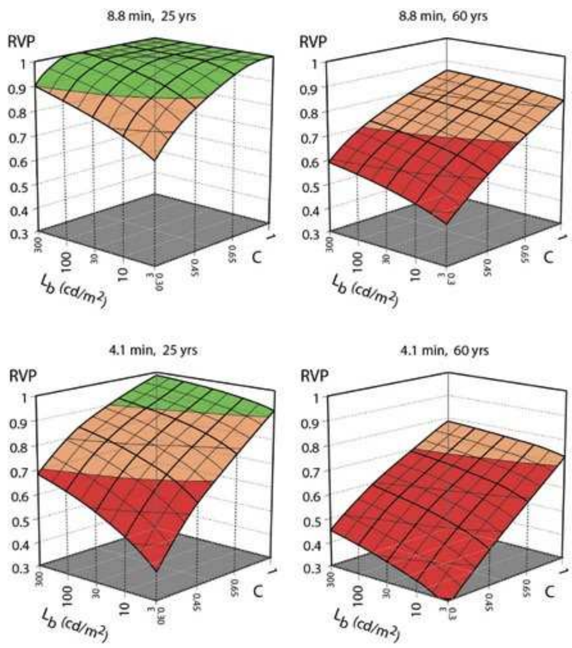

Fig. 4. RVP bodies: Relative Visual Performance (RVP) as a function of object contrast (C) and background luminance (L_b); top: visual angle 8.8 min (same size as an 8.5-point Times letter viewed from 50 cm); bottom: 4.1 min (same size as a 4-point Times letter viewed from 50 cm); left is the 25 years of age and right is the 60 years of age

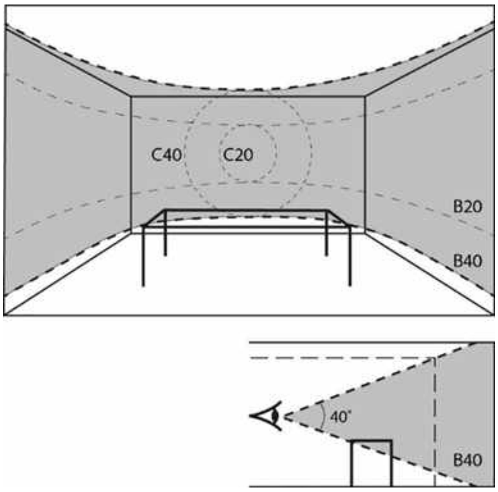

Fig. 5. Mock-up conference room with different dominant areas that were investigated in [20]

more information about the spread of the results, which can be important for research reasons. The IES-TM-30 graphic is more intuitive and therefore more suitable for general use.

1.3. Visual Performance

Visual performance for tasks of different size and contrast as a function of background luminance provides information about what lighting levels in interior working situations are required as a minimum for efficient performance. In almost every human activity, visual performance should be well above its visibility threshold to perform efficiently. Efficiency depends on speed and accuracy with which visual tasks can be detected and identified. Many researchers have carried out suprathreshold investigations into the relationship between lighting level and speed and accuracy of work. The tasks used in these experiments vary from Landolt rings [12, 13] search tasks using test sheets with a random distribution of all numbers from 1 to 100 [14], verification tasks in which two printed number lists were compared [15, 16] and computer input data tasks [17]. CIE compared the different methods and concluded that the model based on Weston's data (Landolt ring tasks) provides the best prediction for visual performance under office conditions [18]. We, therefore, used Weston's studies as a basis to calculate relative visual performance (RVP) for different contrasts between task and background, and for different background luminances. Fig. 4 shows, for a visual angle of 8.8 min (same size as an 8.5-point letter seen from 50 cm) and 4.1 min

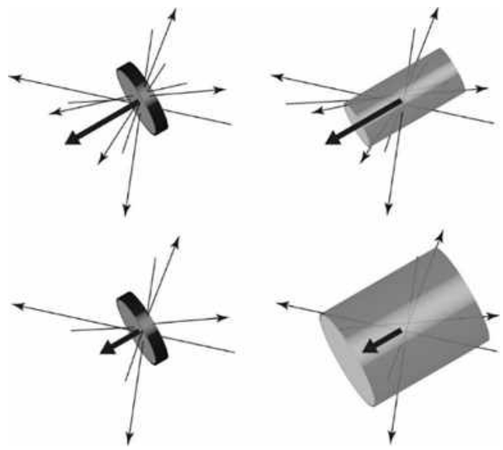

Fig. 6. Difference between light rays and light flow: small arrows represent light rays and the broad arrow the illumination vector; the diameter of the light tubes is inversely proportional to the magnitude of the vector: top: large illumination vector and corresponding small light tube; bottom: smaller illumination vector and corresponding wider light tube
Note: disks on the left are in reality infinitesimally small

(same size as a 4-point letter size from 50 cm), the so called RVP (Relative Visual Performance) bodies as calculated for observers of 25 and 60 years. For easy to moderately difficult tasks, as occurring in many offices, it is shown that visual performance is not a key issue for determining what lighting level is required for young persons. In situations with more difficult visual tasks, visual performance becomes an issue. Visual performance of older workers deteriorates considerably, and their performance should always become a consideration in setting lighting levels.

Disability glare, which is the form of glare that is responsible for a negative influence on visual performance, has a neglectable effect on visual performance under most interior lighting conditions. Glare in interiors should be limited by restricting discomfort glare. Discomfort glare will be discussed in the next Section 1.4: "Visual Satisfaction".

The spectrum of light influences the threshold performance measure of visual acuity through its effect on the size of the pupil. Under many working conditions, however, this is of limited relevance since most of the visual tasks are far above the threshold of visibility where the spectrum hardly plays a role [19].

1.4. Visual Satisfaction

Visual performance, as described in the previous section, relates to the lighting of the task. The

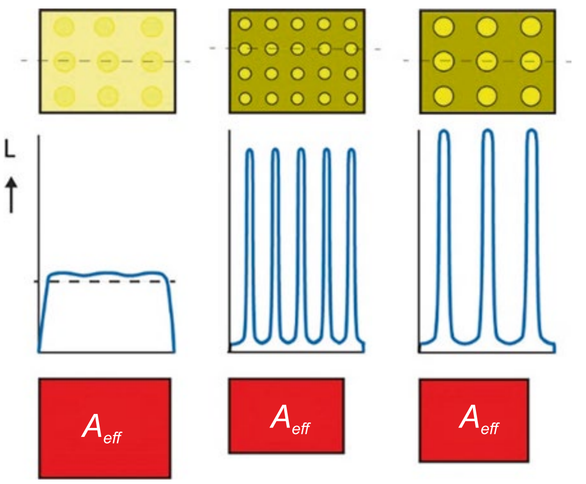

Fig. 7. Illustration of the effective light-emitting area of a luminaire, A_{eff}, as defined by CIE (2019) [32] for non-uniform luminaires to be used in the standard UGR discomfort glare formula

lighting of the whole space determines whether the overall appearance of the space is experienced as visually satisfying. The brightness of a space, the distribution of the luminance in that space, the directionality of the light, the degree of discomfort glare and the colour tint of light determine visual satisfaction.

For the characterisation of the visual appearance of a room two different metrics are proposed: the average luminance in a horizontal band with a width of 40° [20, 21, 22, 23] and the mean room surface exitance [24, 25, 26]. Fig. 5 shows the mock-up room used by Loe et al. [20] to study how well different "dominant" areas define the visual satisfaction of a room. B40 showed the best correlation.

The directionality of lighting determines the appearance of three-dimensional objects and faces in a space. The concept of flow of lighting, illustrated in Fig. 6, allows for the calculation of the lighting's main direction and strength at a point in space as a result of all light rays at that point. The vector-to-scalar ratio can quantify, and light tubes visualise, the flow of lighting. The latter enables a detailed analysis of the spatial and form-giving potential of lighting designs. With today's available computer graphic software, methods for light tube visualisations of complete lighting installations have been developed [27, 28, 29, 30, 31]. Such software may become an indispensable tool for the modern lighting designer to check the lighting effect at literally every point in the space.

The unified glare rating UGR concept is used as a measure of the degree of discomfort glare. However, the UGR concept needs modifications for glare sources with a non-uniform luminance, such as many LED matrix luminaires. As mentioned in Section 1.1 (Fig. 1), some researchers have recently used as a basis for their discomfort glare considerations the neural response to bright light and the mechanism of receptive fields. The process of neural signals being transformed in ganglion cells into edge detection signals (Fig. 2) is a promising candidate for quantifying discomfort glare from a fundamental physiological point of view. A CIE Technical Committee very recently defined a temporary correction of the UGR method until a fundamental approach based on physiological and psychological mechanisms provides practical results. The Committee concluded that the preferred correction method for UGR is the use of "effective light-emitting area" in the standard (unchanged) UGR formula [32]. The effective light-emitting area, A_{eff}, is determined from a high-resolution luminance image of the luminaire. For non-uniform luminaires, the effective light-emitting area is smaller than the physical light-emitting area, as illustrated in Fig. 7. The measurement and calculation procedure is described in detail in the corresponding CIE publication [32].

The spectrum of the glare source influences also discomfort glare: short-wavelength light sources result in more discomfort glare than long wavelengths.

The correlated colour temperature-based rule of Kruithof [33] works not good enough to predict visual satisfaction with light sources of different tints of whiteness.

1.5. Non-Visual Biological Mechanism

Daily (circadian) bodily rhythms, a fundamental property of human life, are synchronised by the natural 24-h dark-light rhythm. This entrainment by light is one of the non-visual biological effects of light. Without entrainment, the bodily rhythms will deviate from the 24-h rhythm. This misalignment will have negative health consequences, in particular on sleep quality. It also will result in lower alertness and performance during daytime.

An, until recently, unknown type of photoreceptor discovered in 2002, the photosensitive retinal ganglion cell pRGC, connects with the suprachiasmatic nucleus SCN, a structure within the brain that acts as a master biological clock [34]. The SCN, in its turn, has pathways to the pineal gland, where melatonin is produced, and to the adrenal cortex responsible for the production of cortisol. The hormones melatonin and cortisol govern sleep and alertness. Cortisol increases glucose to give the body energy. It is sometimes, popularly, referred to as the energy hormone. Melatonin slows down some bodily processes and evokes sleep. Melatonin, popularly called the sleep hormone, reaches, in the case of proper entrainment, its maximum level in the middle of the night and is, again in the case of proper alignment, nearly entirely absent during daytime. Cortisol, which produces glucose, provides the body with energy. It should have a sufficiently high level during daytime and reach its minimum during nighttime.

Light may, apart from effects on circadian rhythms, also have direct, acute photobiological effects that directly influence alertness and performance.

The spectral sensitivity of the pRGCs, given by their photopigment melanopsin, is different from that of rods and cones. Its sensitivity peaks in the blue part of the wavelength range. Rods and cones have a neural connection with ganglion cells, and consequently, their signals interplay with the signal obtained from the pRGC itself (Fig. 8). Much of this neural wiring is as yet unknown. Primarily because of this, it is impossible to define a single spectral sensitivity function or action spectrum for all non-visual effects of light. The correlated colour temperature can be used only as a rough indication for the characterisation of the spectrum of lamps for non-visual biological use. The spectrally weighted irradiances for the five human photopigments together are the best characterisation. Of these five, the pigment of the ipRGC, called melanopsin, is the more important one as far as non-visual biological effects are concerned.

The absorption spectra of the cones and rods are already long time known. CIE defined the spectral "melanopic sensitivity" based on measurements of the absorption spectrum of the photopigment melanopsin in its international standard CIE026:2018 [35].

The collective name for the five spectral weighted irradiances is "*α*-opic irradiance". Each of the five individual *α*-opic irradiances is named after its photopigment name, melanopic (pRGC), rhodopic (rod), cyanopic (S-cone), chloropic (M-cone) and erythropic (L-cone) irradiances. Fig. 9 gives for some lamp types the calculated *α*-opic irradiances for the five photoreceptors, for the condition

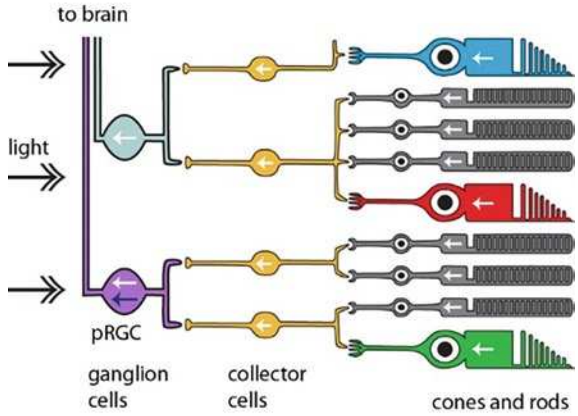

Fig. 8. Part of the retina with photoreceptor cells, including photosensitive retinal ganglion cell, pRGC (in purple). White arrows represent signals to the brain as a result of the transformation of light incident on cones and rods, the blue arrow represents the signal from light incident on the opsin melanopsin of the pRGC

1000 lx at the outer surface of the eye. These five "irradiances per 1000 lx" give a good insight into the effectiveness of a lamp in evoking a reaction in each of the five photoreceptors. For non-visual biological lighting applications, it may often be interesting to compare the melanopic irradiance of a particular light source with the melanopic irradiance by daylight (of the same lighting level at the eye). For this purpose, Fig. 9 also gives, for each lamp type, the "melanopic equivalent daylight ratio Melanopic equivalent daylight (*D65*) factor DL_{eq}". It is the ratio of the melanopic irradiance of the lamp to the melanopic irradiance of 6500 K daylight (CIE standard *D65* sky). This ratio is also referred to as melanopic daylight (*D65*) efficacy ratio (CIE2018) [35].

1.6. Light, Sleep, Alertness and Performance

A classical sleep model is based on an interaction of two different processes. A homeostasis process is characterised by increasing and decreasing sleep pressure after waking up and while asleep, respectively. The other process is a circadian one which provides the possibility to sleep: the sleep window. Light and darkness at the appropriate times strongly influence the latter process: daytime light influences sleep possibility during the subsequent night. Here, both the level and the spectrum of light play a role. Cooler white light is more effective than warmer white light.

Light affects sleepiness, alertness and performance during daytime through two different routes (Fig. 10). Route 1 represents the circadian route de-

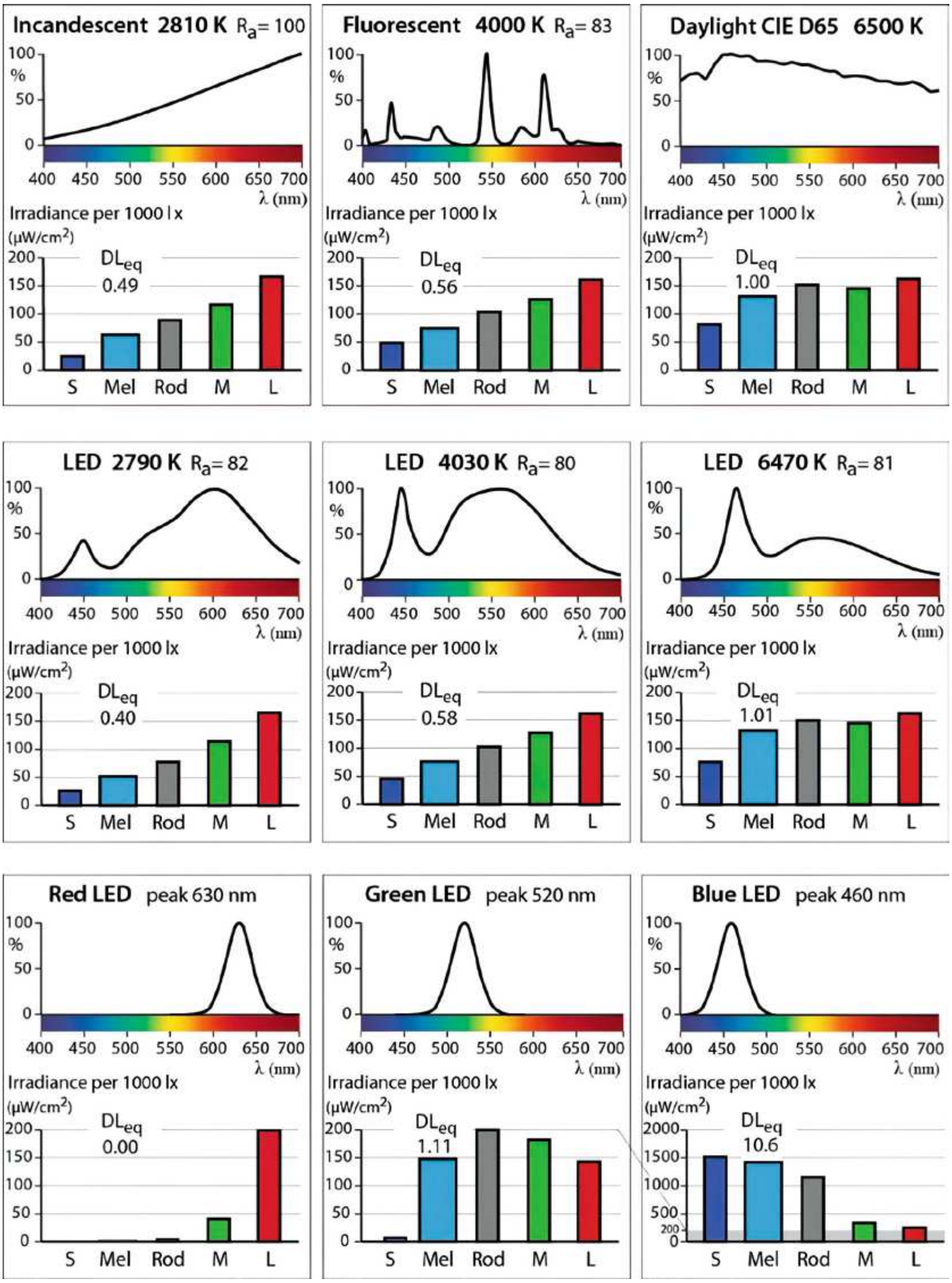

Fig. 9. Alpha-opic irradiances of different lamp types for 1000 lx at the outer surface of the eye: S (S-cone) is cyanopic irradiance, Mel (melanopsin) is melanopic irradiance, Rod is rhodopic irradiance, M (M-cone) is chloropic irradiance and L (L-cone) is erythropic irradiance, DLeq is the melanopic equivalent daylight ratio (CIE D65); bars for melanopic irradiances are shown somewhat broader to make them stand out

scribed above and route 2 the direct photobiological one. Route 1 starts at the moment of daytime light on the previous day ("yesterday"). Daytime light of yesterday affects the night-time sleep quality of yesterday, as discussed in the previous chapter. Therefore, the daytime lighting of yesterday influences sleepiness, alertness and performance of today. Route 2, the direct photobiological route, concerns light that invokes an acute activating effect as long as the lighting is available because of direct photobiological processes. A dynamic lighting scenario for daytime workplaces, which dynamically

Table 1. Three Causes for Circadian Misalignment in Shift Workers

Nighttime lighting:	**horizontal illuminance of 500 lx not effective in phase shifting**
Daytime lighting before and after daytime sleep:	Bright daylight helps to stay entrained to the natural day-night rhythm
Days off:	Switch back from "nighttime work" and "daytime sleep" to the natural day-night rhythm

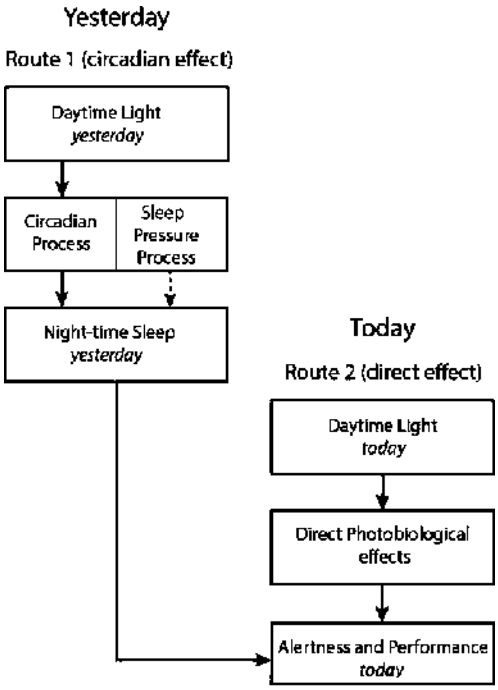

Fig. 10. Two routes through which daytime light may influence daytime alertness and performance

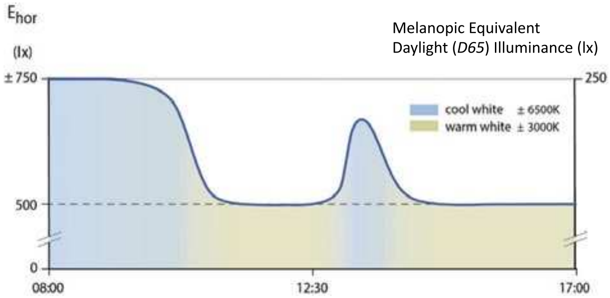

Fig. 11. Lighting scenario for human-centric lighting in offices: the value of 250 lx melanopic equivalent daylight (*D65*) illuminance is the basis for the scenario. It corresponds to roughly 750 lx horizontal illuminance (for 6500 K, conventional type of light distributions and luminaires arrangement); the value of 500 lx for 3000 K corresponds to roughly 85 lx melanopic equivalent (*D65*) illuminance

changes both the lighting level and colour to ensure the positive effects of the two routes, is proposed in Fig. 11. It optimises between energy requirements on the one hand and requirements of visual and non-visual effects of lighting on the other hand.

1.7. Shift Work, Light, Sleep and Performance

The circadian rhythm of most night-time workers who work under no extra bright light does not shift much [36, 37, 38, 39, 40]. It leads to a mismatch of the body circadian rhythm and the night-time work–daytime sleep rhythm. The body is as far as its circadian phase is concerned in the "biological night" at the moment it has to work and in the "biological day" when it has to sleep. Table 1 lists the most important causes for the misalignment. The phase shift and thus, misalignment between the body circadian rhythm and the work-sleep rhythm have adverse effects on the health of the shift worker. It also affects sleep, alertness and performance adversely. Specifically designed shift work lighting can help reduce these problems. The night shift is considered to be the most disruptive one.

Depending on the duration, timing and rotating frequency of shifts and of the risk of work, the objective of shift work lighting is different. For permanent night-shift work and slow-rotating shifts, the goal should be a complete resetting of the circadian rhythm. For fast-rotating shifts, with change over periods of some 3–7 days, usually partial or compromise phase shifting offers an adequate possibility that also allows the shift worker to have a relatively normal social life. The circadian rhythm of workers in single-night shifts or very-rapid-rotating shifts should preferably not be phase shifted. These objectives can only be obtained with different lighting schedules. Recent research results are available as a basis for such schedules. Some lighting schedules use bright white light of gradually changing colour temperature; others use intermittent very bright light pulses of relatively short duration and again others, light of which the short wavelengths are filtered (short-wavelength depleted white light).

1.8. Age Effects

The changes that occur with age in the optics and retina of the eye, and in the neurological pathways into the brain, have thoroughly been investigated

Table 2. Combined Effect of Reduced Pupil Size and Reduced Eye Transmission due to Lens Yellowing on Light Reaching the Retina of Older Persons Relative to a 25-Year-Old, for Phosphor LEDs with CCT of 2700 K and 6500 K at an Adaptation Level of 10 cd/m² and 100 cd/m²

Age	Transmission for 2700 K		Transmission for 6500 K	
	L_{adapt} = 10 cd/m²	L_{adapt} = 100 cd/m²	L_{adapt} = 10 cd/m²	L_{adapt} = 100 cd/m²
50 relative to 25 years	0.84	0.91	0.83	0.90
65 relative to 25 years	0.75	0.86	0.72	0.83
80 relative to 25 years	0.65	0.78	0.63	0.76

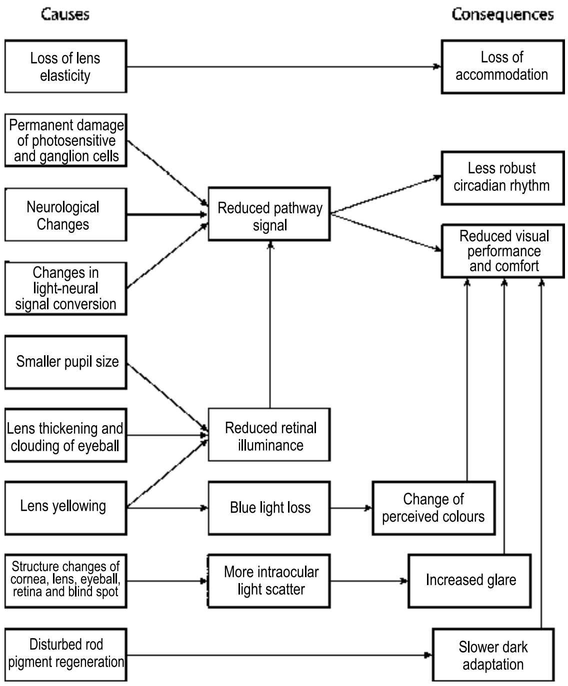

Fig. 12. Causes and consequences of the adverse effects of the ageing eye

and are well documented [41, 42, 43]. These changes have adverse effects on vision and on the circadian system. Fig. 12 lists the causes of these adverse effects together with the adverse consequences for the visual and circadian system.

The optical changes in the eye with age concern loss of eye-lens transparency because of yellowing of the lens, structural changes in the cornea and eyeball (clouding), and a smaller pupil size due to loss of elasticity. They all have negative consequences for the amount of light reaching the retina. The effect of the yellowing of the eye lens also leads to loss of blue light which is especially a problem for both acute and circadian non-visual effects of light. Structural changes of the cornea, lens, vitreous body, retina and blind spot increase the scattering of light by these structures towards the fovea and consequently increase glare in the elderly. With increasing age, regeneration of the rod pigment takes more time, and consequently, dark adaptation is slower.

Table 2 gives the combined effect of reduced pupil size and reduced transmittance of the eye due to lens yellowing for an adaptation luminance of 10 and 100 cd/m², for a phosphor LED with a CCT of 2700 K and 6500 K, respectively (R_a > 80).

1.9. Therapeutic Effects

Light can sometimes be a therapy for a disrupted circadian system. Light therapy, specifically timed exposure to light, is a particular form of chronotherapy. Sometimes, light therapy does not cure the disease itself but helps to reduce negative symptoms of the disease.

SAD is the first disease that was treated successfully with light therapy, nearly 35 years ago [44]. Seasonal affective disorder (SAD) is a type of mood disorder in which people with normal mental health experience severe depressive symptoms during the same period each autumn or winter. SAD is sometimes referred to as winter depression. SAD related problems usually disappear after two weeks of daily clinical light therapy of white light of 2500 lx for some two to three hours or 10.000 lx for 30 to 45 minutes [45].

In some cases, specific interior lighting can be applied as light therapy, next to its task of providing proper visual conditions. Light therapy for depressions (seasonal and non-seasonal), sleep disorders, sleep disorders connected with Alzheimer's and Parkinson's disease, attention-deficit hyperactivity disorders (ADHD) and eating disorders are examples of this. In demented patients, the usual circadian sleep-wake rhythm becomes often disturbed, in particular in patients with Alzheimer's disease. Nighttime sleep is fragmented, and daytime activity is intermixed with napping. Nighttime wandering and daytime aggression rather often accompany these symptoms. All these side effects of Alzheimer's disease can often be relatively well treated with light therapy by specific interior lighting in the room of the patient [46, 47, 48]. As an illustration of the positive effects that can be obtained with light therapy for Alzheimer patients, Fig. 13 shows the activity data, measured with an action watch, of an Alzheimer patient who participated in a classical study on this subject [49]. For the actual patient, the measured number of movements per hour is displayed on the vertical axis, while the horizontal axis gives the time for five consecutive days. The upper graph, measured before the treatment of the patient, shows the typical irregular sleep-wake rhythm of an Alzheimer patient. The lower graph gives the situation near the end of the light treatment period of the same patient with white light during each day (morning and afternoon) of an average illuminance at the eye of 1140 lx (4100 K). The variability of the activity pattern is considerably reduced with much activity during daytime and little activity during nighttime.

Irregular light-dark rhythms quite often occur in the patient rooms of hospitals. Specifically designed daytime artificial lighting that supplements daylight entering the patient room can improve the sleep quality and mood of the patient and reduce the length of stay in the hospital.

1.10. Hazardous Effects

1.10.1. Lamp Flicker

Visual adverse effects because of lamp flicker fall into three categories: visible flicker effects, stroboscopic effects and phantom array effects.

Visible flicker stands for the annoying visual impression of unsteadiness induced by light whose luminance fluctuates with time. The term "visible flicker" is usually shortened to just "flicker". The stroboscopic effect relates to the change in the perception of moving objects under flickering light. When a static observer looks to a continuously moving object, the object is typically seen as moving continuously and smoothly. However, under certain forms of flickering light, such an object is perceived as moving discretely, i.e. jump-wise in staccato. Where the stroboscopic effect is caused by moving objects, the phantom array effect may arise with non-moving time-modulated lights when the eyes move across these lights. In addition to the real lights, non-existing phantom or ghost lights may appear. A typical situation where the phantom array effect may arise is when driving behind a car of which the two rear lamps have a bad light-modulated waveform. The lamps are seen as an array of many more than two bright red lights stretched out around the car.

A metric to characterise the severity of visible flicker is the "short-time flicker severity", P_{st}. [50], produced a standard that gives a functional and design specification for a flicker-measuring apparatus: the IEC flickermeter that measures P_{st}.

A metric for the stroboscopic effect is described as the "stroboscopic visibility measure", SVM [51, 52].

The phantom array effect can only occur in situations of high contrast between the light source and its background, with light sources smaller than two degrees while viewing directly into it. These situations are typical for night-time outdoor situations and do not occur in interior lighting applications.

Modern luminance and spectrophotometers can measure in an installation the frequency of flicker. Some can visualise the time-modulated light graph. Accurate meters for the measurement of the metrics P_{st} and SVM have been developed. A kid's spinning top can easily be made into a simple tool to check whether the light of a particular lamp contains flickering frequencies. For this purpose, the surface of the top must be provided with small white rectangles regularly distributed in one or more rings on a black surface (Fig. 14).

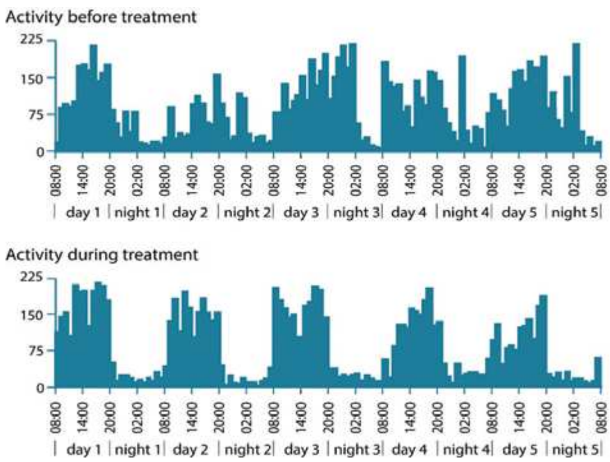

Fig. 13. Activity per hour shown for a period of two times 24 h of an Alzheimer's patient with at the top the data before treatment and at the bottom after 2 weeks of treatment with light during the whole day of an average illuminance of 1140 lx on the eye [49]

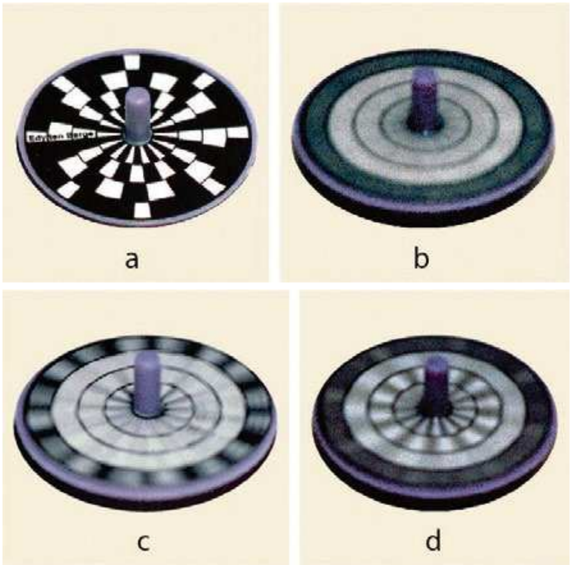

Fig. 14. Spinning top used to check whether or not light contains flicker frequencies; blurred rings at all spinning speeds (b): no flicker frequencies; static white-grey rectangles at some spinning speeds (c, d): the light contains flicker frequencies (design of the top's surface: Edy ten Berge)

1.10.2. Blue Light Hazard

The wavelengths range of (400–500) nm of light associates with a relatively strong photochemical effect in retinal tissues. This range corresponds to blue light. The possible hazard associated with this visible wavelength range is therefore called "blue light hazard". CIE (2002) [53] has defined a system of blue light hazard risk groups for light sources. It is based on the action spectrum (sensitivity spectrum) for retinal damage risk by visible light of different wavelengths. A survey of recent publications on the subject shows that the blue light hazard is not an issue in general lighting that uses white-light sources, including white LEDs [54, 55, 56, 57].

1.10.3. Bright Light at Night

Bright light at night has the potential to disrupt the circadian rhythm which in turn could have adverse effects on health in the form of gastrointestinal, cardiovascular, metabolic (diabetes and obesity) disorders and possibly cancer. In this context, bright light is lighting level of at least 300 lx horizontal illuminance. Van Bommel's Interior Lighting book [1] summarises research in animals and epidemiological studies with humans to provide information about a possible link between cancer and bright light at night.

2. TECHNOLOGY

2.1. Lamps, Gear and Drivers

Today, for almost all lighting applications, LEDs have taken over from all traditional light sources including gas-discharge lamps. This is in particular for reasons of efficiency and long lifetime.

Quality LED light sources have nowadays such a long life, 50,000 hours and longer, that it is not the failure rate that determines how long the LED light source continues to provide lighting up to specification. It is, in particular, the LED parameter "lumen output" that determines operational life. When the lumen output becomes so low that the LED light source has to be replaced, that LED source has a so called parametric failure, although the LED source may continue to function for a much longer time. IEC defines LED lifetime by the parametric failure: "too low lumen output" (IEC2015) [58]. The moment at which the LED light source completely stops functioning is referred to as an abrupt or catastrophic failure. LED lifetime (by "too low lumen output") is specified as *Y* hours of useful life based on the condition $Lx\ B_{50}$. Here *Y* is the time (in hours) after which 50 % (B_{50}) of a population of LED modules parametrically fails to provide at least a percentage *x* of the initial luminous flux. If only the *Lx* value is given (what is usually the case), *B* is assumed to be 50, meaning that 50 % of a set of LEDs of the same type failed to deliver the declared percentage *x* of lamp lumen, i.e. B_{50}. Which lumen depreciation percentage is relevant, is dependent upon the type of application. L_{90}, L_{80} and L_{70} are values that may be relevant, and lifetime specifications without such *Lx* indication are senseless.

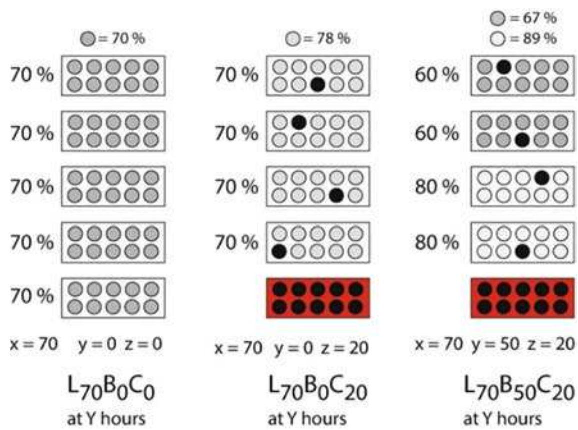

Fig. 15. Examples of different *LxByCz* conditions of a LED module

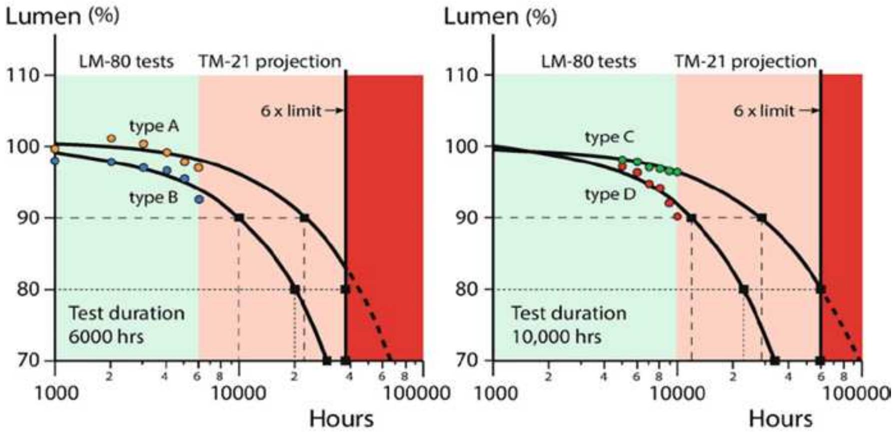

Fig. 16. Examples of lumen maintenance interpolated curves for four different LED types according to IES TM-21, calculated from measurement points obtained from tests based on IES LM-80; the coloured circles are measuring points; the black squares represent the projected lifetime for the conditions L_{90}, L_{80} and L_{70}

An essential point in the IEC standard is that it considers failures of single LEDs in a multi-LED module to contribute to the gradual lumen output degradation. The effect is incorporated in the lamp lumen depreciation and thus in the *Lx* condition. Abrupt, catastrophic, complete failures of a LED module are referred to as *Cz*: length of time during which *z*% of a population of LED modules of the same type fail to produce any luminous flux. Fig. 15 gives typical examples of different *LxByCz* conditions for a LED module.

The industry standard for lumen maintenance testing of a batch of LEDs is IES Document LM-80 [59, 60]. The IES LM-80 documents prescribe the LED sampling method, the laboratory environment conditions, the photometric measurement protocol and the operating conditions (electrical and thermal) of the LEDs to be tested. The tests of one batch shall be done for at least 6,000 hours with data collection at a minimum of every 1000 hours. However, 10,000 hours (or more) are preferred for improved predictive modelling. A LED type has to be tested at a minimum of two LED case temperatures which have to be specified by the manufacturer based on the recommended operating condition. However, one of the two case temperatures shall be 55 ºC or 85 ºC to allow for mutual comparison of results, also between different manufacturers.

Tests according to document LM-80 provide no lifetime of the LED type tested. The data obtained are the input for another IES document, TM-21 [61], that predicts through interpolation of the LM-80 data, useful life. The latter report permits for a prediction of the lumen maintenance percentage at a life six times that of the tested period (based on a minimum sample size of 20 pieces). More extended predictions are unrealistic because of limitations in the extrapolation and lack of confidence in the data beyond. For an LM-80 tested period of 6000 h, this corresponds to a prediction for maximum 36,000 h. For a tested period of 10,000 h, the prediction is for maximum 60,000 h. The measuring points of the last 5000 h of the LM-80 test are used for the prediction. (For a test period of more than 10,000 h, the data of the last 50 % of the total duration are used). Shorter measurement intervals than 1000 hours provide, of course, more accurate results and are therefore preferred. Fig. 16 shows an example of the result of the mathematical interpolation for a test sample of 20 LEDs of four different

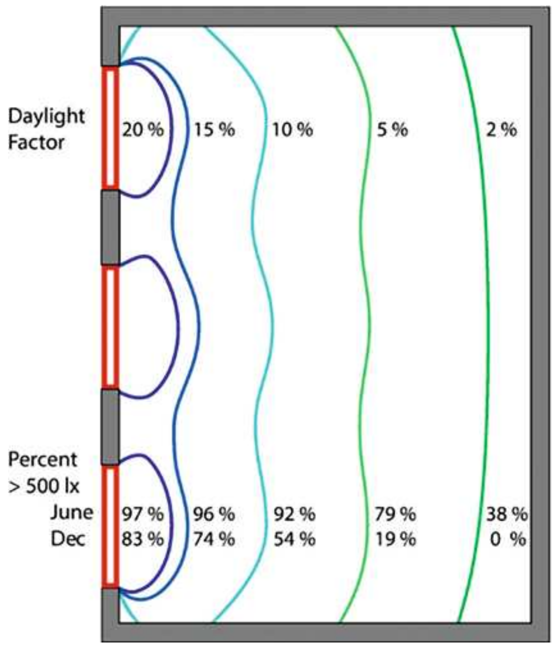

Fig. 17. Daylight factor contours for an office of 5.4×3.6 m with window height and vertical position (as for the window shown in red in Fig. 12.7 in [1]); at the bottom, the corresponding percentages of the time that more than 500 lx will be obtained, are given for June and December (based on daylight measurements in Bratislava, Fig. 12.3 right in [1])

Table 3. Lifetime Values for the Conditions L_{90}, L_{80} and L_{70} of the Four LED Types of Fig. 16

LED type	Test duration, h	life for L_{90}, h	life for L_{80}, h	life for L_{70}, h
A	6000	22,000	> 36,000	> 36,000
B	6000	10,000	20,000	30,000
C	10,000	28,000	60,000	> 60,000
D	10,000	12,000	22,000	33,000

LED types. Two of them are tested over a period of 6000 hours (Fig. 16-left) and two over 10,000 hours (Fig. 16-right). Table 3 gives for each type the projected values of L_{90}, L_{80} and L_{70}.

2.2. Daylight

Light is emitted at the outer layer of the sun, the photosphere. Due to the earth's atmosphere, we also receive indirect sunlight that is scattered from microscopic particles in the earth atmosphere, which makes the sky bright and bluish. The daylight varies with the sun's position, which is dependent on the time of the year and day and on the location on earth. Weather conditions influence the sky condition and therefore, also the daylight level and spectrum.

CIE has defined spectra for a series of standard illuminants that represent the spectra of daylight of different correlated colour temperatures [62, 63]. Daylight *D65* with a correlated colour temperature of 6500 K is the most known type. The correlated colour temperature varies not only with the sun's position but also with the presence and position of clouds and with the viewing direction of the observer. Table 4 gives an indication of the variation of the correlated colour temperature of daylight for different conditions.

CIE also defined different standard luminance distributions of skies for the purpose of daylight calculations [64]. The CIE standard overcast sky is usually used to determine the daylight factor that predicts the potential of daylight in buildings depending on exterior obstructions, fenestration and interior inter-reflection. At many locations on earth, daylight measurements have been made that give quantitative data on the amount of daylight. By combining these location-specific data with daylight factors, detailed insight is obtained in how much of the time and where in a lit space, sufficient daylight will be present. The daylight factor is defined as the ratio of the illuminance at a point in an interior space on a given plane due to the light received from a sky of a defined luminance distribution (excluding direct sunlight), to the illuminance on a horizontal plane in the open outside (without obstructions). The daylight factor is dependent on the dimensions and locations of the daylight openings in the building and of the position in the building. Usually, the CIE overcast sky and the horizontal plane are used as the standard situation. As an example, Fig. 17 gives daylight factor contours for a typical one- or two-person office room. The daylight factor at a specific point in the room gives the daylighting potential of a building at that point for the poorest type of sky represented by the CIE standard overcast sky. What the actual illuminance at that point will be depends on the time of the day, the time of the year and the actual location on earth (sun position). As an example, the daylight factors of the contours in Fig. 17 have been converted based on daylight availability data of Bratislava, into percentages of the time that more than 500 lx horizontal illuminance is obtained in June and December respectively.

2.3. Luminaires

The optical system of a luminaire may make use of mirrors (reflectors), micro lenses (refractors) and diffusers. With the introduction of LEDs, another possibility, that of total internal reflection (TIR), can also be used to produce precisely controlled beams. Total internal reflection may occur if light travels from a medium with a higher optical density to a medium with a lower optical density, i.e. from high to low refraction index. Glass and plastics have higher refraction index values than air. This means that at the boundary between the medium and air, refraction is away from the normal to the boundary layer, as shown in Fig. 18-left. The middle picture of Fig. 18 shows the situation where the light incidence angle is such that the refraction angle is 90° and thus parallel to the boundary surface. That in-

Table 4. Approximate Indication of Correlated Colour Temperatures (CCT) of Midsummer Daylight under Different Conditions

Shortly before sunrise	±4000 K
Shortly after sunset	±4000 K
Sunrise and sunset	±2000 K
Direct midsummer sunlight (midday)	5800 K
Overcast sky	(5500–6000) K
Shadow in clear sky (midday)	(7000–8000) K
Clear sky (midday)	(9000–30,000) K
Clear sky (midday)	(9000–30,000) K

cidence angle, corresponding to 90° refraction, is called the critical angle. It varies, depending on the type of plastic or glass, between approximately 30° and 40°. If light incidence is larger than this critical angle, light cannot leave the medium and is reflected with a very high reflection percentage (nearly 100 %) as shown in Fig. 18-right.

Total internal reflection with its extremely high reflectance is often used in combination with LEDs to produce efficient and precisely controlled beams in downlight and small floodlight type of luminaires. Often this TIR-optics is combined with a collimator lens. Fig. 19 shows an example of such a "hybrid" TIR-lens system. The TIR part controls the largest part of the light radiated from the LED chip, while the integrated collimator lens, located in the centre of the system, controls the light radiated from the chip into the central directions.

2.4. Connected Smart Lighting

Connected smart lighting refers to lighting installations in which the luminaires, with integrated sensors, are interconnected in a wired or wireless network to both control and monitor the lighting. Microcontrollers and many sensors, like light, occupancy, temperature, humidity and noise sensors, are small enough to be incorporated in a luminaire. In this way, the luminaire becomes both a source of light and information. Connected, smart lighting systems using such luminaires can be used for many more purposes than energy conservation alone. By collecting, for example, data on the actual use of a space and the movement of people, automated space management is possible while ensuring user satisfaction. The sensors used in the smart lighting network can be expanded with sensors that mea-

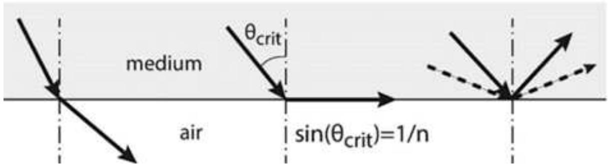

Fig. 18. Refraction and, for $\theta > \theta_{crit}$, total internal reflection (TIR)

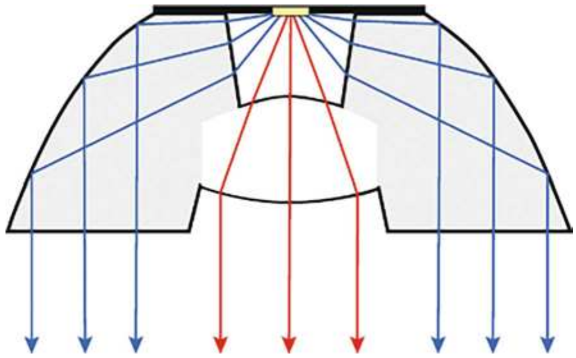

Fig. 19. Example of a rotation-symmetrical TIR lens solid body for an LED; blue rays are the result of TIR and red rays the result of the integrated collimator lens (indicated with a lighter tint)

sure parameters needed for other installations in the building such as temperature, humidity and air quality sensors. The smart lighting network so becomes the "heart" of a smart building.

Smart networks can use many different protocols for communication between all the connected devices. For wired networks, the 0–10 V DC, DALI, DMX 512 and DMX 512-RDM protocols, and for wireless networks, for example, the ZigBee, Bluetooth and Wi-Fi protocols. Fig. 20 shows an example of a ZigBee network.

Ethernet data communication cables can be used, simultaneously, for data communication and for supplying power to connected electric devices including LED luminaires: power over Ethernet (PoE). The latest standard of IEEE (2018) increases the maximum power to 90 W per connected device. This is possible because this standard allows for data over all four pairs of the ethernet wires. Since the power is DC and the data communication signals are of high frequency, there is no interference between the data and power signals over the same cables. Power of 90 W makes it possible to provide power for LED luminaires over ethernet in many smart lighting installations. The use of a separate mains power cable net is thus no longer needed. It reduces cable and installation costs considerably, makes the system more robust and simplifies maintenance and making changes.

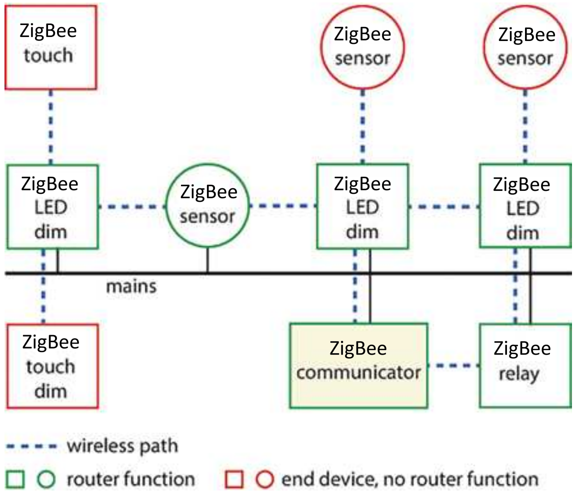

Fig. 20. ZigBee wireless network with a coordinator, devices with a router function to their neighbour devices embedded in smart lamps and sensors, and end devices without a router function

2.5. Light beyond Illumination

Light from LED luminaires can be used simultaneously for lighting a room and for wirelessly transferring data in that room. The term used for this emerging kind of wireless data transfer is "Visible Light Communication, VLC". For VLC purposes, the light is encoded and modulated without affecting the illumination quality. Of all light sources, only LEDs are suitable for visible light communication. This is because the luminous flux of LEDs varies nearly instantaneously with a variation of current through the LED. Only in this way, light can be modulated at high speed, i.e. the light "on" and light "off" condition can be produced at extremely high frequencies.

VLC can be extended into a bidirectional data communication system with a down- and uplink. It is referred to as Li-Fi. It is a much-needed alternative for, or a complement to, the congested Wi-Fi wireless communication system. Of course, it would be disturbing if for the uplink visible light is used. Disturbing light beams would be radiating from all connected devices in the room, such as PCs, laptops and smartphones. So, while with Li-Fi, the downlink indeed uses visible light, the uplink uses either invisible infrared radiation or Wi-Fi (Fig. 21).

The dual function of LEDs enables, apart from data communication, many new applications. Examples are the use of room lighting for indoor navigation and for sensing objects in a room. Using light as a sensor with only the light itself enables the determination of the contours of objects and even the pose and movements of persons (sitting, standing, laying, and walking). This information, in turn, can be used as input for all kinds of automated reactions.

3. APPLICATION

3.1. Lighting Quality and Standards

The quality of an interior lighting installation must be expressed by photometric values that influence visual performance, visual comfort and non-visual biological effects. The photometric parameters that can be used for specifying, designing and measuring the quality of interior lighting installations range from parameters for illuminance level and illuminance uniformity, wall and ceiling luminance, glare restriction, three-dimensional object and face recognition, modelling, colour appearance and colour rendering. However, international standards and recommendations prepared by recognised lighting standardisation bodies that specify lighting from the point of non-visual biological effects do not yet exist. CIE issued a standard that defines the spectral sensitivity function for the photosensitive retinal ganglion cells in terms of the melanopic irradiance [35]. In a 2019 position statement, CIE proposes to take the non-visual re-

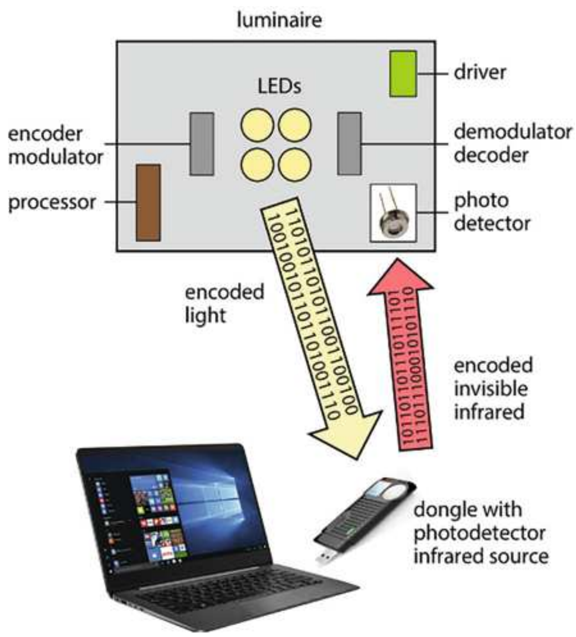

Fig. 21. Bidirectional Li-Fi data communication network with visible light downlink and invisible infrared uplink

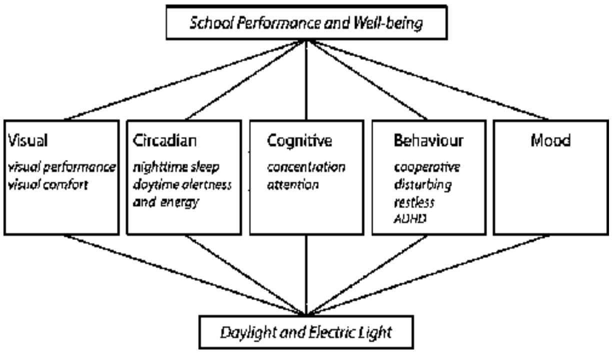

Fig. 22. The relations between lighting effects that together influence school performance and well-being of pupils and students, [66]

sponses to light into account by using the melanopic equivalent daylight (*D65*) illuminance, the melanopic EDI [65]. This unit is recommended to be used in future recommendations for non-visual biological effects.

3.2. Design Aspects

The lighting design process varies with the type of application and with the character of the designer. As far as the technical aspects of the lighting design process are concerned, five steps can be identified that are common to most lighting applications. They are listed, in the sequence of the design process, in Table 5.

With regard of the choice of the lighting system, the advantages of general lighting, localised lighting and their combinations have to be considered, just as the advantages of direct, indirect and combination of direct and indirect lighting. Dynamic lighting scenarios for office and industrial lighting that optimise performance, health and well-being have to be defined. For classroom lighting, dynamic automated lighting with the possibility for the teacher to put the lighting in a concentration or relaxation mode is a possibility. Fig. 22 shows a scheme that shows the relation of most of the beneficial lighting effects on the performance and well-being of the pupils.

For wardrooms and intensive care units in hospitals, lighting that provides a robust and regular circadian rhythm for the patients can result in potential advantages for their recovery. Dynamic lighting in nursing homes for the elderly can provide not only a robust circadian rhythm but also a therapeutic effect for many Alzheimer's patients with regard to their sleep-wake rhythm.

Table 5. The Five Phases of the Lighting Design Process

1. Analysis of the lighting functions
2. Determination of the relevant lighting quality parameters and their values
3. Choice of the lighting and control system
4. Choice of the lamp and luminaire types
5. Determination of the number and positions of the luminaires

Emergency lighting has to be designed to ensure the safety of users and visitors of a building when, in the case of a calamity, the normal lighting fails.

3.3. Calculations and Measurements

The lighting designer has to perform lighting calculations in order to arrive at solutions that satisfy the relevant lighting requirements. Universally applicable computer programs are available for this purpose. The lumen method of calculating the lighting level on the working plane is a simplified "calculation-by-hand" method. It provides inexperienced lighting designers with a tool to learn to understand, for different types of light distribution, the effect the room dimensions and reflectances have on the resulting average horizontal illuminance of the room.

The measurements carried out in connection with interior lighting fall into three categories: those to determine the lamp properties, the luminaire properties and the installation properties. The measurements of the first two categories are mostly carried out in laboratories. They concern the measurement of the luminous flux of lamps and luminaires, the light distribution and light-emitting area of luminaires and the spectral data of lamps.

Field measurements are carried out on new installations to check whether they fulfil the quality specifications, and on installations already longer in use to reveal whether there is a need for maintenance, modification or perhaps replacement. They concern illuminance, luminance and glare measurements. Light-logging devices are used to gather information about the light dose persons are receiving under different circumstances.

Today, with the availability of LEDs with widely different light colours, it is essential that the lighting professional can check the colour properties of light in the field. Fortunately, relatively low-cost

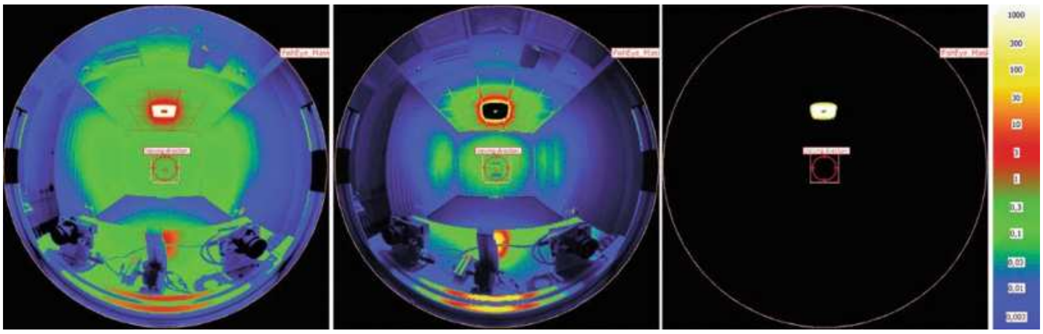

Fig. 23. Luminance mapping to measure UGR; left: map of the whole office; middle: map with the glare source eliminated to determine the background luminance; right: map with the isolated glare source to determine the glare source luminance and light-emitting area; red circles in the centre of the map: viewing direction (photograph: Christoph Schierz)

spectrophotometers, without moving parts (contrary to most laboratory devices), have become available. Most such meters have embedded software that calculates from the measured spectrum all kind of colour characteristics such as chromaticity coordinates x and y, position in any chromaticity diagram, CCT, R_a, R_f and R_g values. These values can be displayed together with the spectrum itself on the meter immediately after the measurement.

For the measurement of the detailed luminances of a lighted scene, luminance mapping technology is more and more used. This technology makes use of CCD cameras. The perspective image of the scene to be measured is projected on the CCD's pixel matrix. The signal of each pixel is proportional to the luminance of the corresponding scene element. Depending on the meter's position and orientation relative to the scene, the perspective image can be converted through complex mathematical calculation software into a plane, non-perspective, image in which each pixel represents a small, same-sized scene area. From a single measurement, the software subsequently calculates the average scene luminance and the luminance uniformities. Cameras with incorporated luminance mapping software are also referred to as imaging luminance measuring devices (ILMDs). Sometimes it is desired to measure glare on location. For this purpose, ILMDs devices can also be used. Fig. 23 shows an example for an office with one single Luminaire.

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LIGHT SIDE OF DESIGN: PROFESSIONAL VECTOR

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"The main enemy of knowledge is not ignorance, but the illusion of knowledge"
Stephen Hawking

ABSTRACT

This article addresses one of the most actively developing types of design activities – light design. The article comprises quotes of the leading Russian and foreign light design specialists published over the previous five years, as well as the authors' own conclusions. The thoughts quoted in the article are sometimes opposite to each other and reflect the wide spectrum of professional practice. They reflect the initial opinions of analysts and experts which are often diverging. All of the specialists point at the interdisciplinary nature of the new profession, which imposes additional load on a designer overloaded enough already by the scope and speed of the problems being solved nowadays. The discussion of the new profession of light designer initiated on the pages of professional publications is especially important in view of the development of professional standards and standards of design and architectural education, as well as creation of new educational programmes based on various approaches to the subject in technical and humanitarian institutions. The goal of this article is to introduce light design into the field of fully legitimate sections of design culture, to define the authentic scientific basis of the new creative profession, to initiate a foundation for self-determination of the new synthetic area, which materially affects the state of the profession as a whole and the life standards of a wide variety of consumers. In order to reach the set goal, a comparative and analytical method of study was selected, which allows studying the problem to a large extent and from all angles and finding the ways of overcoming the challenges emerging in the area of the new activity.

Keywords: light design, design culture, comfortable habitat, creative imagination, architectural illumination, illuminating forms, video mapping, light festival, light engineer, light designer, art devices of illumination, light architecture

1. INTRODUCTION

It is probably hard to find a design sphere, which has been developing with the same speed as the light design over the recent years, except the media design, which has been steadily developing by virtue of intensive advancement of technologies. That is why the goal of this article is to introduce light design into the field of fully legitimate sections of design culture, to define the authentic scientific basis of the new creative profession, to lay a foundation for emancipation of this new synthetic area which materially affects the state of the profession as a whole and the life standards of a wide variety of consumers. In order to reach the set goal, the comparative and analytical method of study is the most appropriate, as it allows studying the problem to a large extent and from all angles and finding the ways of overcoming the challenges emerging in the area of the new activity.

The rise of the new design profession is largely related to its multidisciplinary nature originating in engineering and technical, digital and design and cultural fields. The technical component has become the initiating force, which constantly fuels, transforms, advances and enriches the design and art sphere of light design occupying new areas, changing formats and developing art devices.

The God's phrase: *"Fiat Lux!"* ("Let there be light!") would always be an invisible component of any design action filling it with sacral mysticism. The ultimate priority faced by light designers places their idea in close quarters with the unparalleled act of the Lord. According to N.I. Shchepetkov: "appearing of light design and its development in industrially-developed countries is related to sufficiency of produced electrical energy, the progress of lighting devices and constant enhancement of life standards, among which visual comfort, informative value and art perfection of the created environment are playing an important role" [1].

Self-determination of the profession remains the most important problem of the industry. Experiencing certain responsibility for the fate of the new profession, D.N. Makarov notes: "…to define the border between functional illumination designed by a light engineer and light design remains a complex and diverging problem… Who is a light designer? Is this term based on deep engineering education with addition of architectural and/or design ones or vice versa?" [2].

The discussion determining the borders of the term "light design" involves also the objects created by means of light technologies, the works of "light art" and functional light design. If we go by different art and technological factors, the problem of search for the uniform determination of the profession seems to be almost infeasible. Determining light design, a number of authors emphasises the architectural genesis of the profession studying "…interaction of light with the environment and its impact on visual perception, emotions and health…" [3], categorising the new profession as "architectural illumination" and "light architecture". According to competent authorities (N.M. Gusev, V.G. Makarevich), "light architecture" considered as the dialogue between architecture and natural and artificial light [1] has been giving way to light design which is nowadays being supported by such participants of the dialogue as, in particular, N.I. Shchepetkov, the founder of contemporary Russian light urban studies. Besides, as a section of light design, light architecture becomes light-emitting, fundamentally differing from "daytime" architecture.

A number of specialists consider the architectural component of the profession the main one using such expressions as "light architecture", "architectural light engineering" and even "light science" [4]. Determining the new profession, A. Kovshova writes: "…a light designer is a mix of the professions of architect, light engineer and artist " [5]. Supplementing his colleagues, D.N. Makarov notes: "…it's a person who is able to paint with light but at the same time understands the nature of his/her "brushes" [2] and, at the same time, it's "a specialist who is in charge for design of a lighting installation for… the environment where people are present for a long period of time", who acts within the framework of an architectural project, in close contact with, and under supervision of an architect [2]. All of the above unites the description of the "contemporary view on matters of illumination" (A.G. Khadzhin [5]). The master of the light design N.I. Shchepetkov draws the line: "…to sum up, light design is just a visual component of architecture with artificial light… It has originated, exists and is developing in the fold of architecture,… a part of material and engineering structure of an architectural, engineering or landscape object. It is fundamentally wrong to set light design apart out of architecture" (N.I. Shchepetkov [6]).

2. FACTOR MODEL OF THE PROFESSION

Nowadays, the planet of artificial illumination is based on three pillars, the three main basic aspects of light design: aesthetic perception, ergonomic component, i.e. functionality of illumination, and energy efficiency [7]. The light design is recognised as the interdisciplinary specialty requiring fundamental knowledge of engineering, architecture, history, design and culture (V.P. Budak [5]). "Nowadays, light design has been becoming the most important element of visual culture integrating artistic expression and compositional vehicles, functionality aesthetics, which design objects are distinctive for, as well as the newest scientific and technical advances in optics and engineering", justifiably states N.V. Bystryantseva [8].

The authors consider the project component of "architectural lighting" or "light design" proposed by Ju.B. Aizenberg, as the most appropriate basic definition. It is the intersection of science (light engineering), visual arts, engineering work and architecture; "a designer is not an artist at all; *design* means drafting, fabrication, and *lighting design* means lighting decoration[1]" (Ju.B. Aizenberg [6]). "Light design is designing of light or is designing by means of light," where the bivalence is expressed in priority of sometimes aesthetic component and sometimes of functional component of light design [9].

Still the profession of light designer is not able to find necessary stability. Over the first two decades of the new century, still without complete self-determination, it was forked at different directions aiming at occupying new spheres. The priority of design approach to variable format of light design has helped the authors to express its most important vectors of development.

The variability of **design strategies in light design** is directly related to dramatic change of the light paradigm itself in design culture. That is where the problems of light environment organisation the scientific and practical community faces derive from. The light is used as a tool to form and space modelling in visual arts, architecture and design at the level of experimental and practicable designing. The precise order of the light design process is a methodological support here: from "light plastics", "light form" and "light area" (N.I. Shchepetkov), to the concept of designing of an urban light panorama as a large-scale light and silhouette component (V.E. Karpenko).

The contemporary potential of light technologies assisting in appearing of new methods of work with "light-bearing matter" is based on a wide range of materialised innovations. Primarily, these are the products based on energy-saving technologies (luminaires with LEDs). However, the process of light design development in Russia in the area of energy-saving technologies was distinctive for "extremely low price of electric power, which created favourable background for inefficient solutions based on incandescent lamps, halogen and fluorescent lamps with primitive luminaires…" [10], unlike the European countries and the USA where, thanks to expensiveness of power and extreme level of competition, the energy-saving programmes with LED lighting, being appropriate to a large extent, have spread. Since 2011, the projects based on organic LEDs have started appearing, namely the technologies of shadow-less light sources (in particular, displays made of organic carbon molecules), which are much cheaper in production than LEDs, and these light sources themselves provide a full scope to designing imagination [11].

Minimisation and energy saving have formed a section of a fashionable and innovative industry. "Integration of technological innovations, including light design, with the morphology of modern costume, use of retro-reflective fabrics, LEDs and other technological methods assisted in enhancement of aesthetic and ergonomic features of costume: refreshing the thesis of the post-industrial society *"the form follows the emotion"* as well as just ergonomic reasons related to higher visibility of an illuminated costume during night time." [12]

3. LIGHT ART SHOWS

The festivals and competitions are becoming the media for the newest trends of the profession. The most integrated picture of the newest design trends in the sphere of light design is provided by conventional contest programmes such as Russian Light Design and a number of other projects. The scientific and creative subject of the Light Architecture festival and contest organised by the Moscow Union of Architects with support of the Government of Moscow and the Architectural and Town-Planning Committee of Moscow in 2015 as part of the International Year of Light and Light-based Technologies was architectural lighting and interaction of light and architecture on the basis of contemporary light engineering solutions. It is LED technologies that the most of the noted contemporary professional trends in the sphere of form making derived from as they provided portability (minimalism of a LED module) and flexibility of structures capable to change form and assisted in invention of a brand new light source with corresponding potential of decorative lighting (priority of lighting element, the "form" of light).

According to the experts of the competition, the potential of light as an object and subject of design included a number of parameters:

– Environmental friendliness;

– Integration of light into different surfaces of design and architectural objects;

[1] As it is noted below, *lighting design* is primarily understood as illumination design. – Ed. Note.

– Perception of light as a material: the newly designed construction and finishing materials are already the sources of light;

– Adjustment of luminous flux and chromaticity of radiation, temperature settings, light spectrum and intensity dynamics, control of emotions;

– Capability to control light devices using scripts and different technical units including remotely-operating ones [13].

4. CONCEPTUAL APPROACH TO LIGHT DESIGN

Light design approaches have been increasingly basing upon the concepts, which blaze a trail towards new solutions. Gradual complication of the goals of light environment design has required a more convincing elaboration of both art and content-related components of any object. Over the last five years, the requirements to projects have significantly risen in the international market: now customers are attracted by "comprehensiveness" of solutions. "Now it is not sufficient just to create a design of illumination, now it is necessary to work out its integration into urban environment as well as the scenario of the area being created" [14]. The era of light scenarios witnesses emancipation of the profession, indicates transition to captivating, theatrical lighting projects.

Interest in scenarios marks the transition from "sense-based architectural lighting (light design) to entertaining commercial and advertising light design" [6]. Visual environment of events acted as a catalyst for development of one of the areas of light design related to show business, museum and exhibition spaces, city festivals, etc. Multimedia developments of light scenarios of the era of digital technologies still remain an experimental area of work with light as a form, actively creating new forms of light presentations. This includes video mapping based on 2*D* and 3*D* projections (architectural structures, natural objects, water fog, waterfalls, etc. act as a screen), laser installations, holographic sculptures, art objects based on light and colour dynamics, etc. Light becomes a part of a director's game with a spectator, means of communication and orientation. A convenient scenario may be selected for each form of leisure. At the same time, scenarios are appropriate anywhere, even in the bathroom… [15]

5. DIGITALISATION OF LIGHT DESIGN

Scenarios added dynamics to perception of originally static "light architecture". The pursuit of form-creating potential of light on a kinetic basis in art practice which had been initiated by designers of the avant-garde era had been continuing during the whole 20th century and transformed into experiments with light based on the newest digital methods. A wide range of light media objects finds real contours in the creative dialogue between the engineering, directing and art components dynamically actualising technical innovations of media and light industry. This shining planet may be identified by the term "intelligent light".

Enhancement of software creates opportunities for creation of interactive objects where a human is integrated into a dialogue with a "smart" light source. Here are some examples. The *iBar* technology is an intelligent surface of a bar counter with an integrated video projector, intelligent object-tracking system for dynamic interaction with movements on the counter, illuminated or virtual sensor objects, etc. The *Light ID* intelligent light technology by *Panasonic,* which allows information reading from any object illuminated by a LED light source, was used in The Pushkin State Museum of Fine Arts in Moscow. The mobile application designed for this purpose includes a multilingual database of exhibits.

The Smart City project opens large opportunities for enhancement of the intelligent light. "In the standard of a smart city developed by the Ministry of Construction of Russia in October, 2018, the criteria of "smart" cities include modernisation of street and indoor lighting; at technological level, a city is made smart by means of a complex multi-level system… The first and the largest Russian product developed with fully-featured application of digital content of smart city technologies was the Light City project (Ivanovo)" [16]. The innovative technologies of light design with computerised illumination system were applied to famous architectural objects of Rostov-on-Don.

Development of interactive, multimedia light models and selection of a smart design solution requires development of a new and more perfect **software and technological support** (IT and multimedia technologies). In his comment to the design specification for the best concept of exterior facade of the General Staff Building on the Palace

Square in Saint Petersburg, V.P. Budak notes that the *DIALux* software as a project modelling tool should be replaced by *Lightscape* and similar software [17].

Despite the importance of the engineering and technical component of the profession, according to the Dutch light designer Rogier van der Heide, creative impulse retains its priority: "You have to discover new methods of lighting, to understand optical properties of the Sun and artificial light sources to find new solutions. Also, never reject good ideas if you think there are no appropriate technologies for them. These technologies, sometimes, just need to be searched… " [14].

6. LIGHT DESIGN AS ART

Recognition of light as a tool for artistic from-making takes light design to the level of genuine art. According to G. Nelson: "…when it comes to creation of a work of art, *technical enhancements*, whether they are related to the process of processing or to materials, *absolutely don't affect the final goal…*" [5]. Technological breakthrough in light design has allowed us to create new genres in the multimedia format. Video mapping is a genre of audiovisual art which uses visual illusions projected onto different surfaces. The *LUX AETERNA* Light Theatre (established in 1982) functions on the basis of unique light technologies and creates a light and music show comparable with limitless outer space by means of a light brush and lasers in total absence of actors. The director Daniil Fridman based his light and music visions addressing sensory perception of spectators on the idea of composer Alexander Skryabin on colour perception of music.

Experimental searches of light designers related to technical know-how are based on emotional nature of light visions, which allows viewers to recognise them as related to the sphere of artistic creativity. In the A. Walter's theory, "emotional design" (similar to the Maslow's hierarchy of needs) occupies its lawful "superstructural" position: "the product shall become functional, reliable and convenient before it is able to give pleasure" [18]. According to the Russian light designer S. Sizy's interpretation of the emotional design theory, any light environment is created not only to implement the necessary functions but also with consideration of perception experience of users, their emotions and the mood appropriate in the given context [19]. The emotional and artistic aspect opens a wide field for original versions of light design.

In 2017, in his lecture "Concrete, Steel, Light and Emotions", light designer D. Skira (the founder of the *Skira* studio) claimed that "customers are attracted by comprehensiveness of solutions, today it is not enough just to create a project of illumination, it is necessary to work out how it is integrated in the urban environment as well as the scenario of the space being created" [14]. The emotional setting of illumination becomes a part of comprehensive light design solutions at the same level with functional requirements of work processes acting as a motivating factor.

The original version of stylisations in light design is closely related with the concept of emotional design. The methods of form-making in design of luminaires of the *Radio Lamp* collection are based on constructivism approaches, transformation of the shape of the Shukhov tower in Moscow. Designer O. Podolskaya creates luminaires using stylistic reminiscences of the spires of Stalin's skyscrapers. Stylizations of visions of nature supported by high technological level open the "bionic direction" of light design "providing creation of complex bionic forms" [13].

The enhancement of social status of light design, increase of its role in arrangement of public interior and urbane spaces, turn a designer into a subject of the new cultural tradition. Creative space of light design becomes an area for solving of current problems of modern society.

Urban holiday environment is one of the examples of use of different light scenarios**.** New Year's performances of the recent years provided examples of art objects representing Christmas trees, Christmas fairs, examples of New Year illuminations of outstanding architectural and engineering objects (e.g. the Eiffel Tower), illumination of ice figures. In Moscow, the Christmas Light annual festival has become a tradition. Big cities, such as Moscow, St. Petersburg, Ekaterinburg, develop special programmes for creation of architectural illumination under the "Light City" slogan.

Creation of new behaviour scenarios introduced into the urban culture promotes active lifestyle. Popular online magazine *4living* provides an example of Sweden where a programmed interactive light installation has solved several tasks at once: illumination of a dark district eliminated the problem of attacks on cyclists and creation of a light dominant element helped hooligans become admirers of street art, and popularity of evening running and cycling of urban citizens has increased at the same time. Interactive elements of a costume form new culture sets: additional functions stimulate an active life because activation of built-in gadgets often directly depends on physical and social activity of their owner. "Being an irreplaceable tool of artistic expression in… spatial, temporal, and spatial-temporal arts, light is a potential medium for a number of such properties, as… picturesque, architectonics, graphics, scenarios, etc. Therewith, it may be considered as a cultural phenomenon in which the dialectical conflict between design as understanding/constructing of objective and social world surrounding human and "high" art as artistic and visual understanding/exploration of reality has been manifesting itself to the fullest extent" [9].

The phenomenon of light filled with social-cultural senses was reflected in the proceedings of the conference "Light Design 2015. Light Culture". The agenda was opened by the speech of N.I. Shchepetkov (MArhI (GA)) who indicated the recurrent theme of the conference: "Light design and light culture" [20]. Light design has found its place in the informational and cultural space of the Internet. Based on the *LightOnline.ru* project of 2004, in 2009, the portal *http://lightonline.ru/svet* appeared, which is represented by a team of professional light engineers who have many years of experience in the Russian light engineering market.

7. LIGHT DESIGN AND LIGHT ENGINEERING: DIALECTICS OF INTERCONNECTION

Since the first decades of the 20th century, light design has acquired a stable theoretical basis in light engineering. However, the scientific ambitions of the profession have turned out to be much wider over time. The scientific component of the profession developed gradually filling with knowledge of allied disciplines such as architecture, art history, etc.

Part of the authors is depriving the design and artistic components of the profession of scientific basis. "The utility nature of light design is the share of science whereas the artistic one is the grand purpose of the new art" [21]. Some authors unite the terms "light designer" and "light engineering" saying that "the former implies transition to the international light engineering language and the latter implies transition to the regional one" [2]. In Dr. Aizenberg view "You have to discover new methods of lighting, to understand optical properties of the Sun and artificial light sources to find new solutions. Also, never reject good ideas if you think there are no appropriate technologies for them. These technologies just need to be searched…" [14].

Ju.B. Aizenberg: "…the considered field of activities is by no means based on any scientific foundation apart from the laws the "light engineering" is based on, so it cannot be called a scientific discipline. …architectural lighting ("light design") stands at the interface of two interesting and important sciences: light science and architecture…" [6]). Priority of architectural scientific basis for light design is confirmed by definition of "light design… as its new section… a light designer should know the basics of light engineering and architecture. Light engineering studies not only the physical laws of optical radiation but also psycho-physiologic basics of visual perception of light by human. And almost the whole assessment base of architecture as expressive art rests on visual assessments impossible without light in its theory and practice. Light design hits the "bull's eye" of the synthesis of these scientific disciplines and their practical application…" [21].

The era of digital design has supplemented light design with new theoretical achievements of computer modelling. This opens prospects of studies not only in the sphere of technical aesthetics but in the allied sphere of physiology of vision, new energy-saving technologies, etc. It becomes necessary to establish an integrated infrastructure of the theoretical base of the discipline, namely "…technical committees, conferences, professional communities and research facilities which provided the authorities and business with information for making correct, scientifically and technically grounded decisions…" [10].

Apart from fundamental studies, annual international scientific and practical conferences "Light Design" (2014–2015) have become a part of such infrastructure. The topical issues proposed by the conferences for discussion include, among others: colour theory; light and art; light design and science; unlocking interdisciplinary potential of light design; consideration of the practice and prospects of interaction between scientific, artistic and technical components of art design.

The capabilities of the Internet become prospective for scientific discussions erasing the geographical boundaries and other barriers. The first international light design online conference "Light Ideas 2016" has gathered the best of Russian and foreign specialists on one online site.

The professional discussion of the design and theoretical situation in the contemporary light design sphere published in the Svetotekhnika Journal in 2018 has indicated the most acute problems noted by the professional community. And the question of the artistic strategy of light design, namely its criteria, design principles, level of the dialogue with technical and technological parameters etc. appeared to be the theme line of all of the expressed positions.

"Light design definitely may become a self-consistent creative specialty… The only problem is that the scientific and theoretical basis of this activity lags significantly" [1]. The non-stable situation in the scientific framework witnessed by confusion of basic terminology confirms non-availability of the unified system of assessment criteria of light design objects not only in objective light engineering terms (they already exist) but also in artistic and aesthetic terms. "The light, which is the fourth dimension of architecture, is much more complex than just illuminance calculated in accordance with rules and standards" [2]. The latest studies in the sphere of Technical Aesthetics and Design discipline related to light design theory are still just at the stage of gaining scientific potential. In Russia, there is still no specialist who has advanced more in the areas of light aesthetics and understanding of psychological and physiological effects of light than A.B. Matveev[2] and G.V. Kamenskaya[3]. The questions raised by these authors still have no answers. Moreover, they are accumulating given the "deficiency of the up-to-date scientific grounds" [5].

8. TRAINING OF SPECIALISTS

Any profession starts with education. The experience of Western light design schools accounts for several tens of generations of light designers. The experience of the Russian educational school, including higher school, accounts for just a couple of decades of active pursuit. Nevertheless, some methodological experience is already accumulated. First of all, a portrait of a specialist solves the issue of interactions between art, science and technologies with consideration of multi-level nature of light design. No matter whether the question is forming of the language of the profession of light designer or the training programme of a future specialist, in any case, recognition of their multidisciplinary structure is unquestionable. "The combination of elements of science and art" [Smirnov, 6], "the dialogue of visualisation, implementation of a lighting project and a set of mathematical data, quantity characteristics curves" [2], "integrative" nature where interdisciplinary and comprehensive approach combines the methods of both logical and intuitive analysis [Bystryantseva, 5].

Training of light design specialists became a part of scientific discussion in the agendas of the First All-Russian Scientific and Practical Conference Light Design 2014 and the International Scientific and Practical Conference Light Design 2015. The participants confirmed the scientific, artistic and technical components of educational methodology. Special attention was paid to development of experimental methods of education. Each school, with its own traditions and experience, has demonstrated its own "shade" and stressed a special edge of light culture. They included MArhI (GA), NIU MEI, Higher School of Light Design of the ITMO University, A.L. von Stieglitz SPbGHPA, IDI SBGUTD, SBbGUKiT, etc. Considering the prospect of education in MArhI, Professor N.I. Shchepetkov

[2] **Alexander B. Matveev (2.01.1926–22.01.2008)** – Doctor of Technical Sciences, Full Member of the Russian Academy of Electrical Engineering, Professor of the light engineering sub-department of NIU MEI. His work "On Theoretical and Experimental Studies of Metrics of Colour and Light Environment in Light Engineering" is still a gold-mine of new ideas and directions of studies in light engineering.

[3] **Galina V. Kamenskaya (5.10.1934–9.01.2018)** – Candidate of Technical Sciences. The head of the electric lighting laboratory in CNIIEP of Engineering Equipment of Residential and Public Buildings. Developer of lighting equipment in the sphere of theatrical illumination with the Experimental Stage Laboratory of the Moscow Academic Art Theatre. The author of the unique installation for surface modelling of street and architectural illumination and the methodology of design of architectural lighting. The results of her experimental studies of street and architectural lighting have been introduced in regulatory documents and instructions on designing of electric equipment of public buildings and were taken as a basis for standardisation of outdoor architectural lighting.

sees "the architectural and artistic training as the top priority and light engineering training as allied but still fundamental field based on computer-aided design technologies" [Shchepetkov, 6]. The new approach of the light engineering department of NIU MEI offers the method of lighting installations design training by means of computer graphics software forming aesthetic background of a designer [22]. Thus the educational institutions introduce the humanitarian component common to architecture and design into the new discipline of light design.

The strategy of the Higher School of Light Design of the ITMO University (headed by N.V. Bystryantseva) is an example of methodology of comprehensive professional training of professionals aiming at solving of problem-based tasks (*Problem Based Learning*). This implies participation of different specialists such as marketers, architects, cultural scientists, artists, designers, urbanists, IT specialists, experts in the fields of healthcare, robotics and contemporary engineering in the education process [Bystryantseva [5].

The promising trends are introduced in methodology of light design schools which turned out to be more adapted for rapid change of priorities in the profession. The example of the first Russian light design school *LiDS* led by S. Sizy provides experience of a unified universal methodology in designing of light and spatial environment based on sensory perception, with consideration of recipient's emotions and mood. This methodology is based on S. Sizy's emotional design theory, which practically develops and provides theoretical justification of N.M. Gusev's ideas on light formation of interior with consideration of our natural associations [2].

The school is based on an experimental programme with its theoretical basis included in the mandatory part of education. The Lighting Psychology course experimenting with colour light in human perception allows us to use this device in projects. There are also experimental courses including allied areas of light design: Light Therapy and Biological Effect of Light on Human (author: Doctor of Medical Sciences K. Danilenko). Some of the projects are without parallel: the Sketch for Designers course, the package of applied software *LightCAD* developed by *intiLED* [23].

The experience of the *LiDS* school marked with close relations between the educational methodology and international trends, reinterpretation of the world's experience of light design learning in the USA, England and Germany, introduction of travelling courses in different European cities, is undoubtedly a positive example. The new education forms adopted by the School such as webinars, duplicating of workshops in the form of online courses, the video library of light design presentations simplifies acquiring of information irrespective of a student's location.

More specific matters of professional education methods are considered at the level of different workshops not aiming to become a field of serious studies. The *Artplay* centre trains to use light not only as a functional tool but also as a tool for controlling of own emotions [24].

The educational matters find solutions within the framework of the new (for Russia) format of interdisciplinary platforms. The PROJECT LIGHT special project (supervised by E. Lobatskaya) focuses on the theory and practice of light design. Apart from exhibitions, discussions, workshops and a periodic publication, it includes educational programmes. The main target of the platform is assistance in establishment of the Russian light design school and professionalization of the light solutions market.

As a result, creation of the methodology of profile education includes works in the three main directions:

– The theory of light design (according to N.V. Bystryantseva [5], not a single textbook had been published since 2006);

– Transfer of the educational process to the interdisciplinary basis;

– Development of cooperation between leading Russian (and international in the future) higher education institutions in the area of educational programmes, research and project activities, advanced training programmes. A contemporary specialist should possess knowledge and skills in "comprehensive light design" [20].

Competitiveness of the trained professionals is witnessed by their participation in serious international scientific and research works such as participation of the Higher School of Light Design of ITMO University in the *Strategic Partnership* project on an interdisciplinary (combining photonics, IT, light design, architecture and environment design) topic *LIGHT FOR HEALTH*.

9. CONCLUSION

The strategy of development of light design as a profession in Russia may be defined primarily through establishment of the Russian light design school as a priority area of activities. Its components become both basic principles and distinctive features allowing this organism to exist and develop. The school becomes an open system sensitive to rapid changes of the profession, with its parameters of “creative laboratory” where ideas are generated as a product of science, art and engineering; the integrative nature of light design implies creation of new grounds for joint development and mutual enrichment of technical and artistic potentials laying a foundation for culture of the 21st century [8]. The school is ready to unite all innovative trends of the developing profession. The unified basis of the school will promote unification of still separated endeavours thus enhancing the results of each of them.

Comprehensiveness of the approach and interdisciplinary prospects of development of light design are starting to take shape beyond the framework of aesthetics of architectural environment. Development of the profession should take into account the multi-level nature of light design (scientific, artistic and aesthetic, technological, social-cultural, environmental and other aspects). The new format of light design using psychophysical characteristics of colour (colour therapy) is treatment by means of energy of colour luminous flux. The emotional aspect of colour therapy is used for solving of physiological problems, such as healthy sleep, psychological relief, etc. Supposedly, introduction of colour therapy as a separate discipline may help challenged children and adults [25]. The discoveries of light psychology are becoming a property of design practice with consideration of functions of the environment: “…attention may be drawn by means of contrast and intensive light; warm light creates cosiness in a flat and cold light stimulates activity and is more appropriate in an office” [15]. New hybrid professional structures capable to become self consistent spheres of activity appear on the periphery of the profession. “…We consider that the Light Ecology will be developing in the two areas: environment affecting human and human as a centre of arrangement of environment” [Bystryantseva, 5]. Growing of an interdisciplinary structure should be stabilised by scientifically justified assessment criteria of the product being created, be it an embodied project, service, etc.

As an open system, the school of light design becomes a space for free professional discussions. The discussions in the formats of conferences, publications in media, roundtables, etc. will be a guarantee of maximum objectiveness in selection of assessment criteria for light designer activities and self-identification of the profession: its ideology, philosophy and aesthetics, design and educational methodology.

For legal establishment of light design [6], concrete and real tactical steps are necessary, and establishment of a light engineering association may act as such step. Considered as the area of social activity of the light engineering school, this association may be a non-profit professional community, “the union of Russian light designers” similar to the “union of designers” marked with corporate independence, helpful cooperation of the leading ventures of the industry, corporate and personal membership, interaction with state structures [10], with mandatory formulation of “the membership criteria” of such organisation [2]. Establishment of such association will promote “official registration of the profession” leading to the following necessary stage, “introduction of the system of assessment of specialisation and qualification of practising light designers… by the professional community” [Prikhodko,5]. This step of professional self-identification of a light designer within the framework of the school involves formulation of competences which still require clarification, also serious elaboration of the professional standard will be necessary [21].

With all importance of the above mentioned criteria, light design should remain art. The key feature of any practising specialist including light designers is creative imagination. Without this key component, any technical, economical and business skills will not allow us to create an original and attractive design work, including in the area of light design. Each talented designer creates an own model of the profession and this is the guarantee of uniqueness and diversity of the appearing design and artistic solutions according to view of Yu.V. Nazarov [5]. According to the founder of the urban light architecture Professor N.I. Shchepetkov, modern light designers are still “swift learners”, birds “with one wing” who came to this profession from architecture, light engineering, allied specialties, the areas which still remain priorities in terms of the obtained fundamental education. To correct this situation, the future of the Russian light design should be given to real professionals.

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CONCERNING THE CONCEPT OF LIGHT-COLOUR ARRANGEMENT OF THE URBAN ENVIRONMENT IN THE CENTRAL PART OF TYUMEN

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ABSTRACT

The article provides a comprehensive analysis of outdoor lighting in the central part of Tyumen (with consideration of conducted field observations) and prospects of its development on the basis of the general plan of illumination of the central part of the city being under design. Main provisions of this general plan as well as methodological principles and assessment criteria of design solutions illustrated by photographs, schemes and visualisations of the illuminated objects are described.

Keywords: light-colour arrangement of the urban environment, light design, general plan of illumination, light “framework” and “fabric” of the light arrangement structure of the city

Tyumen is the administrative centre of a large region in Western Siberia, one of the cities rich in historical and architectural heritage, culture and landscape. The ancient centre of Tyumen, the first Russian city in Siberia founded in 1586 upon the confluence of two rivers Tura and Tyumenka [1], is marked with a square (where the Lenin and the Republic streets cross) with a monument to founders of the city. In 1601, the first Trans-Urals post coach station was built in the city, and in 1843, the first steamship in Siberia was heaved off. In 1941–1945, the sarcophagus with the body of V.I. Lenin was kept in Tyumen. Since 1953, it is the oil and gas industry capital of Siberia. By the end of the 18th century, about 3 thousand people resided in Tyumen [2] and nowadays the population of this rapidly growing city numbers 770 thousand people. It was established as a trading centre crossed by numerous trading routes. Its contemporary development is performed both in free peripheral territories and by infill development of established low-rise districts, often with associated problems of historical and architectural heritage preservation.

It is the only capital of a constituent entity of the Russian Federation where the governor liquidated the position of chief architect of the city, however in 2017, Tyumen was the first in the contest of Russian cities in nomination of the Best Russian City for Residence.

There are several universities in the city including the Federal Tyumen Industrial University (TIU) formed in 2016 by merging the Architecture and Construction University (TyumGASU) and Tyumen State Oil and Gas University (TGNGU). In 2012, the Architecture and Design Institute (ARHID) was founded, it united two sub-departments of TyumGASU: Architecture and Architectural Environment Design. As part of its educational, research and international activities, it implements a number of projects aiming at development of architectural environment and preservation of the historical and cultural heritage of the city and the region; since 2003, it also holds the Zolotaya ArkhIdeya International Youth Architectural and Art Festival which includes creative contests for children and young

Fig. 1. Scheme of compliance of the illuminance level of the Lenin st. with norms of SP 52.13330.2016 based on the report of instrumental observation of priority objects of urban environment (August 2017)

people and scientific conferences. The student projects of ARHID take high prize place in international architecture and design contests every year. Many of its graduates successfully work not only in Tyumen but also in other regions of Russia and abroad.

Since 2016, ARHID (being a part of TIU) has been developing the strategic concept project "Architectural Image of the Region" which aims at forming of an innovative, comfortable and investment-attractive image of the region located in harsh Siberian climatic conditions, increase of the role of architecture as an integral and distinguished part of its history and culture, adaptation of the historically established environment for contemporary reality with preservation of valuable heritage. One of the sections of the project is "Development of the Colour and Light Image of the Region and Central Part of Tyumen", and its light design, colouristic and land improvement aspects are being developed in cooperation with MARHI (SA). The list of the studied towns includes also Tobolsk, Salekhard, and Yalutorovsk.

As part of the project, comprehensive pre-design study was performed, priority territories and objects were defined, and their hierarchy and problems were identified. The "tourist" streets where visitors start sightseeing were selected in the first instance. The roads from the airport, the bus station and the railroad station intersect in the central part of the city and coincide with its historical development structure. They include the Lenin st. (Spasskaya before the October Revolution) which crosses a number of public areas and links Yamskaya st. (leading to the Roshchino International Airport) with Pervomayskaya st. (leading to the Privokzalnaya square). The street (with length of 2.5 km and remaining sites of architectural, historical and cultural heritage) is the main ensemble of the city. Previously there were the temples of four religious denominations in it, namely the Archangel Michael and Spasskaya churches, the St. Josef Roman Catholic temple, Muslim mosque and a synagogue, some of them are lost.

The main goal of the Light Design section of the project is "development of the concept and methodology of light and colour arrangement of the urban environment with consideration of regional distinctions and with efficient use of energy-saving technologies with comprehensive solving of design problems of outdoor illumination and architectural colouristic."

In 2017, with participation of educators and students of TIU, visual and instrumental field observations with photographing of daytime and night-time situations and measurement of existing light engineering parameters of illumination were performed in pedestrian areas of the central part of Tyumen (Fig. 1) and on facades of architectural objects located in guest streets, squares and parks of the historical centre. The obtained picture was rather variegated and contrast: the measured levels of horizontal illuminance E_h and non-uniformity of its distribution over surfaces of pavements, lanes and alleys were lower than the standard values in some areas (twice as little) or, less frequently, exceeded them (fivefold), just as the values of luminance of illuminated facades of selected buildings and structures did (Fig. 2).

On the basis of the observations, the analysis of the state of light environment in the centre of Tyumen and the quality of architectural illumination of outstanding objects was performed, and common disadvantages of the existing light environment were found: in particular, non-uniform, insufficient or excessive illumination distorting facade plastics, dazzling pedestrians, etc. [3] At the same time, the

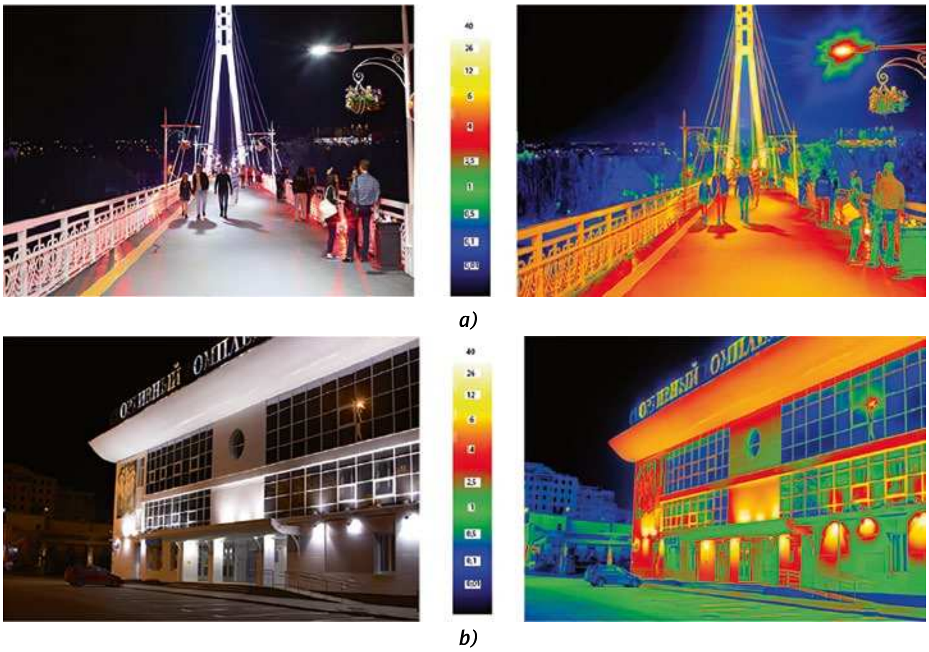

Fig. 2. Night-time photographs of the illuminated objects with facade luminance distribution presented in pseudo-colours: *a* – dynamic illumination of the pedestrian cable Bridge of Lovers across the river Tura at the intersection of Lenin st. and Republic st.; *b* – main facade of the Central Sports Complex

domination of yellow light of high-pressure sodium lamps (HPSL) traditional for many cities (not only Russian ones) still remains in outdoor lighting including pedestrian areas. Lighting devices (LD) with discharge and LED sources of white light are still of low proportion (which is rising year by year but without visible system of sequence and priority). Outdoor lighting installations (LI) are mostly characterised by archaic aerial power lines, primitive design (with some exceptions) of light post luminaires including retro luminaires with inefficient LDC.

There are hundreds of buildings and structures equipped with facade architectural lighting (AL) installations and electrical advertising of different quality in the city ranging from classic Soviet monumental palaces of the Government of Tyumen region (Fig. 3, *a*) and Regional Duma (Fig. 3, *b*) with "modest" and not tectonic enough local and spotty lighting to small private objects equipped with rope light. In short, virtually the whole range of light engineering methods and light-and-composition techniques is used which is not always appropriate for historical buildings in terms of art (Fig. 4, *a* and *b*) but creates rather decorative "pointillistic" effect on modern glass facades (Fig. 4, *c*) or symbolic coloured image of buildings (Fig. 4, *d*).

Singleness and variety of urban AL objects which are in a varying degree typical for all Russian cities and towns including Moscow do not allow us to say that there are harmonious urban light ensembles formed in Tyumen which are of significance for the city and the region. For example: colour and dynamic lighting of the pedestrian ca-

Fig. 3. Architectural lighting of the main facade of the building of the Tyumen region government at Lenin square (*a*) and the building of Tyumen regional Duma (*b*)

Fig. 4. House of G.T. Molodykh (*a*) and House of M.A. Bryukhanov (*b*) are the examples of stone buildings of the second half of the 19th century – early 20th century with commercial premises on the first floor (Pervomayskaya st.) illuminated by advertising lighting alien to the nature of historical architecture; Tyumen Infection Pathology Research Institute (*c*); Sberbank building in green light (*d*)

ble bridge across the Tura river is well-perceived at a distance but not nearby where the glare effect caused by non-accurate installation and aiming of LD are obvious; varying chromaticity of the facade lighting of TyumGASU (building of TIU (Tyumen Industrial University) – ex-Kolokolnikov college) does not fully comply with the status of neoclassical building of early 20th century (Fig. 5). However, existing AL of a number of objects deserves appreciation, for instance: traditionally floodlighting white AL of Krestovozdvizhenskaya and Spasskaya churches (Fig. 6); combined light AL of the Drama Theatre (Fig. 7, *a*) and colour lighting of Orion shopping centre (Fig. 7, *b*). However, unfortunately, the main historical and architectural dominants of the central part of the city, the Svyato-Troitsky monastery and Voznesensko-Georgievskaya church, are still not illuminated.

The functioning mode of LI of some of the above listed objects is unpredictable (sometimes they work, sometimes not), adjustment number of operating LDs, and chromaticity of LSs in a united group of LDs are unbalanced. These are defects of work of operation services which to a certain extent are peculiar not only to the Russian practice of urban light design.

On the basis of the materials of field observations and contemporary light design ideas and methodology, the concept of the general plan of illumination of the central part of Tyumen is being developed[1]; it can serve as a strategic systematising and regulating document for the existing and prospective reconstruction of the outdoor illumination of the city as part of the general land improvement works. It solves three groups of interrelated and the most significant urban light problems: light-planning, light-spatial and visual-artistic ones [4]. The light-planning problems of light-and-colour zoning of the territory are based on the classification of the general plan elements (per A.E. Gutnov) as "urbanised" areas (transport and pedestrian streets and squares), "natural" areas (woodlands and watercourses), "structure" and inter-route "fabric" (residential areas). Creation of differences in levels and chromaticity of illumination of "structure" and "fabric" elements visible during night time with consideration of their town-planning hierarchy is the main tool for solving of this problem, mostly by means of utility outdoor illumination with different scale and design in transport and pedestrian areas providing the required level and quality of lighting. And while the quantitative characteristics (luminance

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a)

b)

Fig. 5. Dynamic colour lighting of the Bridge of Lovers (*a*) and the historical building of TyumGASU TIU (*b*)

and illuminance of road surface, semi-cylindrical illuminance in some pedestrian areas) and their distribution are regulated by standards, selection of chromaticity of illumination in different areas is an issue of concern due to introduction of LED-based LDs and expected end of operation of HPSL in the city, which, to some extent, leads to loss of one of the tools of light-and-colour zoning of urban space. The concept specifies stage-by-stage replacement of yellow light of HPSL-based LDs in outdoor illumination with white light of LED-based LDs with different T_{cp} in different areas (white light is used primarily in central "guest" streets and squares).

For solving of the problem of light and spatial arrangement of the urban environment, all three groups of LIs are forecast: utility, architectural and informational lighting. Special attention is paid to lighting of pedestrian areas [5]. Due to lighting of the ground and facades of objects forming it, the light environment of the city obtains three-dimen-

Fig. 6. Floodlight illumination of architectural monuments of the 18th century: Krestovozdvizhenskaya (*a*) and Spasskaya (*b*) churches

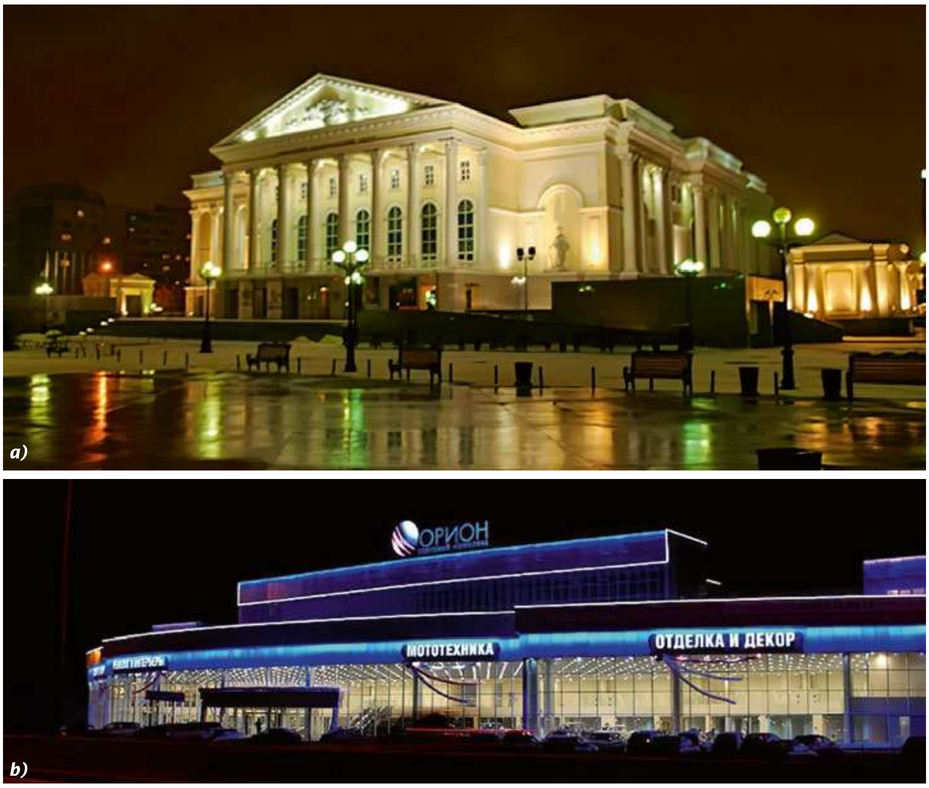

Fig. 7. "Classic" illumination of the Tyumen Drama Theatre (*a*) and modern colour illumination of the Orion shopping centre (*b*)

sionality. Its optical structure is an intermittent and continuous system of areas with different scale, designation and hierarchic level modulated by light, with specific rhythm, discrete and heterogenic light engineering parameters in which, in turn, the hierarchic system of light ensembles and dominants, which dominates in the light composition of the city and is very important for it, should be distinctive. Light modulation is performed on the basis of conceptual light-and-colour zoning by selecting corresponding means and modes of illumination of the ground surface and objects forming the light environment in specific situational spaces and light architectural ensembles which are radically different from daytime ensembles in terms of visual characteristics.

Evening perception of the light ensembles and dominants is calculated at far, medium and close distances, for this purposes the concept specifies the tourist view points of light panoramas and deep light perspective views, though basically flat and low-rise Tyumen development does not give many reasons for it so far.

The conceptual visual and artistic problem consists of visible finding and creative interpretation of expressive features and distinctions of the architectural shape of objects and ensembles, creation of their original light images using the principles of associative resemblance to daytime images or creation of an alternative "counter-image" [4].

As the field observations showed, the best examples of AL of the objects in the centre of Tyumen, including that of architectural monuments, follow the former principles while a lot of the others are variably compromise and controversial.

So, in the general plan of illumination of central Tyumen, the "urbanised" and "natural" light structures (Fig. 8, *a*) and the residential areas forming the development "fabric" of the city may be identified. The hierarchy of the light ensembles of the city and night-time dominants with consideration of already established situation and prospects of development of centre is forecast (Fig. 8, *b*).

Inevitable modernisation of LIs of the "urbanised structure", i.e. the transport and pedestrian streets and squares, is already begun by replacing discharge lamps LDs with LED-based LDs. So the design of LI elements and chromaticity of outdoor illumination are changed, aerial power lines are replaced with modern underground cable lines (unfortunately, not everywhere), etc. According to the concept, it is necessary to solve the problems of light-and-colour zoning of urban areas (primarily transport and pedestrian zoning) clearer using the available means: different levels, chromaticity, techniques and modes of illumination operation, design

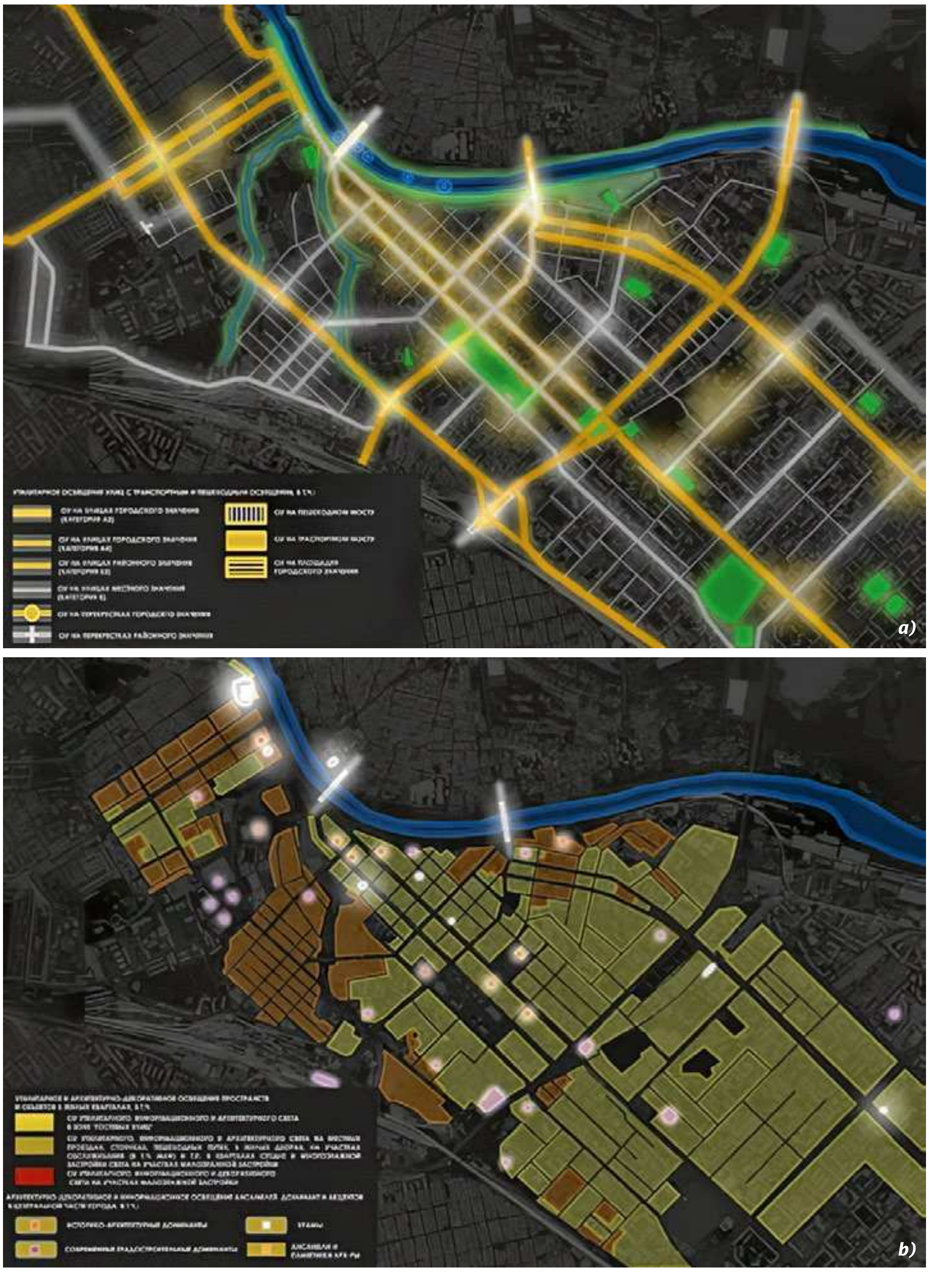

Fig. 8. General Plan of illumination of the central part of Tyumen:
a is the the urbanised and natural "light structures"; *b* is the "light fabric" and the system of lighting dominants

and scale of LIs. These parameters are presented in the legend and explanatory note to the general plan of illumination.

Similar measures are specified for the "natural structures" and the residential "fabric" of the city. When looking at the general plan of illumination, it becomes clear that there is obvious deficiency of woodlands as the main elements of the "natural" structure in the central part of Tyumen: only the Tura river with the improved embankment on a high right bank forms its reliable "trunk" which requires a developing natural "canopy" in the residential "fabric".

By morphology, the elements of "fabric" in the central part of the city are categorised as follows: the quarters with dominating contemporary high-rise buildings and predominantly low-rise development with consideration of its historical value. It is crucially important to select and provide such light-and-colour parameters and design of LIs in all internal areas so that the created environment is intimate, human-scaled, visually comfortable and safe, and provides positive emotions.

The French call this quality "*ambiance*", i.e. pleasant atmosphere, or, as a synonym, "favourable psychological climate", which is extremely

Fig. 9. Computer visualisations of the fragments of night-time light environment in sketch projects of Lenin st. improvement

important in residential areas during long autumn and winter evenings in Siberian climate. The important social task of yard spaces and recreational environment, and, in the first place, of outdoor illumination is to make residents (children with parents, grand-fathers and grand-mothers) to go out to communicate and have some rest after a working day. To solve these tasks, not only the utility lighting installations dominating in urban illumination (in terms of the number of lighting points, power consumption, etc.) should be used but also other groups of architectural and informational lighting.

Unlike the city streets and squares where conceptual recommendations may be followed not from scratch but mostly by stage-by-stage reconstruction of existing LIs, improvement and lighting of residential areas which in many cases does not comply with contemporary standards requires taking drastic measures. That is why the authorial team of TIU with participation of educators, architects, and students alongside with general conceptual design performs more detailed and attentive sketch designing of comprehensive landscaping, including lighting and colouristic, of the fragments of urban environment in the centre of the city at the streets Lenin, Republic, and etc.

The visual characteristics of the fragments of light environment and light ensembles provided by different techniques and means of architectural lighting of facades of buildings, structures and urban landscape objects are forecast in sketch computer visualisations of development and perspective views in pedestrian perception scale (Fig. 9).

A specific light design problem is AL of one- and two-floor historical buildings, frequently wooden and with original decoration, where use of local illumination by means of LDs mounted on facades seems to be not appropriate enough. It means that original solutions of LDs should be found at the following stages. Different styles and heights of development in many streets with existing spatial "gaps" also complicate the use of "classic" light-ensemble techniques, which becomes evident during development of lighting "tapes" at both sides of streets. That is why the ideas of comprehensive reconstruction of the architectural environment with extensive use of small forms, including original lighting forms, and increasing volume of deficient landscaping to fill these "gaps", seem prospective and are supported by the authorities in Tyumen.

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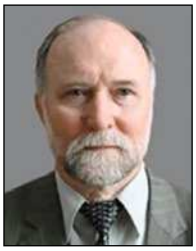

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MODERNISATION OF LIGHTING SYSTEMS OF A CASTING AND EXTRUSION PLANT IN KRASNOYARSK

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ABSTRACT

The article describes modernisation of the lighting systems of Segal Casting and Extrusion Plant LLC in Krasnoyarsk and technical solutions of its implementation. The parameters of the new lighting system based on *Diora Craft* LED luminaires are presented and it is shown that replacement of luminaires based on high pressure mercury lamps (HPML) with LED luminaires allows saving 73.5 % of power consumed by lighting with high quality of the light environment established in the shops of the plant. Payback period of such modernisation is 1 year.

Keywords: light emitting diode (LED), lighting devices (LD), industrial lighting, lighting systems, lighting installation, LED luminaires, modernisation of lighting systems, energy saving

1. INTRODUCTION

Numerous studies have found significant impact of artificial lighting of industrial facilities on visual performance, physical and mental states of workers and, subsequently, labour efficiency, quality of products and work place injuries. Correct lighting of work places is the key factor of safeguarding and health protection of workers [1].

The informational field regarding developments and innovations in the area of industrial lighting has reduced dramatically over the previous 30 years; publications in scientific and technical journals are nearly non-existent and are replaced by news websites. The requirements to installation and operation of lighting installations (LI) for different production facilities are specified in federal regulatory documents [2–4], unfortunately, the applicable industry regulatory documents are compiled back in the Soviet period (1970–1990). After Perestroika, the industry regulatory documents virtually were not developed; therefore the obsolete regulations do not reflect the current level of development of technical means and technologies of lighting.

At the current stage of development of artificial lighting, due to well-known reasons, LED lighting holds the leading position (the main reasons include energy saving requirements in lighting [5] and international treaties aiming at solving of global environmental problems [6–8]).

With consideration of the above-mentioned circumstances, lighting of industrial facilities, being the most energy-consuming, must be transferred to application of LEDs on a first-priority basis.

This article describes the results of modernisation of lighting systems of Segal casting and extrusion plant (CEP) in Krasnoyarsk which included replacement of HPML-based luminaires with LED-based luminaires for increase of both quality of the light environment in shops and energy efficiency of LIs. The related programme of modernisation of lighting systems comprises three main stages: the first one (2015) – design of modernisation; the second one (2016) – implementation of the modernisation project (the said replacement of luminaires); the third and final one (2018–2019) – painting of vertical structures, ceiling and metal structures of floors white (as an indirect method of increase of quality of light environment). At all stages of modernisation, the characteristics of LIs were measured, and the results of these measurements are presented in Table 1.

Segal Casting and Extrusion Plant LLC (a branch of GC SIAL) produces aluminium cast alloys, extruded aluminium profiles and products made of the same. The annual capacity of the plant is 32,000 tons and current volume of output is 26,000 tons per annum.

The structure of the facility includes cast, extrusion and painting workshops, anodic treatment section, production of suspended facades, formworks and products of aluminium profiles, analytical laboratory and packaging section.

Aluminium profiles are manufactured by means of automated extrusion systems based on presses with workload of 2,750; 2,500; 2,100; 1,200; 2,750 and 1,460 tf (1tf = 9.807 kN). For painting of aluminium alloy products, the facility employs *Trevisan* (Italy) and *TNE* (Singapore) vertical automatic painting sections and a *NEWLAC* (Spain) horizontal automatic powder painting section.

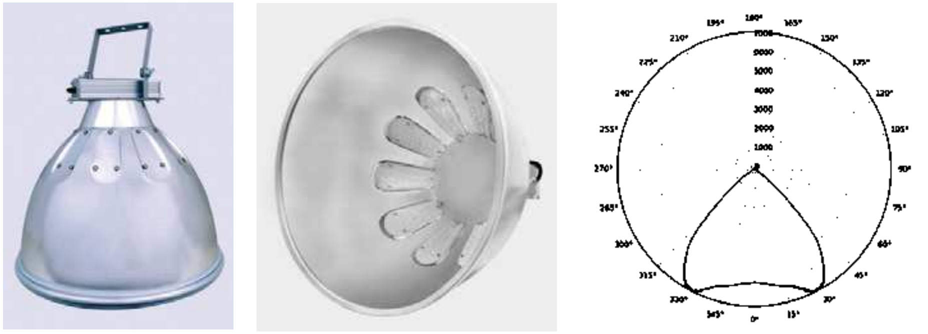
2. MODERNISATION OF LIGHTING SYSTEMS OF CEP WORKSHOPS

The aspects of industrial facilities lighting are defined by the sphere of production activities, lighting standards, category and characteristics of visual performance, nature and distinctions of process equipment, natural lighting conditions and workplace assessment requirements. It is implied that the workplaces are illuminated with standardised natural lighting and quality artificial lighting compliant with labour safeguarding and health protection requirements. An optimal LI solution complies in a compromising way with requirements of visual comfort ability and high energy efficiency which may be assessed by standard values of maximum acceptable specific installed capacity (SIC) of the system of production premises artificial lighting.

LDs for lighting of industrial facilities are selected with consideration of light-engineering and economic parameters of LDs including light distribution and luminous efficacy. Optimal selection of LD based on light distribution (with light distribution curve (LDC) and LD allocation scheme optimal for the given mounting height) allows power consumption for lighting to reduce by (30–35) %. For production premises with higher mounting height of LD (exceeding 6 m), LED-based narrow angle luminaires are efficient with their uniform allocation over the area of the production section. Necessity of use of LDs with concentrated light distribution increases with increase of ceiling height.

In workshops of cast plants, general lighting systems are primarily applied. The norms and quality indicators of lighting of cast plants production sections with visual performance category of Vb are well-known [2, 4]. As the production sections of case workshops are usually located in buildings with high ceilings (more than 8 m), general lighting LIs are equipped with LDs of high single capacity. In terms of the state of air environment, the premises of cast workshops are usually categorised as "dusty", which determines the recommendations to use partially or fully dust-protected LDs (with protection class of at least *IP53*). But it is worth noting that contemporary mechanised and automated technologies promote enhancement of production practices and improvement of sanitary and hygienic conditions of workshops, which, in fact, makes conventional classification of air environment of modern industrial production facilities as "dusty" not necessary. Such situation fully relates to highly-automated workshops of CEP with their ceilings and walls being painted white at the final stage of modernisation. By content of dust, smoke and soot in the air environment, the production premises of Segal CEP are categorised as 1c [2, Table 4.3]. According to the calculations, painting of vertical surfaces, ceiling, and metal structures white increases average illuminance by (25–30)%, which has defined painting of enclosing structures of the workshop at the final stage of modernisation of the plant LIs. The efficiency of the effect of painting of the enclosing surfaces is demonstrated by increase of illuminance by 30 % in the workshop with the 2500 tf press (building No.2), from 267 lx to 348 lx, after painting the walls and the ceiling white (Table 1). This fact confirms efficiency of comprehensive approach by which high quality of the light environment is formed not only by correctly selected LDs but also by the state of the surrounding area.

Modernisation of LIs of the workshops of Segal CEP should serve as an example of progressive approach to modernisation of lighting of an industrial facility with its design comprehensively solving the issues of increase of energy efficiency, integrity of light environment in different operation



a) b) c)

Fig. 1. *Diora Craft* 110/13000 luminaire (capacity of 110 W, luminous flux of 13,000 lm, T_{cp}=5000K, *IP65*): *a* and *b* – general view of the luminaire; *c* – LDC

Fig. 2. Lighting of CEP workshops after modernisation of LIs:
a and *b* – building No. 4, bay No. 5, automatic packaging line of painted profiles; *c* – building No. 2, workshop (2500 tf press)

modes of process equipment (in particular, blocking by gantry cranes), optimisation of the operation conditions of lighting equipment, convenience of installation and maintenance of LDs, comfort-ability of light environment. Modernisation was related to general lighting of workshops as part of the combined lighting system. Almost all production lines are automated; local workplaces are defined by location of equipment and are most frequently located in the beginning of a bay. Most commonly, these are the workplaces of production process operators made in the form of transparent unit of transparent protective glass.

Local lighting at workplaces is part of process equipment and is based on fluorescent lamps (FL) with *T5* bulb, which is specified by manufacturer of this equipment. Average illuminance at workplaces in the system of combined lighting is about 500 lx with the level of general lighting exceeding 200 lx [2]. The other part of the workshop is represented by automated lines providing general monitoring of the course of production process. Hereinafter the results of modernisation of the general internal lighting of Segal CEP will be described.

The *Diora Craft* industrial luminaires were specified by the modernisation project. General view of one of them is presented in Fig. 1 *a, b*. Light distribution of these narrow angle luminaires corresponds with Deep LDC (Fig. 1 *c*). Luminous efficacy (at least 120 lm/W), directed luminous flux (deep LDC with large mounting height) and rational allocation of luminaires in the premises provided high energy efficiency of LIs with maximum value of SIC of LIs of the plant workshops and sections not exceeding 3W/m^2 at average illuminance exceeding 200 lx (average value of SIC is 1.25 W/m^2 at 100 lx). Capacity of LED-based luminaires selected by calculation provides standardised illuminance (Table 1). According to the customer's design specification, the category of visual performance in the

Table 1. Characteristics of LIs of Production Areas of Segal Cast and Extrusion Plant LLC after Modernisation

Area	U_o, per unit		$E_{h\ av}$, lx			K_f,%		$P_{sp\ max}$, W/m^2		UGR		R_a	
	standard	after*	standard	before**	after*	standard	after*	standard	after*	standard	after* (*max*) design	standard	after*
Formworks (the area is not shown in the photographs)	0.40	0.90	200	152	253	20	0.2	5	≤ 3	25	20	80	80
Building No. 4, bay No. 5, automatic painted profile packaging line, thermal processing section		0.70		231	276								
Building No. 3B, workshop (with 2750 tf press)		0.80		204	269								
building No. 2, workshop (with 2500 tf press)		0.60		212	348								

Notes:
- *standard* – standard values of parameters in accordance with [2, 4];
- after* – characteristics of LI after modernisation and after two years of operation (measurements of 2018);
- before** – characteristics of LI before modernisation (measurements of 2016).

Legend:
- U_o – uniformity of illuminance distribution: $U_o = E_{min} / E_{av}$;
- $E_{h\ av}$ – average horizontal illuminance on work surface in the workshops;
- K_f – flickering index;
- $P_{sp\ max}$ – maximum acceptable value of specific installed capacity;
- *UGR* – unified glare rating;
- R_a – general colour rendering index.

Table 2. Example of Print out of the Calculation results: Summary Results of Average Illuminance E_{av} calculation for building No. 4

№	Обозначение	Тип	Растр	E_{cp} [lx]	E_{min} [lx]	E_{max} [lx]	E_{min}/ E_{cp}	E_{min}/ E_{max}
1	Пролет 1,2	по горизонтали	128×32	201	128	217	0,640	0,592
2	Пролет 3,4	по горизонтали	128×32	202	131	216	0,651	0,609
3	Пролет 5	по горизонтали	128×32	250	154	275	0,615	0,558
4	Пролет 6	по горизонтали	128×32	254	157	282	0,615	0,556

modernised workshop is Vb and the standard value of illuminance is 200 lx [2]. All local workplaces with higher category of visual performance are equipped with local lighting.

For minimisation of costs of modernisation of the plant LIs according to the customer's design specification, *Diora Craft* luminaires (analogues of RSP-400, GSP-250, ZhSP-250 luminaires) are installed at existing light positions instead of obsolete luminaires with HPML 400 lamps (RSP-400). In each workshop, there are two components of LIs: stationary, with luminaires installed on floor frame work (Fig. 2, *a*), and mobile, with luminaires installed on the cross beam of gantry crane (Fig. 2, *b*). In the course of the production process, the mobile cranes are active in the workshops and their movement may cause blocking of stationary luminaires, impair stability of light environment and create discomfort for workers. To eliminate this unnecessary effect, the luminaires are installed on the crane beam and act as stationary ones at moments of blocking by the crane. Under-crane lighting is higher than general lighting by 15 %, which accentuates monitoring of crane work and increases safety of the works. Therefore, comfortable stability of workplace lighting during operation of mobile cranes is maintained in the workshop.

The progressive design and technical solution of LIs is supported by audacious design of the luminaires with their bell-shaped body of anodised aluminium serving as a reflector (integrated reflectance of 85 %) and a radiator at the same time. The protecting diffusing glass is made of optical polycarbonate and fixed to the body of the luminaire by means of an elastic silicone rim acting as a sealing. Integrated transmittance of the diffuser material is 0.91.

Despite the low thickness of metal, original allocation of LED-modules on the inner surface of the body (Fig. 1) provides optimal heating mode for LED (temperature of the LED module does not exceed 80 °C) within the whole range of capacity of the *Diora Craft* luminaires line, from 55 W to 150 W, at operating temperatures varying from –60 °C to +60 °C. Operation of the body as a radiator makes an additional radiator which is usually massive and cast unnecessary. That is why the weight of a luminaire does not exceed 3.2 kg, which is significantly less than that of Russian analogues and provides significant advantages during height works and maintenance of LIs. Smooth bell-shaped body of the luminaires made using cold roll forming technology makes it free of ribs and angles (Fig. 1, *a*) on the outer surface, which virtually excepts accumulation of dust and other dirt on this surface and thus provides stability of LED heating mode, increases reliability and durability of luminaires and facilitates their cleaning. Allocation of LED modules in the upper part of the reflector provides the luminaires with additional useful features: high protective angle eliminating dazzling effect with mounting height of (6–15) m. The luminaires have high ingress protection rating (*IP65*), may be operated in areas with different air environment conditions, are categorised as the 4th operation group [2], comply with the requirements of [9], and their T_{cp} = 5000K.

The LED modules are of petal shape and are allocated in the upper part of the body (Fig. 1, *b*); they are equipped with *LM561C* LEDs by *Samsung* with maximum single capacity of 0.6 W. The number of LEDs on a module board depends on capacity of a luminaire: 250 pcs. at 110 W and 420 pcs. at 130 W. LEDs are operated at lowered capacity in the luminaires, which, as it is known [10], increases their luminous efficacy. At the same time, in a *Diora Craft* 130 (130W) luminaire, single power of LED is 0.285 W (47 % of the maximum value) and in *Diora Craft* 110 (110 W), it is 0.405 W (67 % of the maximum value).

As a result, power allowance of 50 % and 30 % respectively provided luminous efficacy of the luminaires of at least 120 lm/W, increased their reliability and durability (due to facilitation of heating mode as compared to the maximum capacity mode of LED) and allowed the structure designing of luminaires using thin-wall body metal as a cooling radiator for the LED module.

It is obvious that reduction of single capacity of LED in LED modules increases their number to achieve optimal value of luminous flux, which principally makes the luminaires more expensive. A compromise in selection of single operating capacity and number of LEDs was defined by optimal quality-price ratio**.** The principle of design of a luminaire allowed to achieve high consumer characteristics and to set warranty period of 5 years with competitive price. In *Diora Craft* 110 and *Diora Craft* 130 luminaires, *PS130–700* power supply unit was used with minimum efficiency of 92 % at operating current of 700 mA and maximum power of 130 W.

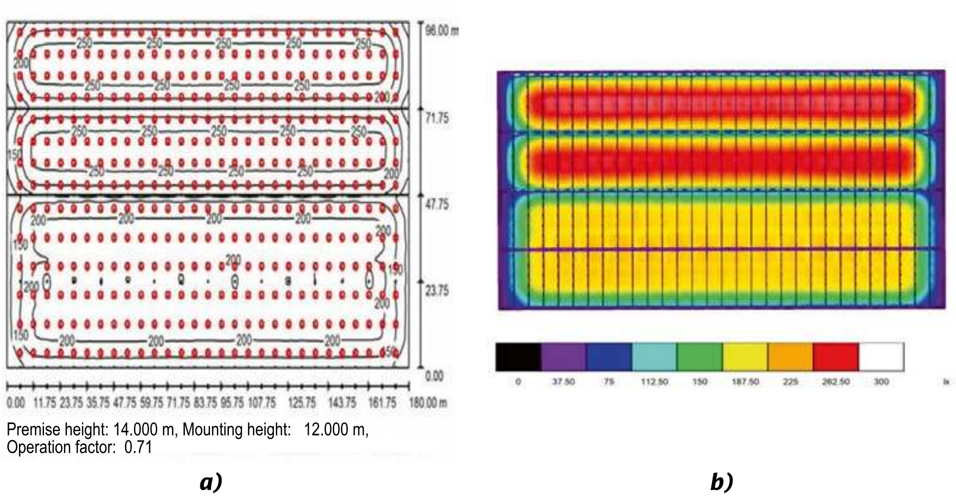


Fig. 3. Design fragments of the project of lighting of production areas of building No. 4. Design distribution of illuminance in iso-illuminance curves (*a*) and fictitious colours (*b*)

At the first stage of the plant LI modernisation, in 2016 (the first tenders were conducted in 2015), 632 *Diora Craft* 110/13000 and 33 *Diora Craft* 130/17000 luminaires were installed. As a result, even given the achieved enhancement of light-engineering parameters (Table 1), the power of LIs was lowered by 73.5 %, from 279.3 kW (before the modernisation) down to 73.8 kW (after the modernisation). With tariff equal to 4 roubles per kWh, annual saving of electric power costs was equal to 7.2 million roubles. Due to significant saving of energy for lighting, the investments in modernisation of the plant LI (with the cost of equipment procurement of 6.82 million roubles) were returned after a year of operation.

The programme of comprehensive modernisation of lighting of Segal CEP specifies stage-by-stage installation of LED luminaires in all workshops and painting the walls, ceiling and load-bearing metal structures white at the final stage of modernisation.

For all workshops of the first phase of modernisation, light engineering calculations and modelling were performed using *DIALux 4.13* software. Fig, 3 provides an example of calculations for production areas of building No.4. Building dimensions: area – 17,288 (180×96) m^2; mounting height of luminaires – 12 m; ceiling height – 14 m; spacing between rows of luminaires – 6 m; spacing between luminaires in a row – (6–8) m depending on the structure of floor slab in different bays. The operation ratio for *Diora Craft* luminaires categorised as the 4th operation group was taken equal to 0.71 [2, table 4.3 with consideration of note 4]. The values of reflectance of the ceilings, walls and floors taken for calculations are 0.70 (whitewash), 0.50 (grey plaster) and 0.20 (concrete). In Table 2, calculated values of illuminance are presented with consideration of the selected operation ratio of the luminaires.

Table 1 contains the results of implementation of the design solutions for production areas of the first phase (2016) of modernisation of the plant LIs and the results of measurements of illuminance conducted after the two years of operation of LIs (2018). Actual levels of illuminance are higher than the calculated values, which witnesses correctness of selection of the values of luminaire operation ratio and values of reflectance of the walls, ceilings and floors. Before the manuscript of this article was sent to the journal, as part of monitoring of LIs at section of thermal processing in building No. 4, additional measurements were conducted; they revealed reduction of illuminance over the third year of operation (July 2018 – August 2019) within the range of 3 %. (The operation mode of the plant is continuous.)

Fig. 2 shows the general view of the production areas in buildings numbers 2, 3B, 4 and the scheme of allocation of the luminaires after modernisation of LIs of Segal CEP. The LIs are distinctive with uniform allocation of the luminaires in rows parallel to the walls. The illuminated space of the workshop is saturated with light and is a comfortable light environment (Table 1) for performance of profile works.

Currently, Segal CEP is continuing the modernisation of lighting by stage-by-stage replacement of HPML-based luminaires with LED-based luminaires (*Diora Craft* series) and painting the vertical surfaces, ceiling and metal structures white.

CONCLUSION

Introduction of LED-based luminaires in general industrial lighting installation is of great potential in terms of energy saving and quality of light environment in facilities. The example of comprehensive modernisation of CEP in Krasnoyarsk demonstrates such opportunities: the power of LIs was lowered by 73.5 %, from 279.3 kW (before the modernisation) down to 73.8 kW (after the modernisation) with high quality of light environment (Table 1). With annual reduction of energy costs by 7.2 million roubles, due to significant saving of energy for lighting, the investments in modernisation of the plant LI were returned after a year of operation.

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EDITORIAL NOTE

Publishing this article by G.M. Belan and A.T. Ovcharov, it cannot go unmentioned that it reviews the results of modernisation of lighting of an industrial facility for the first time in more than a decade.

Alongside this, publication of this article poses a very important question of further design of LIs not only for production buildings but also for public buildings: whether it is necessary to aim at maximum reduction of specific installed capacity (SIC) at minimal values of standardised illuminance as the main problem of design using high difference in values of luminous flux of the new and old LDs, or to aim at comfortable light environment conditions with mandatory (but not maximum) reduction of SIC by (3–4) times. With this, it is necessary to increase the values of illuminance (exceeding the current standard hygienic values) and comfort-ability of chromaticity of light environment in the course of design. In this case, it is necessary to select LEDs with the values of correlated colour temperature necessary in every particular case simultaneously reducing operation costs and increasing reliability of LI operation by correct selection of LD operation ratios. The new approaches to formation of light environment will obviously require advancement of hygienic standards of lighting.

Considering the above-mentioned question very important, the editorial board invites all specialists to discuss this problem with participation of the authors of this article and its reviewers as well as specialists of ROSKOMNADZOR, hygienic organisations and standardisation bodies.

Julian B. Aizenberg

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ASSESSMENT OF ARGENTINEAN LED LUMINARIES FOR STREET LIGHTING

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ABSTRACT

The work presents a statistical summary of the results obtained in the photometric, thermal, chemical and mechanical tests carried out in the Laboratorio de Acústica y Luminotecnia (LAL) for street lighting luminaires with LED technology in the period 2017/18. The study covers 152 luminaires and includes samples from different manufacturers or origin, same type or model (for example, a same body) with different alternatives of LED plates. The results of luminance and illuminance evaluations carried out in converted facilities (or in the test stage) are also discussed. The results presented are important both for importers and manufacturers of LED luminaires and for designers and installers, since they allow visualizing the points that deserve attention in order to achieve a product of suitable quality.

Keywords: LED, energy efficacy, street lighting

1. INTRODUCTION

The new PLAE (Plan for efficient lighting), from the Ministry of Energy and Mining under the Nation Presidency, proposes the luminary replacement for more efficient devices with LED technology. It consists of a state funding for conversion to LED technology, with the main objective of reducing consumption in street lighting. The PLAE sets technical specifications [1], which define the minimal requirements, must meet up by devices have to be installed. These technical specifications resulted from discussions with different experts involved in this sector: Lighting Argentinean Association (Asociación Argentina de Luminotecnia – AADL), Deputy Office of Public Services of Buenos Aires Province, national and provincial laboratories, etc., and they were based on the current national standards, such as IRAM AADL J 2021, J2022, J2028, J2020 [2, 3, 4, 5].

In this framework, LAL–CIC, as one of the accredited laboratories for carrying out technical tests, studied an important deal of national and imported samples. In its specifications, PLAE added special tests of duration, thermal stress and cycling to the traditional photometrical, mechanical, thermal and spectral tests, based on IRAM AADL standards. The results obtained have been dissimilar, verifying that the local standards are not comparable to other markets.

2. TESTS REQUESTED IN THE PLAE FRAMEWORK

The required tests are listed in the Technical Specifications of the plan [1]. They involve a set of tests taken mostly from Standard IRAM AADL J 2021 [2], which are shown in Table 1.

In addition, it is compulsory to verify the cover impact strength, according to Standard IEC62262–2002[6]: IK=8 or higher for glasses and IK=10 or higher for polymers.

As it is observed in Table I, the required tests can be considered as the typical ones that are applied in our country. In this sense, it is worth mentioning

Table1. PLAE Tests

Requirement and Test	Description
IRAM AADL J 2022–1	Photometry
4.1–3 and 5.1–3	Salt spray for complete luminaire (240 h)
4.4 and 5.4	Gear winding resistance
4.6 and 5.6	Adhesiveness of the paint coats
4.7 and 5.7	Resistance to the indentation of paint coats
4.8 and 5.8	Accelerated thermal aging of joints in elastomeric material
4.10 and 5.10	Vibration
4.11 and 5.11	Impact
4.12 and 5.12	Plastic deformation of elements in plastic material
4.13 and 5.13	Torsion resistance of threaded superior connection luminaries
4.14 and 5.14	Torsion resistance of lateral connection luminaries
4.15 and 5.15	Fixation system of luminaries mounted in suspension
4.20 and 5.20	Thermal shock for glass covers
4.22 and 5.22	Crush resistance in closing joints
4.24–25 and 5.24–25	Rain water tightness and dust tightness of the device unit housing
4.24–25 and 5.24–25	Rain water tightness and dust tightness of the optical housing
4.27 and 5.27	Main connection block
4.29 and 5.29	Hail
4.39 and 5.39	Grounding
Aditional test	Thermal stress
Aditional test	Ignition Cycle
Aditional test	Luminous flux maintenance in time, assessment of CCT and colour rendering index R_a
Aditional test	Weight determination of the complete luminaire

that they are mainly based on [2], whose first version is from 1974. The novel nature of PLAE is the flux maintenance test, which tries to evaluate the expected duration for LED luminary and whose details are further commented.

3. GENERAL FEATURES OF THE MAIN TESTS

3.1. Photometry and Colour

Photometry is the test with a strong tradition in Argentina. Based on the IRAM standard [3], standardization dates back to the mid-70s. LED luminaires introduced two changes in the norm (2013): the use of absolute values for intensities and efficacies, and the spectra radiometric measurements for colour parameters, for example. Figs. 1 and 2 show the LAL equipment and characteristic results of this test.

3.2. Paint Quality Tests

The salt spray test refers to IRAM 121 [7] from 1957. The test is based on an old version of ASTM 117 [8] and consists of putting the complete sample to a salt environment in order to verify the level of mechanical protection given by protecting coatings (paints). The requirement is regulated by the length of the test, 240 h is the minimal time indicated by IRAM for paints, though it can be extended to 500 h or 1000 h in special situations and/or by agreement between suppliers and buyers, (the typical case is the installation in sea coast zones). The result is assessed by inspection in frame of our standard, which not allowing coating blisters or lifting, and by no means, oxidation or cracking of base material, either. Fig. 3 shows LAL equipment and examples of studied samples.

In connection to this test, it then follows the resistance test to the gear of threaded pieces, which

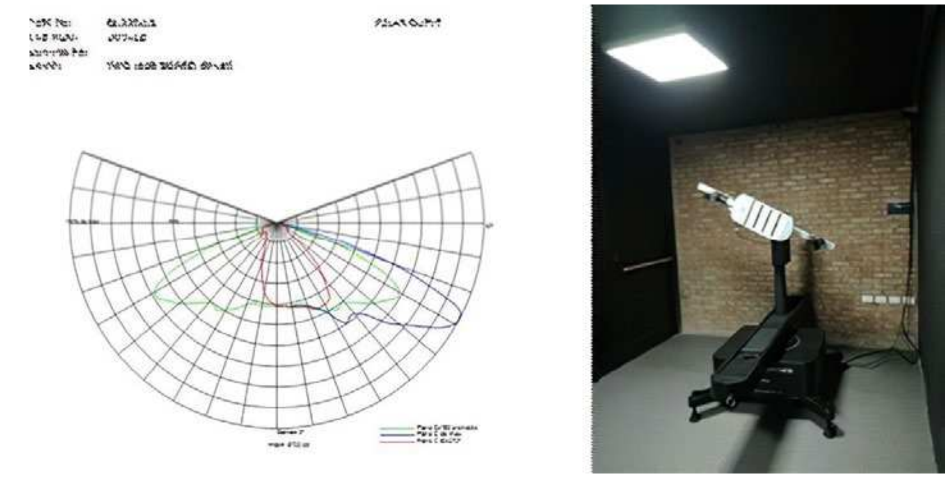

Fig. 1. An example of photometric results and LAL equipment

consists of practically verifying that the anchoring or fixation screws can be removed without difficulties after exposure to salt environment by using the suitable tools for this work.

As a complement, adhesiveness and resistance to indentation of paint coats are checked in order to determine the coating quality and its fixation to the base. In this sense, a low-quality paint or badly applied will not guarantee the protection needed for the coated material and will be detrimental for the product lifetime.

3.3. Another Mechanical and Electrical Tests

The vibration test uses a machine capable of inducing an acceleration of 2 g in the most requested point of the luminaire, during a span of 100,000 cycles ± 1,000 cycles at the resonance frequency in order to determine the clamp fixation capacity and the mechanical resistance of all the luminary components. With the same equipment, the impact to vibration, with an acceleration of 4 g in the most requested point of the luminary, allows determining the sample behaviour against accidental impacts during its transfer and installation.

It is also worth highlighting the dust tightness test and water tightness of the optical unit and the behaviour of the auxiliary equipment, Fig. 4. Both are intended to assess the closing of different compartments, linked directly with the duration of the device. This test, commonly known as IP degree is also based on an older standard: IRAM 2444 [9].

Finally, we would details more on tests related to electrical safety, terminal boards and grounding verification. The latter uses a source of low-voltage direct current, with which a current of at least 10 A is made circulate between the luminaire ground terminal and each reachable metallic part. The resis-

Table 2. Typical Powers and Efficacies

LED Technology	LED Power, W	Luminous efficacy, lm/W
COB	34–66	110–150
SMD MID	0.26–0.95	108–141
SMD	2.2–3.3	120–155

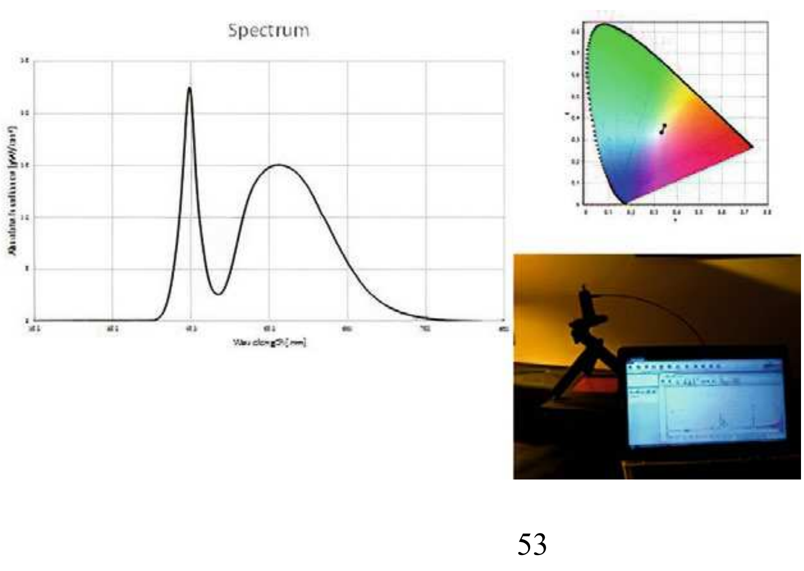

Fig. 2. Example of spectra and colour test

Fig. 3. LAL salt fog test equipment and results (photos from author)

tance value should not be higher than 0.20 Ω, what forces to a design that must address the cover wiring and mobile parts.

3.4. Product Lifetime Estimation

Three tests are combined in this verification, which are worth highlighting for being exclusive for LED products:

a. Thermal stress, which consists of exposing the luminaire off for an hour at a temperature of –10 °C and immediately afterwards at a temperature of 50 °C for an hour, repeating the cycle five times.

b. Cycling, which puts the luminaire under a test of 5,000 on and off cycles (both of 30 s), being carried out after the thermal stress test.

After completion of both tests, the luminary must continue working without apparent damages.

c. Luminous flux decay in time, assessment of correlated colour temperature CCT and colour rendering index CRI, which consists of carrying out an "aging" of the luminary by means of its continuous operation for 6,000 h, period after which the decrease of the emitted luminous flux and the CCT change with respect to the initial value previous to aging are verified, Fig. 5.

4. RESULTS

It is noteworthy the distribution of products in function of the different LED luminaire technologies for street lighting. Fig. 6 shows this distribu-

Fig. 4. IP test: air (left) and water tightness (right) (photos from author)

Fig. 5. Aspects of 6,000 h operation test (photo from author)

Table 3. Installation Assessment

Installation 1	**E_{av}, lx**	**Power in the area, W**	**Density of normalized power, W/(m²· lx)** (6 m × 39 m)
Original (HPS250)	7.6	2 × 250 = 500 +10 % = 550	0.309
Reconverted (LED150)	27.1	2 × 150 = 300	0.047

Installation 2	**E_{av}, lx**	**Power in the area, W**	**Density of normalized power, W/(m²· lx)** (7 m × 30 m)
Original (SAP 250)	18.6	1 × 250 = 250 +10 % = 280	0.072
Reconverted (LED148)	32.0	1 × 139 = 139	0.021

tion for a total of 152 luminaires involved (the total includes the same type or model, but of different power or LED amount). The discriminated categories are COB (Chip on board), SMD MID (Surface mounted device, superficial assembly, medium power) or SMD (High power surface mounted device).

Even though the national recommendation about design [4] stipulates the use of a removable and interchangeable protecting covers, there are other options in the market. Fig. 7 shows the proportion between the different involved alternatives.

In Fig. 7, it is indicated "cover" when there is really an interchangeable and independent flat closing of the lens. "Lens" is referred to a refractor with focus optical functions and that it is also the LED protection, being able to be adhered, fixed with fasteners or screws and, though it can be removed, it is not intended for its change or replacement.

As a complement to the distributions indicated in Figs 1 and 2, Table 2 shows the typical power ranges by LED and global efficacies of the involved samples. The values between brackets correspond to glass covers. It is underlined that the last version of PLAE requirements admits a minimal luminous efficacy equal to 105 lm/W for luminaries having a protecting cover of the glass or polymer optical housing not including lens in it, and higher than or equal to 120 lm/W for luminaries without it.

Tests to the protecting cover: paint and salt spray are among those with more samples not passing the standards set by the norm. Statistics are shown in Fig. 8.

In the paint tests, lack of adherence was the recurrent failure. In salt spray (240 h), it was the oc-

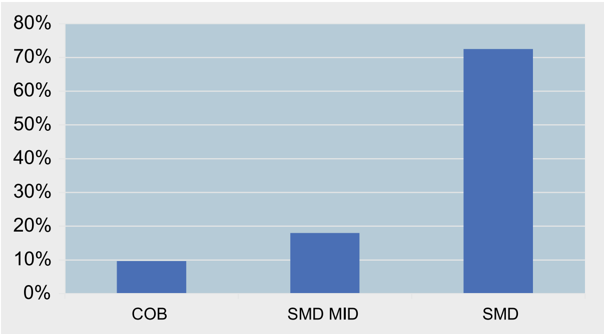

Fig. 6. Types of LED technologies

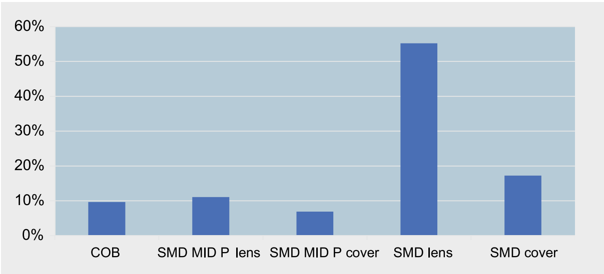

Fig. 7. Types of cover

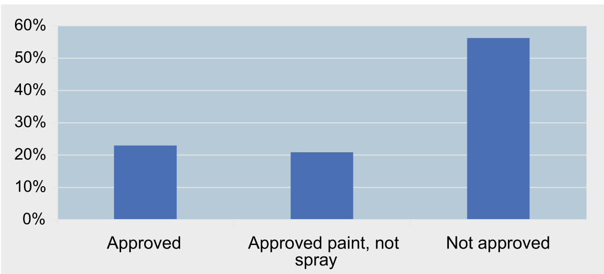

Fig. 8. Failures in salt spray and paint

currence of blisters, especially in zones near the clamps or fastening systems (joints between aluminum and iron alloys). To a lesser extent, oxidation of base material or screws was found.

The failures of water-tightness, mainly in housings for the auxiliary device, were also important. In most of the cases found, the opening systems of the "without tool" type (snap hooks or staples) did not apply enough pressure to ensure the closing. It must be highlighted the fact that the closings with screws, which allow a simpler and safer design for guarantying tightness, were numerous though they were not taken into account in the standard IRAM [4].

The percentage of failures in the rest of the tests was lower.

The recurrent problems were:

– Failures (breakage) in glass covers during IK8 test have shown that percentage was lower than 10 % of the studied samples and mainly affected flat refracting glasses assembled without frame.

– Between 20 % and 30 % with flaws in the wiring: lack of grounding continuity, terminal board with inadequate marking, lack of ground terminal.

– Roughly 30 % of the photometric tests did not verify the PLAE requirement ratio l_{max}/I_0 higher than 2 (I_0 luminous intensity for the zenith) and to an equal extent, the colour temperature was out of the required range (3000–4500) K.

4.1. Result in Installations

Here we mention only a couple of cases taken from the technical assistance supplied by the LAL to municipalities from Buenos Aires province. In these studies, it was possible to carry out a standardized assessment [10] of a new installation (with LED luminaries) and of zones with the previous system (High Pressure Sodium lamps, HPS). It must be pointed out that the original installation dated from the 90s, with minimal maintenance. Table 3 shows these results. Reference [11] has similar information for the case of highways and reconversions carried out in previous periods.

5. CONCLUSIONS

The whole analysis of the results and the origin of the tested products allow establishing a first conclusion: the local standards regarding global protection of the product (paint and resistance to corrosion) are higher than the mean of the other markets products. Moreover, it is observed an excessive focus on the assignment of high IP indexes (66) often unfulfilled by closings of joint systems.

Finally, it is outstanding the importance of establishing quality requirements, such as the PLAE requirements [1] since in some way they establish guidelines then followed by the private specification sheets from different buyers (town hall, cooperatives, etc). The final test of the converted installation is not so generalized (illuminance assessment according to standard); and this is a very important issue to be taken into account in order to really ensure the lighting system enhancement.

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MODELLING OF THE INSOLATION MODE OF URBAN DEVELOPMENT USING AN INSOPLANOGRAM

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ABSTRACT

A design of an insoplanogram of a tablet type that is aimed at simulating insolation and the degree of shadowing of the territory of different-height building system and buildings in southern geographic latitudes by determining the optimal gap between buildings through identifying shading and insolation, is described in action

Key words: insolation, insoplanogram, shading, radiation, light and shade, buildings, development

To regulate the light and microclimate of urban development and ensure sanitary and hygienic requirements, it is important to determine the optimal gap between buildings. Identification of the area of shading and insolation is one of the most important tasks in determining the density or percentage of development of residential areas, as well as urbanized areas in general. Architects, builders, hygienists, doctors, and other specialists pay great attention to this issue, since insolation is the most important natural factor of urban planning.

Determining the location of the building in the development system with the appropriate sanitary gaps and the choice of its orientation is one of the initial tasks of optimizing the insolation regime, which is solved taking into account the insolation, fire protection, and other requirements. Thus, it is necessary to consider purpose of a building, conditions of already developed city building and climatic features of the construction area.

To assess the mode of insolation and shading of urban areas, the author proposes an easy – to-use design of the insoplanogram of the tablet type (ITT), which allows modelling the impact of radiant energy of the sun on buildings and the building area.

Theoretical and experimental studies on insolation and natural light began more than half a century ago (in connection with the problems of architectural design) and are fully reflected, for example, in books [1–5]. They set out the methods of geometric and analytical calculations for insolation of buildings, the principles of sun protection. However, in all these and other similar works, the issues of insolation, natural lighting and UV irradiation of buildings are considered for conditions significantly different from the Central Asian and Asian countries located in the southern latitudes – from 30 to 45 degrees north latitude.

Solar-light conditions in Central Asia are very peculiar: they are characterized by a maximum in the CIS probability and duration of sunshine, the most direct, total and reflected radiation, negligible stray radiation, etc. In this regard, the regime of solar radiation in urban areas and buildings (with a significant contrast of natural lighting and great brightness of surfaces) exposed to the direct rays of the sun influences the character of light and shade.

The issues of insolation of residential premises and territories are regulated by different normative documents, in particular – [6–10].

In recent years, along with the analytical method for calculating insolation indicators, there have been works on methods of modelling the insolation regime and graphical constructions of shadows from buildings and structures in order to optimize their location and orientation on the ground [11–15].

Geometric methods of constructing the envelope of shadows from shading buildings in a given area and determining the duration of insolation in a given time interval are presented in [16,17].

Many programs have been created to calculate the duration of insolation of residential buildings and territories, see, for example, [18–20].

There are examples of underestimation or overestimation of such means of regulation as the impact of radiant energy of the sun on buildings and building areas simultaneously in both qualitative and quantitative terms. All this leads to errors that are difficult or impossible to correct after the construction of buildings and urban structures, especially in regions with hot climate. To get out of this situation, the architect-designer needs to have methods of accounting for local characteristics of insolation that are easy to use, sufficiently accurate and suitable for general practice, and have some additional data.

The analysis of the existing methods of evaluation of the insolation regime and methods of the corresponding calculation shows that the range of tasks solved by them is limited only to certain areas of design (depending on the set architectural, construction and urban planning problems). Today, there is almost no universal method that would allow a comprehensive assessment of both qualitative and quantitative indicators of insolation. The qualitative indicators of insolation include the duration of biological exposure to insolation, measured in hours, and its quantitative indicator, measured in W/m^2, is the irradiation on the surface, which is created by a parallel beam of sunlight entering the premises and on the territory of the building from the direction in which the disk of the sun is visible at the moment.

Currently, there are two ways to calculate the insolation time: with the help of an insolation – manually and with the help of specialized computer pro-

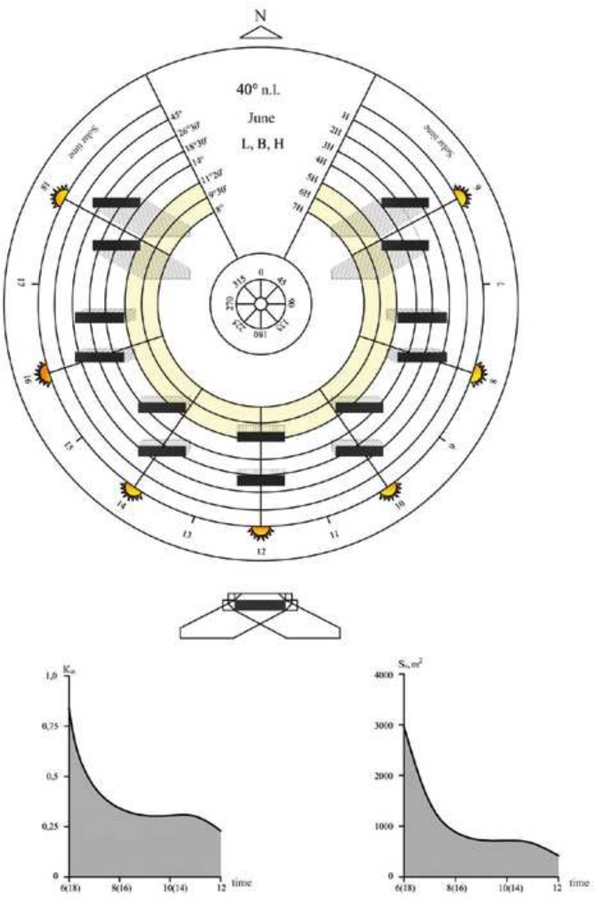

Fig. 1. ITT for evaluation of light and shade from buildings of latitudinal orientation (a) and graph of shading coefficient in the circuit of interbuilding territory K_{se} (b) [$K_{se} = K_s / K_i$, $K_s = S_s / S_g$, $K_i = S_i / S_g$, where S_i, S_s and S_g – areas of insolation, shading and general area]

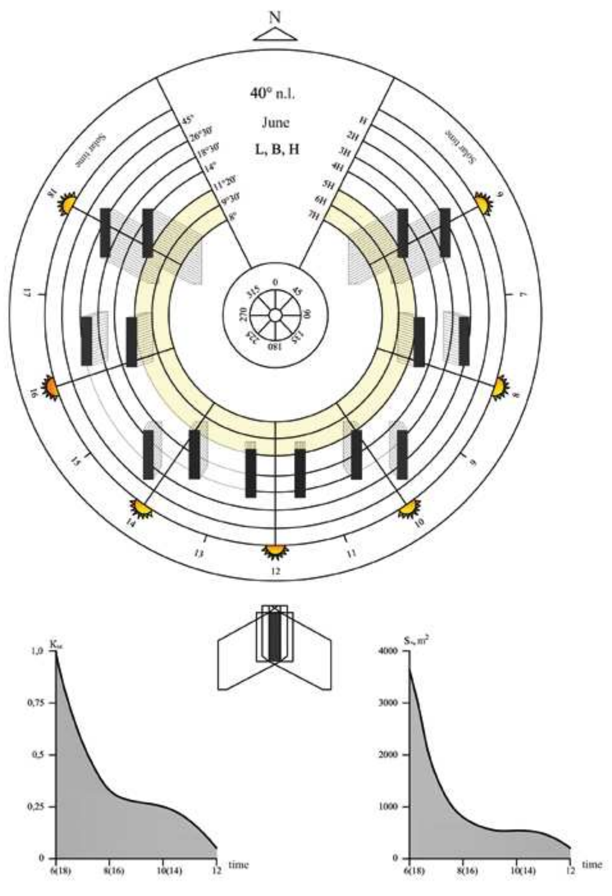

Fig. 2. ITT for evaluation of light and shade from buildings of meridional orientation (a) and graph of shading coefficient in the circuit of interbuilding territory K_{se} (b) [$K_{se} = K_s / K_i$, $K_s = S_s / S_g$, $K_i = S_i / S_g$, where S_i, S_s and S_g – areas of insolation, shading and general area]

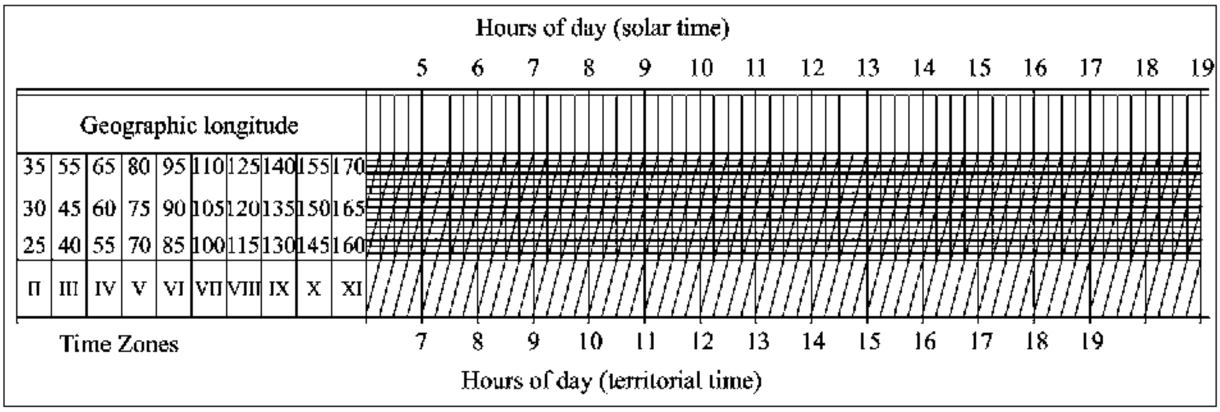

Fig. 3. Scale of solar-daylight savings time

grams. The computer method allows calculating qualitative index of insolation, which is very important for performance of expert works in cases of the compacted building. The manual method is simple, labour-intensive and rather exact way to assess not only this qualitative indicator (at architectural and construction design), but also quantitative insolation index of an object.

In this regard, the calculation methods that simulate the natural course of insolation on the building plan have practical application in urban planning to the present time. They allow using tablet type devices to determine both qualitative and quantitative insolation indicators directly on the scheme of the building plan made at the appropriate scale.

An easy-to-use device for determining the values of qualitative and quantitative indicators of insolation and shading zones is the proposed ITT built on the basis of astronomical data on the positions of the sun and nomogram standards of the Sternberg Astronomical Institute.

The ITT proposed for the practice of designing does not claim to be universal in application. The calculations made with ITT and the graph of solar radiation intensity attached to it do not contradict the existing methods of estimating the insolation regime – with the help of different graphs, tablets and computer calculations. (On the contrary, they make up for the lack of assessment of the “energy side” of insolation).

Difference between calculation of insolation indicators by means of ITT and other methods of calculation consists that ITT allows predicting the insolation mode concerning a chiaroscuro on the plan of different height building and making “energy” calculation.

The construction of gaps between buildings, their comparison and analysis of the conditions of insolation of the territory and buildings using the proposed ITT allow us to conclude that at any orientation of the building, the gaps are a function of the area of the envelope of shadows for the normative duration of insolation (Fig. 1 and Fig. 2).

The principle of construction and operation of ITT is caused by the interaction of the position of the insolated or shaded object on the earth’s surface and the course of the sun in the sky during the daylight hours from 6 to 18 hours solar time. The construction of the envelope of shadows from buildings is made in the period from sunrise to sunset for different geographical areas for the necessary warm and cold months of the year, as well as in the period provided for in the construction and sanitary standards.

ITT consists of a flat transparent base. The trajectory of the sun for the required month of the year within the azimuth from 0 to 360^{o} and the position of the insolated object are given in a horizontal plane and expressed in a circular contour of the Central part of ITT for the period of daylight.

In the upper part of the device, the pointer of its direction to the North is applied when the device is superimposed on the building scheme. Under the direction indicator, there are the latitude and building parameters – length L, width B and height H.

Basis of ITT – circular grid formed by open circles applied at intervals H equal to the height of the shading building in the scale of the drawing. To the right of the direction indicator is the length of the radii of the incomplete circles that are multiples of the height of the shading object 1H, 2H, 3H, 4H, 5H, 6H, and 7H. To the left is the angular height of the sun (45°, 26°30’, 18°30’, 14°, 1 °30’ and 9°30’ and 8°) at the time of the beam passing through the top of the building with a height of *H* in the centre of the device.

On ITT, the insolation time is given by the average solar time. The conversion of solar time to territorial time or vice versa for the territory of the CIS according to the given solar-daylight scale is presented in Fig. 3.

Qualitative indicators of insolation of the building area, facades of buildings and premises, as well as the construction of the envelope of shadows and the shading area, are determined by applying a transparent planchette directly to the development plans.

The duration of the thermal effect of insolation with the establishment of the amount of incoming solar energy is determined in accordance with the schedule attached to ITT, Fig. 4.

ITT determines indicators of insolation and its impact on horizontal and vertical surfaces oriented to azimuths from 0 to 360° and shaded by buildings, canopies, balconies and loggias.

Parameters determined by ITT in assessing the insolation of buildings are the next:

– Direction, area, time and duration of insolation and shading;

– Direction, area, time and duration of UV exposure to insolation;

– Direction, area of irradiation and shading;

– Direction, area, time, duration of thermal exposure to insolation with the establishment of the amount of incoming solar energy;

– Areas for planting trees and various shading devices.

Using ITT and according to development plans made on a scale from 1:500 to 1:2000, the optimal orientation of buildings and the size of the gaps between them in the building are established in the residential area and the territory of cities according to the height of the shading object, and it is also planned to place sports and children’s playgrounds, driveways, walkways, green spaces, recreation areas, public utility sites, etc.

For insolation calculations in flat conditions, the height of a building is usually taken to be its size from ground level to the highest elevation of the building. The ground level under the shading building can be (by horizontal marks) above or below the point under study. In this case, it is necessary to take into account the terrain. The height of the shading object should be taken as the difference between the highest mark of the cornice of the shading object and the mark of the point under study.

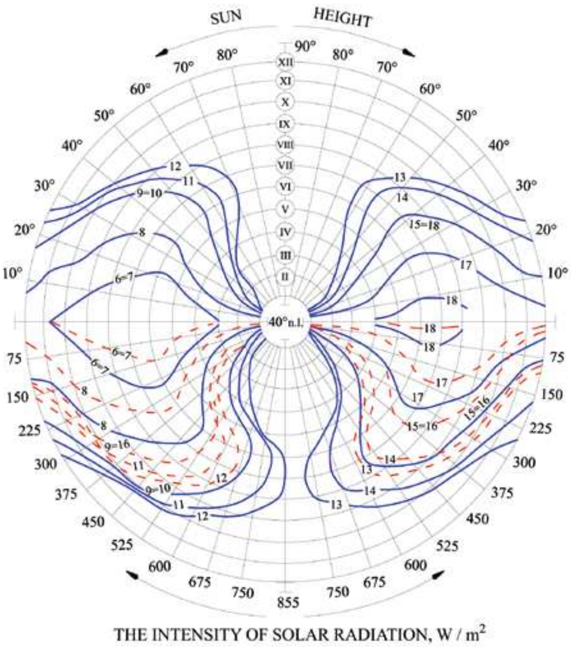

Fig. 4. Intensity of total (—) and direct (—) solar radiation for 40 degrees north latitude during the year from 8 to 18 hours solar time, W/m^2

The selection of the necessary device with the determination of the estimated height of the shading building is the first and mandatory condition that must be observed in all insolation calculations.

The accuracy of the assessment of insolation depends on the latitude, scale of the drawing, the size of the shading object, and the direction of the meridian of ITT.

The proposed ITT is designed to predict the mode of insolation and to identify the degree of shading of the territory of different-height buildings in order to optimize the volume-planning structure of buildings and urban areas, their improvement, landscaping and selection of sun protection devices.

The initial stage of design and survey work on the formation of a planning scheme of urban development with a comfortable environment is the assessment, analysis and regulation of the duration of insolation of the active layer of the building, which is the key climate-forming factor of the premises and the development areas.

Thus, the ecological situation of the territory of urban development and buildings erected in a hot climate depends on the prediction and assessment of the insolation regime in qualitative and quantitative terms at the design stage.

The developed ITT is recommended for use in design and survey works in architectural and construction design of buildings and in urban planning in the development of general plans of settlements, cities, scheme of planning, organization of land plots and in solving a certain range of tasks to assess the insolation regime.

This design of ITT with the schedule of solar radiation intensity attached to it and a technique of using the device were tested in a number of design and survey works and in educational practice of students of architectural and construction universities, having received a positive assessment.

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EXAMINATION OF CONDITION OF HISTORICAL TRANSPARENT STRUCTURES OF THE PUSHKIN STATE MUSEUM OF FINE ARTS

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ABSTRACT

The article describes the results of the second part of examination related to transparent structures of the Pushkin State Museum of Fine Arts: the lantern lights. The structures are cultural heritage of federal importance and are subject to state preservation. Based on the results of comprehensive examination, the conclusions were made that these structures are in unsatisfactory condition and materials were prepared for development of recommendations concerning their restoration.

Keywords: transparent structure, lantern light, heat transmission resistance, thermal behaviour, condensate, metal structures

In the first half of 2018, the Structure Physics Research Institute (NIISF) conducted examination of historical windows of the 1st floor of the main building of the Pushkin State Museum of Fine Arts (hereinafter referred to as Pushkin Museum) [1–3]. This article describes the next stage of examination of the museum's historical transparent structures, namely assessment of conditions of the lantern lights [4].

Fig. 1. illustrates the scale of the transparent structures of the Pushkin Museum.

Such complex roofs are rather common for art museums. Fig. 2, for example, demonstrates the building of the Lille Palace of Fine Arts (France) built in 1897 (15 years before the main building of the Pushkin State Museum of Fine Arts). In the 1990's, the museum successfully undergone restoration and was opened again in 1997. Therefore, the Lille museum somehow becomes a reference point

Fig. 1. Model of the main building of the Pushkin State Museum of Fine Arts

Fig. 2. Lille Palace of Fine Arts

Fig. 3. Systems of natural lighting of museums: *a* – one of the halls of the Pushkin State Museum of Fine Arts; *b* – similar hall of the Lille Palace of Fine Arts

Fig. 4. Roof beam joint with traces of corrosion

Fig. 6. Exterior of the transparent structure in 2018

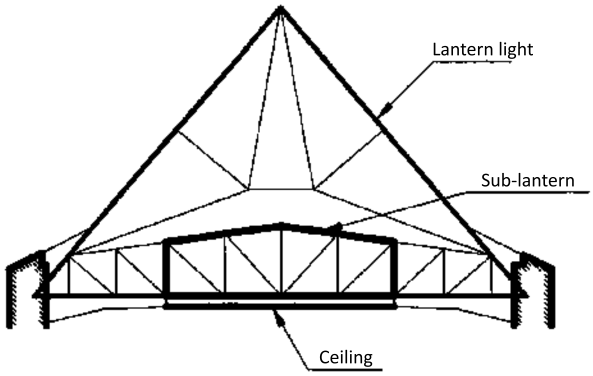

Fig. 5. Cross-section of the transparent structure

for restoration the Pushkin State Museum of Fine Arts on Volkhonka street.

Necessity of such transparent structures in museums of fine arts is substantiated by the fact that most of fine art works look the best way under natural lighting [5]. The basics of natural lighting of buildings (including museum buildings) were developed back in the middle of the previous century [6, 7] and virtually all modern galleries are equipped with lantern lights to the largest extent possible. Fig. 3 demonstrates the halls of the Pushkin State Museum of Fine Arts and the Lille Palace of Fine Arts. General trends in lighting of exhibits in these buildings are obvious.

Due to the decision of establishment of the Museum Quarter on Volkhonka street and adjacent streets, the adjacent buildings were signed over to the Pushkin State Museum of Fine Arts, and, like the main building, these buildings are currently undergoing serious reconstruction, and restoration of working efficiency of transparent structures (lantern lights) should be a part of this process.

The studies, performed by the specialists of N.M. Gersevanov NIIOSP in 2014–2015 [8], have shown that the transparent structures of the main building of the Pushkin State Museum of Fine Arts are in unsatisfactory condition. In particular, 65 dangerous to use sections and 11 sections with limited operating capacity were identified.

The dangerous to use sections are primarily the areas of strong (up to 100 %) corrosion of joint plates, angle legs and inclined elements connecting the frame work to the walls of the building as well as thread stripping of bolts. Such areas are located primarily at corners of the buildings, in the vicinity of neck gutters and ridge part of frame works.

For illustration of the conclusions of the study [8], only one example is presented below (Fig. 4).

The museum’s transparent structures consist of three main elements: the main element (lantern light); the sub-lantern element; the lower element (ceiling of diffuse glass above the exhibition halls).

Nowadays all these elements are made of one glass pieces attached to metal T-profiles (Fig. 5). All

Fig. 7. Elements of the lantern light structure in 2018

Fig. 8. Ridge of the lantern light transparent structure and traces of repairs

the structures were installed during construction of the museum in the beginning of the previous century (some restoration works were performed in the 1960–1970's). Fig. 6 shows contemporary exterior of the transparent structures of the museum.

The transparent structures (at least those of the lantern light and the ceiling) installed in the main building of the Pushkin State Museum of Fine Arts, like most of its other structures, are subject to state supervision and their full replacement is prohibited by law. Each element of the transparent structure is analysed separately.

The current state of the structural elements of the main element of the museum's transparent structure (***lantern light***) is shown in Fig. 7.

Briefly summing up the results of our examination, the following may be noted:

– The roof pitches are made of glass fragments with thickness of 4 mm (average dimensions of glass fragments are (415×1110) mm), the pitch is 50°;

– The glass fragments are installed on T-profiles (35×35×3) mm which are supported by horizontal steel angles (90×10) mm;

– The main frame works are made of two welded (bolted?) beam channels so that they actually have a profile of an I-beam;

– Dimensions of the frame work cross-section are as follows: width of 150mm, height of 140 mm, thickness of 5 mm to 7 mm (depending on thickness of the coating applied over the previous 100 years);

– Spacing between the frame works is not uniform and its average value is 2,850 mm;

– The height of the ridge of main element of the triangular lantern light from the floor of the roof space is about 8,000 mm and that of the semi-cylindrical lantern light is 10,000 mm;

– The glass fragments are installed with higher fragment overlapping the lower one (like roof tiles) with a small spacing providing both additional ventilation and natural removal of condensate generating on the inner surface of glass (V.G. Shukhov's idea);

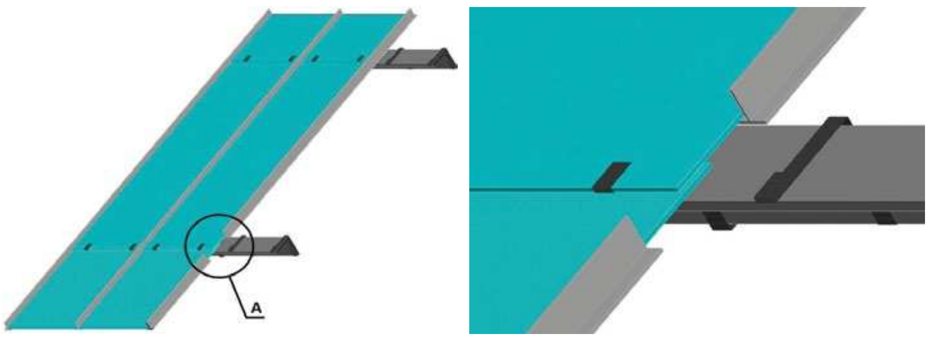

Fig. 9. Fixation of the lantern light glaring elements to horizontal guides

Fig. 10. Inner space and exterior of the sub-lantern

– The glass fragments are fixed to the horizontal steel angles by means of clips made of sheet steel;

– The joints of glass and T-profiles are sealed with joint sealer (with caulking compound in some places) with poor quality: there are holes admitting precipitation;

– Ventilation of the space beneath the glass is performed by means of airways made of sheet steel and located in the upper part of pitches (in each next but one segment);

– The ridge of the roof has numerous traces of leakages and patching up with poor quality (Fig. 8);

– There are numerous traces of leakages as well as broken glass fragments in the lantern light glaring;

– In the course of maintenance of lantern light glaring, glass was replaced by plywood sheets and/or galvanised steel sheets (Fig. 8);

– Lantern light glaring is dirty and was not maintained for a long period of time, which significantly reduces its lighting properties.

The scheme of lantern light glaring is shown in Fig. 9.

The second element of the transparent structure (***sub-lantern***) consists of triangular structures and has the following dimensions: lower width – from 4,000 mm to 7,000mm, edge height – 970 mm, centre height – 1,410 mm. The size of sub-lantern is a little smaller in semi-cylindrical lantern lights. Glazing of sub-lanterns is made of one glass pieces with thickness of (5–6) mm installed in T-profiles similar to those used in the main element of the transparent structure.

The pitch of the horizontal glaring of the sub-lantern is equal to (10–15) angular degree.

Current state of the sub-lantern glaring absolutely does not comply with its intended use, i.e. provision of natural lighting of exhibition halls. That is why there are numerous additional light sources installed in the space between the diffuse ceiling and the sub-lantern (Fig. 10).

Fig. 11. Exterior of the diffusing ceiling with the lighting devices

For prevention of leakages to the main halls, the sub-lantern is currently covered by fabric, polymer film, etc. (Fig. 10).

Due to the constant leakage, the profiles on which the glazing of the side panel is corroded and need to be replaced and or deep cleaned and coated with special compounds

Diffusing opaque glass (with rather dense frosting) in the ***ceiling*** is installed horizontally on the same metal T-profiles with cross-section dimensions of (35×35×3) mm as the other elements of the transparent structure (Fig. 11). Its view from the exhibition halls is shown in Fig. 3, *a*.

To define the areas with uniform heating performance of the examined transparent structure and to discover the ingress zones, thermal imaging inspection was performed. For this purpose, *NEC TH-9100* thermal vision camera and a pyrometer were used. The inspection was performed with consideration of requirements of GOST R [9].

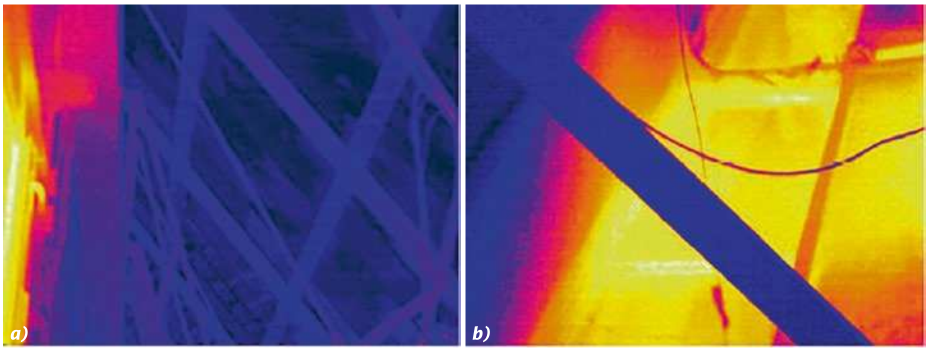

Fig. 12. Thermographics of the transparent structures:
a – the lantern light;
b – sub-lantern and the ceiling

The thermal imaging inspection of the examined structure was performed at ambient temperature of t_a= –4.5 °C and internal air temperature of t_i = +20 °C (Fig. 12).

The temperatures of the transparent structure were measured in some areas above the exhibition halls (27 and 29) and in these premises themselves (with lighting devices on).

Ambient temperature: – 4.3 °C.

The area above Hall No. 27 – temperature under the outer lantern light: (3–5) °C; temperature under the sub-lantern: (9–10) °C; temperature of sub-lantern side glazing: 8,6 °C.

The area above Hall No. 29 – temperature under the outer dome: (3–5) °C.

Fig. 13 shows the layout of sensor positioning and Fig. 14 shows the values of temperature and heat current at different points of the transparent structure.

One of the main conclusions of the examination which may be used for planning of thermal behaviour of the transparent structures during their restoration is that the difference between the ambient temperature and the temperature under the main lantern light in the roof space is (8–10) °C.

In order to define reduced total thermal resistance R_o, the inspection was performed by means of heat current and temperature meters. The measurements were performed in accordance with recommendations [10, 11].

The obtained values of R_o of the lantern light glazing and sub-lantern + ceiling glaring: (0.18–0.20) (m^2·°C)/W and (0.40–0.45) (m^2·°C)/W respectively.

The important result of this part of inspection, which may be used for planning of thermal behaviour of the transparent structures in the course of their restoration, is that R_o increases by (0.20–0.25) (m^2·°C)/W if glazing of the sub-lantern and the ceiling is assessed together.

Based on the numerous on-site investigations of the historical transparent structures of the main building of the Pushkin Museum, the following major conclusions were made:

1. The transparent structures are in a very bad condition (non-repairable in some cases): there is rust on nearly all structures, holes, non-working hardware, etc;

2. The characteristics of the transparent structures (reduced total thermal resistance, air permeability) do not comply with the applicable regulatory documents;

3. The condensate generated on the inner surfaces of the transparent structures in cold periods causes negative impact on durability of the structures;

4. It is necessary to provide special sun-protecting devices and curtains diffusing direct sunlight for the structures of the lantern lights facing the East, the South and the West facades of the main building of the Pushkin Museum;

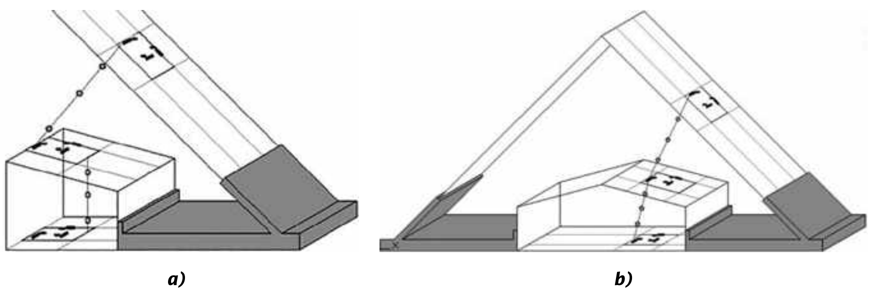

Fig. 13. Scheme of positioning of temperature and heat current sensors:
a – above Hall No. 27;
b – above Hall No. 29

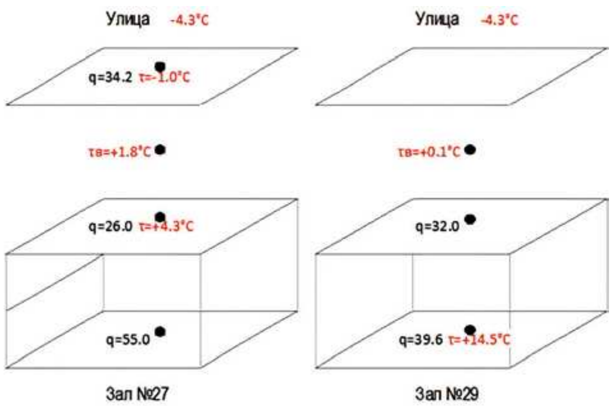

Fig. 14. Values of temperature τ and heat current q (W) at the main points of the selected premises

5. In view of the planned comprehensive reconstruction of the museum, establishment of the Museum Quarter on Volkhonka street and impossibility of replacement of historical transparent structures, which are cultural heritage subject to state supervision, it is necessary to develop the measures aiming at increase of their efficiency.

The results of heat engineering calculations of different variants of transparent structures efficiency increasing and recommendations for their restoration will be presented in the following article by the authors.

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AN EMPIRICAL VALIDATION OF ESTIMATION MODEL (OPTIMLUM) FOR ENERGY EFFICIENT LUMINAIRE LAYOUT DESIGN IN OFFICES

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ABSTRACT

This study performed with the purpose of constructing and validating a model named OptimLUM (Optimizing Luminaire Layouts) to estimate the most accurate location, number and type of artificial light sources according to average illuminance and maximum uniformity in an office. OptimLUM is appling through Excel Spreadsheet to develop the model and uses Evolver, which is basing on genetic algorithm to implement optimization routine. To validate the reliability of the proposed model, luminaire layout scenairos generated for two types of luminaires after taking illuminance measurements in an actual office. OptimLUM illuminance values were comparing statistically with measurement and DIALux results to test the applicability of the model. The model performance is highly accurate in determining luminaire positions: coefficient of determination R^2 and coefficient of variation CV were equal to (86–99)% and to (0.04–0.12) respectively, and for all scenarios. Its outputs are closer to the actual measurements when compared with DIALux outputs.

Keywords: luminaire layout, optimization, offices, artificial lighting

1. INTRODUCTION

Lighting design of a workspace is a complicated task that includes multiple criteria based on many physical and psychological aspects [1]. Occupants need to work in comfortable and healthy environments but also in energy efficient buildings. A significant amount of office buildings' energy consumption is due to artificial lighting [2]. The planning of artificial lighting systems involves in office buildings, like any other buildings, consideration of the metrics of lighting quality and quantity [3]. These metrics are illuminance, uniformity and the location of luminaires. Lighting designers select and decide on the types of lamps and luminaires according to these metrics and as result of mathematical simulations of lighting installations. Softwares, such as DIALux, Relux, Radiance, use engineering computational tools and architectural rendering together. These softwares are good assisting tools for lighting designers, presenting luminaire layout alternatives due to grid layouts [1,4]. However, they are not result in the most accurate or optimum position of luminaires irregardless of array layout arrangement and without the intervention of the user. Potential solutions/designers' assumptions for better performance cannot be confirmed or rejected through effective search mechanism. In this sense, it is necessary to propose optimal and alternative solutions by maximizing comfort conditions and minimizing energy consumption by practical optimization techniques, such as genetic algorithm, heuristics and meta-heuristics etc…

There are some researches about deciding luminaire positions. Mourshed et al. proffer a novel method named Phi-array to fit visualization and decide luminaire position. Authors used the simulation program Radiance to get illuminance performed with a frame, which includes illuminances of reference points. Similar grid frame was appling for lighting source locations estimation. The both illuminance on the horizontal and vertical surfaces are analyzing by simulation program. These, three dimensional, data are evaluating by Genetic Algorithm for optimization process [3]. Researchers continue developing and using different methods while they also validate them to show their reliability. F. Cassol et al. presented a new methodology to find luminaire location by getting satisfying illuminance and lowest power consumption. The generalized extremal optimization (GEO) algorithm is used to solve the problem and this type of solution technique supply a set of luminaire layout solutions [5]. Another study designed a fuzzy logic controller according to daylight, users' movement and lighting comfort. A lighting system was set up in an office and the controller is experimentally tested by getting illuminance measurements [6]. De Rosa et al. prose a new code about prediction of daylight illuminance on the inside surfaces. The code name is INLUX was validated by comparing its calculated illuminance with illuminance measurements inside a scale model 1:5 [7].

There are many ways to validate new proposals about lighting studies. With reference to these studies, the main objective of this study is to evaluate the prediction accuracy of interior illuminances carried out by OptimLUM through comparison of the simulation results with measured data. Thus, the performance of optimization model OptimLUM was empirically testing by getting measurements in a test case and by the DIALux models to explore its applicability and validity. The validation process involves the formulation of a linear regression line developed in scatter diagrams to compare the measurements and proposed model illuminances for different luminaire layouts and observe the strength of their relationship. Coefficient of determination (R^2), root mean square error (*RMSE*), normalized root mean square error (*NRMSE*) and coefficient of variation (*CV*) were also calculated.

2. APPLICATION OF PROPOSED MODEL OPTIMLUM

This section presents process of setting an optimization model through calculating the uniformity and illuminance to conclude the best possible layout design. User's data generation about selected room and luminaire type and the calculation method to acquire the optimum solution are explaining.

2.1. Construction of User's Data Set

Lighting design can be simplified by determination of the correct luminaire positions to avoid unbalanced illuminance distribution while selecting the accurate light source for the volume to be illuminated [8]. User needs to contribute some basic information about luminaire type, office dimensions and surfaces to Excel Spreadsheet. Model was developing through Excel. Information about office consists of room dimensions (height, width and length) and surface reflectances (wall, ceiling and floor). A luminaire database for offices was generating for OptimLUM users to select luminaire type effortlessly. This database includes luminous flux and photometric data of luminaires from various manufacturers. Photometric data not only provides luminous intensity of luminaires that varies according to vertical (Gamma, γ) and horizontal (*C*) angles but also makes it possible to calculate illuminance.

2.2. Calculation Process

The basic metric for visual comfort is illuminance. Calculation of illuminance can be possible through a certain number of mathematical processes related to the behavior of light to get adequate illuminated spaces. These mathematical calculations guide designers to decide lighting sources' layout. Point method is one of them based on illuminance at any point on observed surface [9]. Uniformity is another metric that helps to understand differentiation of illuminance values in the whole space. To make the OptimLUM run flexible at different room dimensions and with different luminaires, calculation formulas were encoding in Visual Basics (VBA). The first step was to generate grids on the working plane and ceiling to determine calculation points and luminaire location points. Their coordinates on x, y and z plane were generated through calculating the arithmetic mean of the room length and width. Calculation points and luminaire location points placed at least of 0.46 m away from the surface of the walls. The grid size of calculation points was set to be (400×600) mm. Furniture not taken into acoount in calculations. Since mostly, their layout can be flexible. Workplane illuminance has the significance in uniformity and average illuminance calculations. Therefore, the model is an abstraction of the empty office geometry. Suspended ceilings generally used in offices and their size mostly (600x600) mm. Because of these reasons, the grid size of luminaire location points was (600x600) mm, and, according to architectural qualities of the space, recessed mounted modular luminaires were selecting. Such non-aligned grids were using to get the contribution of various distribution angles of the luminaires, and that resulted in dissimilar illuminances. Based on these grids, γ and C angles between calculation points and location points of light source were calculating as outputs at this step. C angle is the resulting angle between light source and calculation point on horizontal plane, Fig. 1.

The model provides us flexibility to change the grid size and its distance to the wall so there is a possibility to include different dimensions of luminaires i.e. linear type. The orientation of luminaires to specify their position is defining by C and γ angles.

Two components have impact on illuminance considering point method. These are direct and indirect component of horizontal illuminance. Direct component is the effect of luminous intensity from light source on a point. Direct component calculating according to given formula (1) is using:

$$E_h = \frac{\left(\frac{\Phi}{1000}\right)\cdot I_{rel}\cdot \cos^3\alpha}{h^2}, \quad (1)$$

where Φ is total luminous flux of lumuminaire, I_{rel} is the reduced luminous intensity on the point according to C-γ angles (cd/klm), h is the vertical distance between the lamp and the point, and α is the angle between these [10]. Total direct illuminance would be calculating by repeating this formula (1) for all concided points of space.

To calculate indirect component (E_{ind}) from the operation of the light occurring by reflection from surfaces formula (2) is using:

$$E_{ind} = \frac{\varnothing}{\sum F_n}\cdot\frac{\rho_{avg}}{1-\rho_{avg}}, \quad (2)$$

where $\rho_{avg} = \frac{\sum \rho_n F_n}{\sum F_n}$, Ø is the luminous flux leaving the luminaires, $\sum F_n$ is the total area of the room surfaces, ρ_n is the reflectance of each surface and ρ_{avg} is the average reflectance of all room surfaces (2).

Uniformity is significant to understand differentiation of illuminances on all surfaces. Because different lighting design alternatives proposed may cause some bright or darks regions in the horizontal plane due to the overlap or gap of the luminous intensity distribution curve. Non-uniform light distribution could cause glare when one region in the interior space is brighter than the general brightness [9]. Generally, it is defining as ratio of the minimum to the average illuminance. Yet, this ratio is an overall measure to give an idea about illuminance balance. To test illuminance fluctuations in detail, mean relative deviation (*MRD*) (3) is using to calculate relative deviation of illuminance at each point from the average illuminance of the whole space, as cited in literature [10].

$$MRD = \frac{\sum_{i=1}^{N}\left|E_i - E_m\right|}{NE}. \quad (3)$$

3. OPTIMIZATION APPROACH

Optimization is a progress to find most appropriate solution for a problem having many conceivable solutions. EVOLVER6 (ADD-INS for Excel) was used as optimizer which is for non-linear optimization problems and the EXCEL spreadsheet application [13]. EVOLVER uses genetic algoritm (GA) which is an optimization method based on Darwinian principles of natural selection and OptQuest Engine, which includes metaheuristic, mathematical optimization, and neural network components to get best solutions to decision and planning problems of all types.

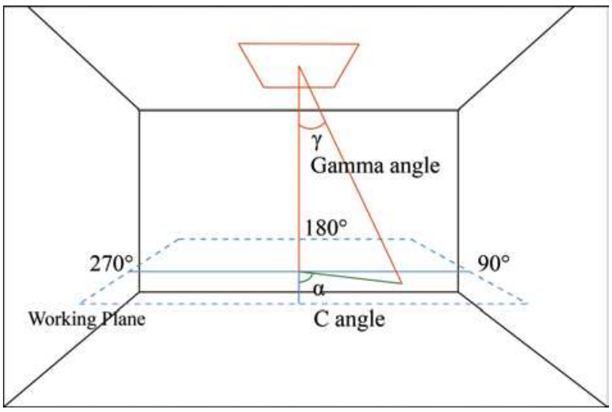


Fig. 1. Gamma(γ) and C angles between calculation points and location points of light source

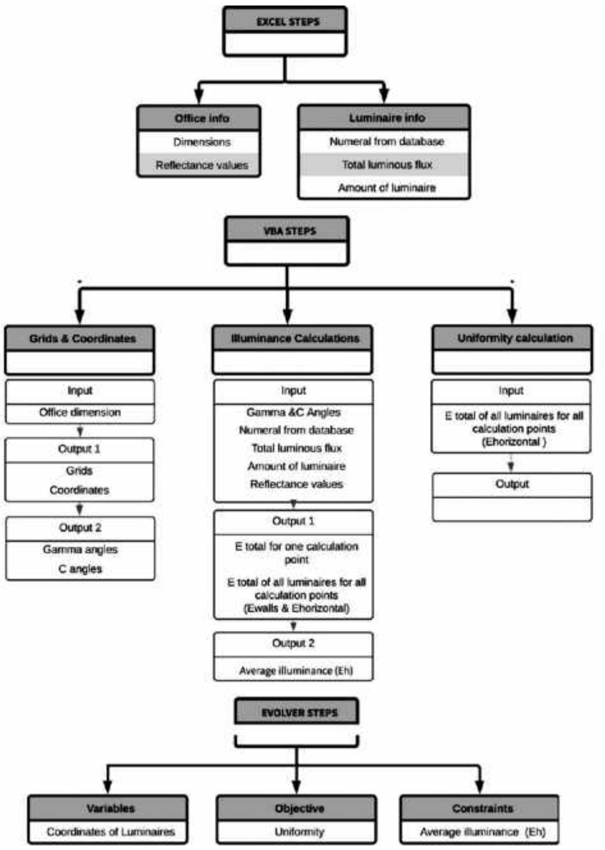


Fig. 2. Flow chart of calculation progress

The optimization model includes many decision variables based on the objective function, and constraints. So, all possible luminaire location points, illuminance at each calculation point, average illuminance and uniformity (*MRD*) were calculated and were used as the main input data in the optimization model. Here, the primary objective of the research is to get illuminance uniformity (4) closer to zero on the working plane (0.8m) that means minimum deviation between illuminance levels at each calculation point [12]. There are two hard constraints, which are recommended illuminance between (300–500) lx [14], (5, 6). E_{avg} is the average illuminance of working place. E_i is the illuminance level at one calculation point, and E_m is the mean of illuminance at all these points.

Variables are to find location of luminaires:
$(x_1,\ y_1,\ z_1),(x_2,\ y_2,\ z_2),(x_n,\ y_n,\ z_n)\ldots\ldots$

Minimize uniformity: $MRD = \dfrac{\sum_{i=1}^{N}\left|E_i - E_m\right|}{NE}$

is subject to: $300 \le E_{avg} \le 500$ (4), [12].

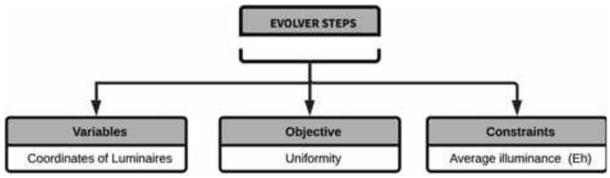


Fig. 3. Flow chart of optimization progress

4. EMPRICAL VALIDATION OF OPTIMLUM

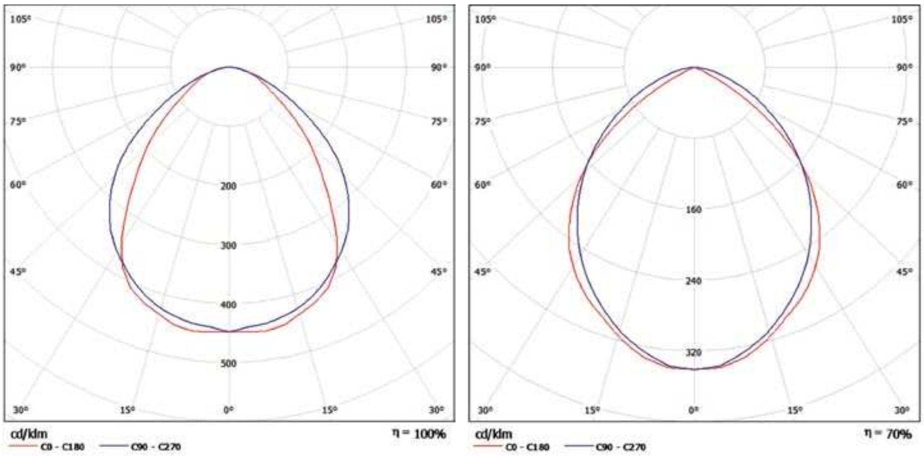
To test the accuracy of the model outputs an office illuminance selected as a case study. An actual office room located at İzmir Institute of Technology, (5.33×3.32×2.9) m in size was testing to check the proposed optimization model. Luminance meter was used for reflectance coefficients measurements, which were calculated for walls, floor and ceiling in accordance with formula (5), [15].

$$\rho_s = \rho_{white}\frac{L_{surface}}{L_{white}}, \quad (5)$$

where ρ_s is the reflectance value of surface, ρ_{white} is the reflectance value of white surface, $L_{surface}$ is the luminance of measured surface, and L_{white} is the luminance of white surface. According to these measurements, ρ_{wall} was calculated as 0.37, $\rho_{ceiling}$ as 0.27 and ρ_{floor} as 0.60.

Two different luminare types were selecting for the test case: LED and FL. Luminous flux of luminaire with LED is 3700 lm while the one with FL is 3780 lm. OptimLUM ran two times with two luminaires, defining luminaire location grids and calculation grids initially. The first grid consists of 40 discrete points to estimate location of light source; while there were 60 calculation points at which illuminance was calculated based on luminare data sheets (Fig. 4) one by one in each iteration.

Each light source location is designating with a number starting from the first upper left grid –1 and ending at the last lower right grid – 40. Employing these two grids, objective function and constraints together, OptimLUM generated in sum 22359 possible installation scenarios for LED luminaires. The 2359 were the best trials among 19626 valid trials. It is also produced 22483 total trials for FL luminaires. The number of best trials was 9691 among 11507 valid trials. The computational times for calculating the optimal solutions were 809 s and 814 s respectively. OptQuest engine was the optimization engine to get solutions of both luminaire types.



CoreLine/ Surface-mounted/ LED
SM120V LED37S/840 PSU W60L60

Centura/ Surface-mounted/ Fluorescent
TCS160 4xTL-D18W HF C3

Fig. 4. Data sheets of selected LED and Fluorescent luminaires

Model estimated two optimum layout scenarios using three LED and fluorescent separately, presenting the minimum deviation in uniformity and satisfying the required average illuminance (Fig. 5).

4.1. Validation of Calculation Process

4.1.1. Layout scenarios for measurements and simulations (DIALux)

Besides layouts obtained from OptimLUM, two alternative ones offered to validate illuminance calculation of OptimLUM and optimized estimation of OptimLUM comparing illuminance and uniformity results (Fig. 6). In Alternative I, three luminaires were located linearly and had symmetrical distance from walls. Alternative II includes three luminaires placed arbitrarily in triangle layout (Fig. 6). One set of these three layouts analyzed including LEDs, while another set involved Fl luminaires.

In addition to these triple layouts above, to find the contribution of each luminaire to each measurement point, new layouts including single and double luminaires were determined for validation of the illuminance calculation process of OptimLUM. During the measurement step, illuminance values of single and double configurations of luminaires measured on workplane (0.8 m height) by switching on while the other luminaires are switching off in the actual test case. After this process, the 36 configurations were simulating in DIALux, additionally illuminance values calculated by OptimLUM (Table1). Calculation grid coordinates defined by OptimLUM used as illuminance measurement points in test case and as calculation points for simulation.

4.1.2. Statistical evaluation of measurements, simulation and OptimLUM calculation

Illuminance measurements and DIALux simulations aimed to test the illuminance calculation method of optimization model and to validate layout estimation of OptimLUM performance by com-

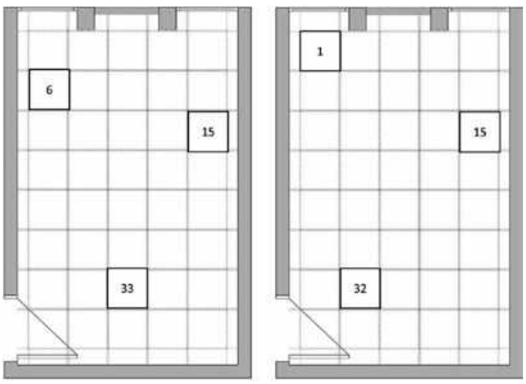


Fig. 5. OptimLUM estimations for luminaires with LED (left) and fluorescent (right)

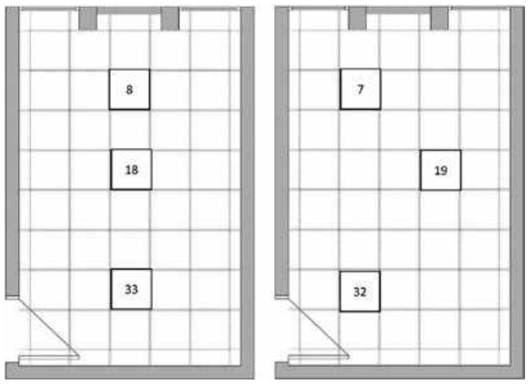


Fig. 6. Alternative luminaire layouts- Alternative I for LED and fluorescent (left) and Alternative II for LED and fluorescent (right)

Table 1. Number of Scenarios

		OptimLUM	Alternative I	Alternative II
LED luminaires	single	3	2	2
	double	3	3	2
	triple	1	1	1
Fl luminaires	single	2	2	2
	double	3	3	3
	triple	1	1	1

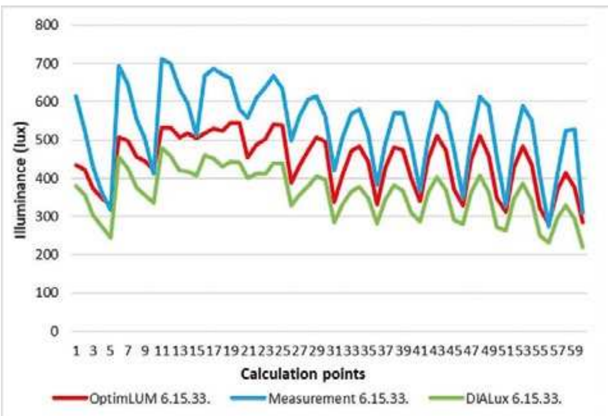
paring illuminance and uniformity. Illuminance distributions of all scenarios were comparing by line charts. It observed that OptimLUM outputs are closer to the actual measurements when compared with DIALux outputs. When we compare OptimLUM layout and Alternative I findings for LED in Fig. 7 regarding minimum, maximum, average values and standart deviations, OptimLUM outputs were very slightly higher than DIALux outputs while both of them remained lower than the measurement values. A few deviations between fluctuation lines of OptimLUM, DIALux and measurement values in OptimLUM layout observed when we compared it with Alternative I layout in Fig. 7.

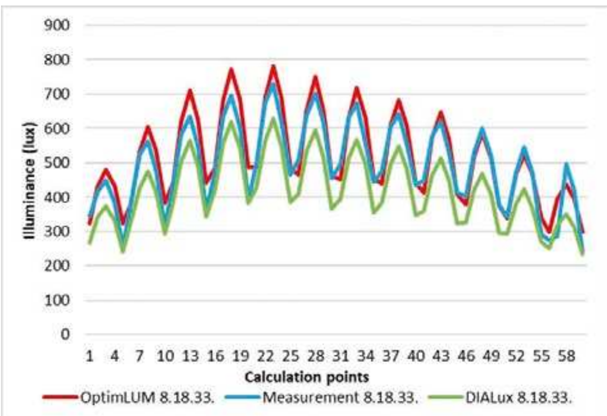
Therefore, calculated by OptimLUM illuminance values fits very well with the measurement values regarding the overall results for luminaires with fluorescent lamps.

Scatter diagrams were using to validate the OptimLUM model by comparing OptimLUM values and illuminance measurements. Excel calculated the coefficient of determination (R^2) and the linear regression equation. The model performance is highly accurate in calculating illuminance values with R^2 in range (86–99)% (Figs. 8,9 and 10). The highest coefficient of determination, which is 99 %, is observed in single luminaire configuration calculated by OptimLUM (Fig. 8) Root mean square error (*RMSE*) which is an indicator to show differences between outputs is calculated by given formula (6).

$$RMSE = \sqrt{\frac{\sum_{t=1}^{N}\left(o_{1,t} - m_{1,t}\right)^2}{N}}, \quad (6)$$

where o is the illuminance output of OptimLUM, and m is the measured illuminance for all calcula-

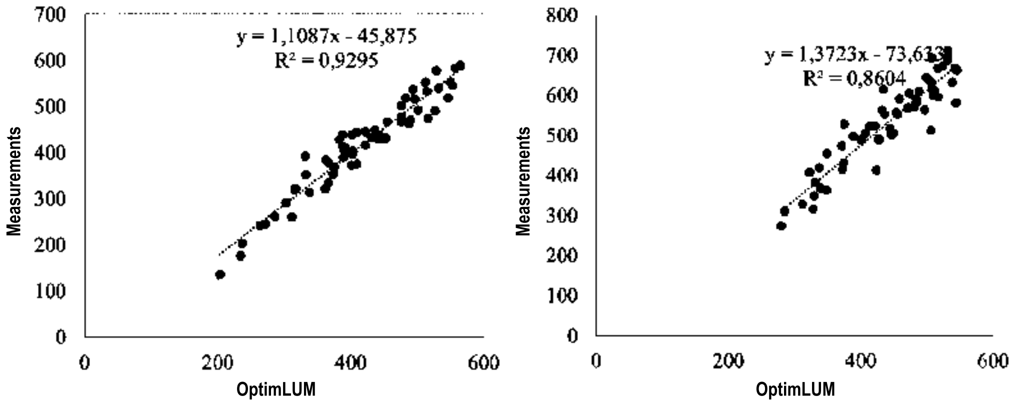




LED MODEL (6.15.33)				
	Min	Max	Avg	SD
OptimLUM	279.92	545.22	441.72	73.17
Measurements	273.90	713.00	532.55	108.25
DIALux	220.00	480.00	360.63	64.47

LED ALTERNATIVE I (8.18.33)				
	Min	Max	Avg	SD
OptimLUM	297.67	780.40	518.10	128.26
Measurements	241.40	730.00	495.63	120.87
DIALux	234.00	628.00	418.27	101.28

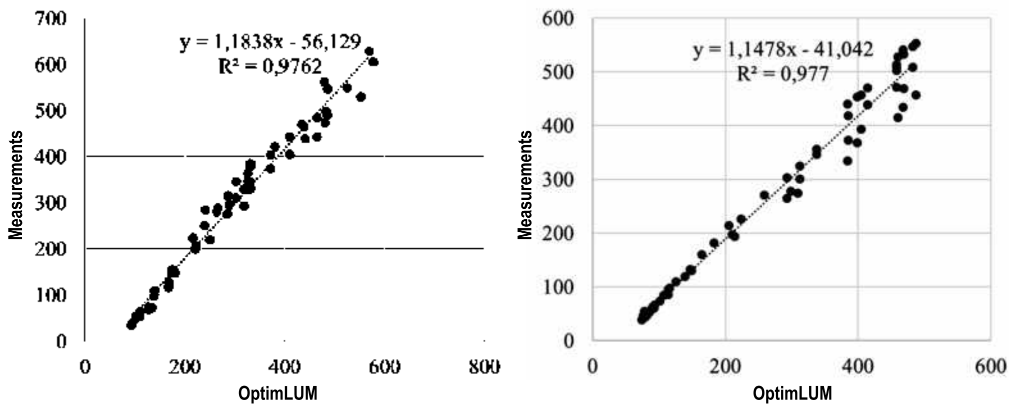
Fig. 7. Distributions of illuminance values in OptimLUM layout (left) and Alternative I layout (right) for Luminaire with LED



FLUORESCENT ALTERNATIVE II (7.19.32.)	
RMSE	25.95
NRMSE	0.08
CV	0.07

LED MODEL (6.15.33.)	
RMSE	102.90
NRMSE	0.04
CV	0.04

Fig. 8. Statistical analysis in Alternative II layout of Fluorescent and OptimLUM layout of LED



FLUORESCENT ALTERNATIVE I (8.18.)	
RMSE	35.70
NRMSE	0.07
CV	0.12

LED MODEL (6.15.)	
RMSE	34.54
NRMSE	0.08
CV	0.06

Fig. 9. Statistical analysis of double luminaires configuration in Alternative I layout of Fluorescent and OptimLUM layout of LED

tion points, N is the number of calculation points. These error values change between 17.88 lx and 102.90 lx in general. *RMSE* in range ± (17.88–18.40) lx is the least errors similarly obtained from single luminaire configuration by OpitLUM. Although model outputs fit the measurements with the highest R^2, the single LED configuration performs better with the minimum error rate. Normalized root mean square error (*NRMSE*) is another statistical error indicator to evaluate outputs reliability calculated by Eq. (7).

$$NRMSE = \frac{\sqrt{\frac{\sum_{t=1}^{N}\left(o_{1,t} - m_{1,t}\right)^2}{N}}}{o_{max} - o_{min}}, \quad (7)$$

where o_{max} is the maximum illuminance output of OptimLUM and o_{min} is the minimum illuminance output of OptimLUM. Similar and lower NRMSE values (0.04–0.08) for all configurations indicate the consistency of the OptimLUM (Fig. 6,7 and 8).

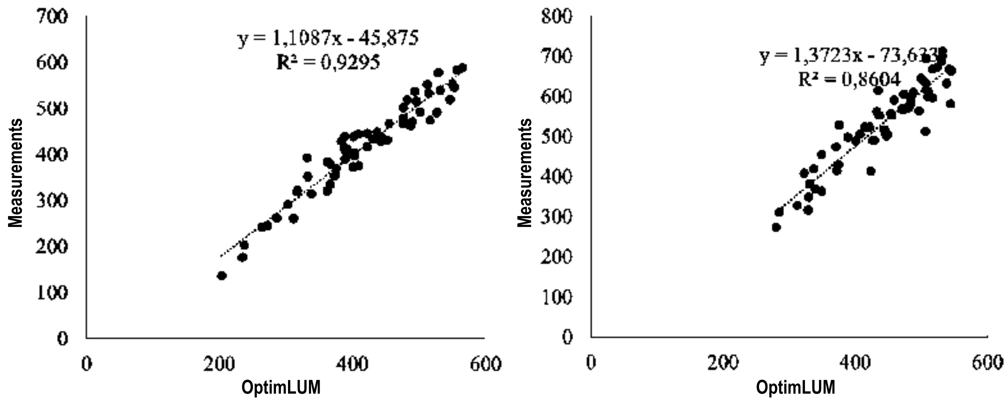
The *CV* (coefficient of variation of root mean square error) is one of statistical indices for determination of the optimization model similarity calculated by given formula (8).

$$CV = \frac{RMSE}{\bar{m}} * 100, \quad (8)$$

where $\bar{m}$ is the sample mean of illuminance measurements. As the *CV* is closer to 0 %, OptimLUM illuminance values are closer to illuminance measurements. *CV* for all scenarios between (4–12)% show the reliability of the model (Figs.6,7 and 8).

Table 2. The E_{avg} and Two Uniformity Results of OptimLUM Estimation layout, Alternative I and II for Luminaires with LED and Fluorescent Lamps

		OptimLUM	Alternative I	Alternative II
LED	E_{avg}	441.72 lx	518.09 lx	491.21 lx
	U (MRD)	0.13	0.21	0.17
	$U (E_{min}/E_{avg})$	0.63	0.57	0.45
Fluorescent	E_{avg}	327.83 lx	407.24 lx	387.89 lx
	U (MRD)	0.13	0.21	0.17
	$U (E_{min}/E_{avg})$	0.52	0.58	0.49



LED MODEL (6.)	
RMSE	18.40
NRMSE	0.05
CV	0.08

LED ALTERNATIVE I (8.)	
RMSE, лк	17.88
NRMSE	0.05
CV, %	0.08

Fig. 10. Statistical analysis of single luminaires configuration in Alternative I layout and OptimLUM layout of LED

4.2. Validation of Optimization Process

Model aimed to optimize the uniform illumination with an average illuminance based on standards [14]. Comparison between alternative layouts and OptimLUM proposed layout shows that the evolved one by OptimLUM achieved an average illuminance closer to the standards (300–500) lx, while Alternative I for luminaire with LED did not. In addition, regarding uniformity, OptimLUM layout provided better uniformity with 0.13 of MRD for both types of luminaires (Table 2). Since this shows us the minimum deviation, which is close to zero. Additionally, $U=(Emin/Eavg)$ is calculated as 0.63 which is the highest among others and closest to the reference uniformity value of 0.8 [14].

5. CONCLUSION

This work presents the development and the validation processes of a new optimization model named OptimLUM to find the optimum position for luminaires providing energy efficient layout and visual comfort requirements. Energy efficient is basing on using the minimum number of luminaires in the best possible layout design, unlike lighting design solutions of DIALux reticulate and symmetrical layouts. This proposed tool is a new alternative approach of applying an optimization model in architectural lighting research. We expect to have a less time consuming, effective and dynamic model for early design phase.

In an actual test case, this new proposed tool was studing by illuminance measurements and simulations. Two different types of luminaires (LED and fluorescent) used for case study. Apart from OptimLUM layout results for two luminaires, two alternative layouts including single and double luminaire configurations were determined. Based on illuminance distributions for all scenarios, OptimLUM outputs are closer to the actual measurements when compared with DIALux outputs. Model outputs present a high accuracy with the illuminance measurements. Considering the validity of the OptimLUM outputs, it can be using by the architect or lighting designer to determine the correct position of the luminaire to avoid unbalanced illuminance distribution while selecting the accurate light source.

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DESIGN AND SURVEY OF LIGHTING AND COLOUR AMBIENCE FOR A SUITABLE ELDERLY ENVIRONMENT

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ABSTRACT

In the context of an aging population, it is important today to take into account the needs of our seniors, to help them better live their aging. The design of colour and lighting ambiance contributes in the practice of their daily activities in their living environment. This study postulates a protocol of good practices in terms of colour and lighting to design a visual environment adapted to the needs of these users. The protocol is based on a combination of chromatic and lighting expertise. Chromatic colour matching based on Natural Colour System tools is combined with a photometric survey to characterize the visual environment. These data make it possible to establish a protocol used to design new chromatic ranges applied to new environments or to evaluate the applicability of the existing ranges.

Keywords: colour, lighting design, experimentation, evaluation, visual environment

I. INTRODUCTION

Demographic changes, affecting France like most developed countries in the world, are marked by an aging population. Projections [1] indicate that the number of people over sixty is expected to double by 2050, representing 22 % of the population. According to the same projections, there will be approximately two billion people aged more than sixty years.

In France, projections of the National Institute of Statistics and Economic Studies indicate that the over sixty will represent 33 % of the population by 2060, with the sharp increase in this population group resulting from the "baby boomer" phenomenon [2]. This significant increase will be observed until 2035 and will continue thereafter but at a much slower pace. Therefore, the problems surrounding aging will be major issues in the future and currently require our attention. For many reasons, aging can be accompanied by multiple and various pathologies, thus affecting the quality of life [3,4]. The elderly may experience feelings of insecurity or frustration with daily activities that may become complicated to implement. Cognitive and visual pathologies, and their inherent symptoms, play an important role in the emergence of difficulties.

Indeed, cognitive pathologies will generate a spatial and temporal disorientation [5,6]. The feeling of insecurity, discomfort, and/or loss of autonomy is then underpinned, especially if problems caused by visual pathologies add to those due to cognitive pathologies. Pathologies such as glaucoma, cataracts, macular degeneration (AMD), and other vision disorders lead to a decrease in the quality of their visual field, their accommodation, their visual acuity, and their perception of contrast. Overall, their perception of the environment is impaired [7, 8, 9]. Therefore, it is important to adapt the environment of the elderly to these various pathologies and their potential consequences on the habits of the elderly concerned. In fact, being disoriented, no longer recognizing space, or not identifying obstacles can be conditions that accentuate the risk of falls, incapacity, or the fear of not being able to move as before.

However, it is possible to prevent or eliminate these situations, especially by changing the visual environment, whether it concerns an existing or a future living environment [10]. Studies by Kutas [11], O'Connor [12] and Yamagishi [13] demonstrate the importance of lighting and colours. Their results show that we can improve the visual performance of the elderly through quality lighting and also give them comfort, both physical and psychological. The results also indicate a need to adapt devices, because the requirements are different for the elderly, particularly those related to aging of the visual system. By reconciling the quality and quantity of light, level of contrast, and chromatic schemes thought by and for the elderly, we obtain light and colour ambiance suitable to their needs and desires.

2. DESIGN

The design of these chromatic schemes (Fig. 1.) is inspired by the work of Frederic Tate [14], Margaret Calkins [15], Linda Adler [16], Maurice Déribéré [17], and Argos Company [18].

The study by Tate suggests a preference of the elderly for light colours, some of which are predominantly preferred, in the order green, blue, red, pink, and orange. It also refutes the preconceived ideas that favour monochromatic sets and shows instead that it is necessary to combine colours. The study by Calkins suggests that it is best to avoid combining colour shades that are too similar because it is difficult to distinguish between them while establishing certain preferences common with Tate's study. It also demonstrates that it is beneficial to combine light and dark colours for better discrimination. The study by Adler supports the above findings by showing a preference for light colours and also suggests that a combination of light and dark colours offers an opportunity for better discrimination, owing to their contrast. In his book, Déribéré presents the most appropriate luminance indices to use for designing harmonious and visually comfortable chromatic ranges, and the Argos company guide presents the optimal levels of contrast, calculated between two colours and their luminance indices, to design environments especially adapted to visual impairments of the elderly. The results thus take into account both the needs of the elderly, associated with the visual pathologies mentioned earlier, and their chromatic preferences. So, we hypothesize the preferences as follows:

1. Light shades should be used for large areas such as ceilings, walls, and floors. Dark colours should be favoured for small surfaces such as joinery elements in order to offer an optimal contrast between different elements constituting the space.
2. The ranges must be based on a three colour model, so as not to produce a visual information overload while avoiding creating a visual monotony.
3. Attention should be paid not to multiply the shades of greens or blues, and especially light blues within the same range, taking into consideration the yellowing of the eye lens in the elderly, which disturbs the reading of colours.
4. Nevertheless, studies have shown that green, and preferably light green, is a popular colour. This is also the case for light blue, red, and shades of pink and orange.

Luminance factor	Corresponding architectural elements
Luminance factor equal to 0.9	➢ Represents the ceiling
Luminance factor between 0.15 and 0.30	➢ Represents the door frame
Luminance factor between 0.6 and 0.75	➢ Represents the wall
luminance factor between 0.15 and 0.30	➢ Represents the plinth
Luminance factor between 0.6 and 0.75	➢ Represents the floor

Fig. 1. Criteria 1; 6; 7 for creating a chromatic scheme

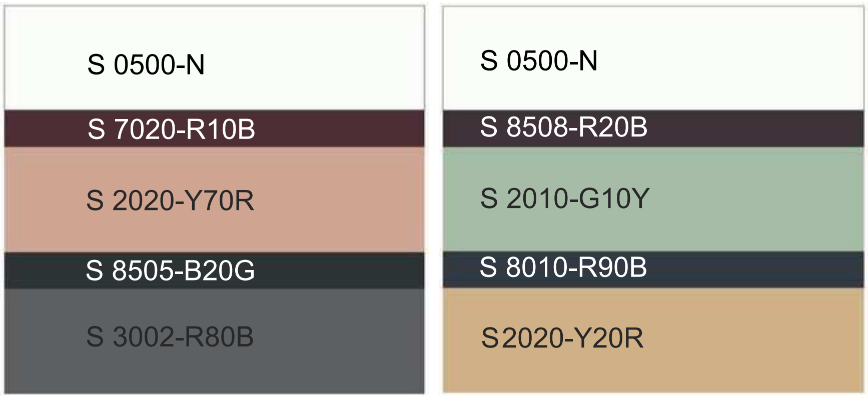

Fig. 2. Chromatic representation of ranges 1 and 2

5. However, yellow should not be a major colour constituent in the chromatic ranges because it would result in an absence of contrast with lighter spatial elements owing to a vision that may already be yellowed.

6. Thus, each colour comprising the chromatic ranges must correspond to particular luminance factor, ranging between 0.6 and 0.75 for light colours, between 0.15 and 0.30 for dark colours, and 0.9 for the colour used for the ceiling.

7. The value of this contrast, considering here the contrast of luminance, between two juxtaposed colours, must be equal to 70 % to allow an optimal visual discrimination.

2.1. Experimentation

We proceed with an experimental and empirical construction method [19], without first match Natural Colour System (NCS) colour range to existing surface colour in the environment. The design of the chromatic ranges combines chromatic knowledge and scientific assessments to allow identification of the most appropriate combinations. The first phase of optical experimentation is carried out using the NCS indexes 1950 Original and NCS box colour samples to produce visually satisfying colour combinations. Natural colour system (NCS) is a colour classification and referencing system based on human visual perception. It is now used for common inter-industrial communication through intuitive and universal coding. Each selected colour is then measured using a portable integrating sphere spectrophotometer (CM 2300d Konica Minolta), using illuminant D_{65}, corresponding to daylight at noon and having a colour temperature of 6500 K. The results are expressed in L*a*b colour model, which allows us to identify the luminance factor of individual colours. These luminance factors allow us, if necessary, to modify our colour selection so that it responds to the luminance factors mentioned in the Fig. 1 above. The contrast values are then calculated according to equation (1) [19], and colours will be selected again until chromatic ranges with contrast values corresponding to the preset settings are obtained.

$$Contrast\ \% = \frac{L1 - L2}{L1} \times 100. \quad (1)$$

In this equation, *L1* and *L2* correspond to luminance of two juxtaposed colours within the range. *L1* represents the luminance of the lightest colour and *L2* represents the darkest colour. It is this ratio between *L1* and *L2* that makes it possible to obtain the value of contrast. The design of these chromatic ranges is carried out in four phases, meeting the seven criteria previously stated. We begin by determining the organization of colours in relation to each other (criterion 1). We then select the colours that will generate the preferred chromatic environment (criteria 2; 3; 4; 5). The choice of these colours is refined by adjusting their saturation and brightness with regard to their luminance factors (criterion 6). Finally, the contrast calculations make it possible to quantitatively finalize the decision process (criterion 7).

2.2. Proposed Chromatic Ranges

The chromatic ranges presented in Fig. 2 are the result of multiple combinations done to meet the chromatic requirements and different luminance factors and contrast values. The two examples have been produced by combining the seven criteria that make up the repository presented above, and they show that it is possible to design different ambiances using colours with a high luminance factor. Such colours allow for greater visual discrimination than

Table1. Numerical Values Associated with Chromatic Ranges 1 and 2

<table>
<tr><th></th><th>NCS codification</th><th>L * a * b</th><th>Luminance factor</th><th colspan="2">Contrast%</th></tr>
<tr><td colspan="6">Colour Range 1</td></tr>
<tr><td>Ceiling</td><td>S0500-N</td><td>94*0*2</td><td>0.94</td><td rowspan="2">75 %</td><td></td></tr>
<tr><td>Door Frame</td><td>S7020-R10B</td><td>23*15*1</td><td>0.23</td><td rowspan="2">68 %</td></tr>
<tr><td>Wall</td><td>S2020-Y70R</td><td>72*13*14</td><td>0.72</td><td rowspan="2">71 %</td></tr>
<tr><td>Plinth</td><td>S8505-R20B</td><td>21*-2*-2</td><td>0.21</td><td rowspan="2">70 %</td></tr>
<tr><td>Floor</td><td>S3005-R80B</td><td>70*-1*-3</td><td>0.70</td><td></td></tr>
<tr><td colspan="6">Colour Range 2</td></tr>
<tr><td>Ceiling</td><td>S0500-N</td><td>94*0*2</td><td>0.94</td><td rowspan="2">76 %</td><td></td></tr>
<tr><td>Door Frame</td><td>S8505-R20B</td><td>22*5*-2*</td><td>0.22</td><td rowspan="2">70 %</td></tr>
<tr><td>Wall</td><td>S2010-G10Y</td><td>74*-13*10</td><td>0.74</td><td rowspan="2">68 %</td></tr>
<tr><td>Plinth</td><td>S8010-R90B</td><td>24*-2*-8</td><td>0.24</td><td rowspan="2">68 %</td></tr>
<tr><td>Floor</td><td>S2020-Y20R</td><td>74*6*25</td><td>0.74</td><td></td></tr>
</table>

colours with lower luminance factor. In both ranges in Fig. 2, the same colour is used for the ceiling because of its ability to adapt to different chromatic conditions that could be experienced.

In addition, some contrast values higher or lower than 70 % can be observed, but they are acceptable because a difference of ≤2 % is considered negligible. Indeed, at such levels of contrast, the human eye cannot perceive such an insignificant difference [20]. Table1 shows the different luminance indices of each colour as well as the contrast values that constitute the presented ranges. These chromatic ranges are examples of results obtainable by using the above experimental method. Using these ranges is recommended for the design of visual environments adapted for the elderly with visual and/or cognitive pathologies. The various colours used and the different levels of contrasts obtained make it possible to create a visual signage, which generates visual cues necessary for recognition of space.

3. EVALUATION

This method of designing appropriate colour ranges is not only a design method but also an evaluation method. We can diagnose the relevance of existing ranges based on the previous model. We identify the indices of each colour and then calculate the levels of contrast. This allows us to check if they comply with the levels recommended previously.

3.1. Materials and Methods

We carried out in a situ study (Fig. 3) at the geriatric day hospital of Robertsau, Strasbourg, France. The purpose of the study was to identify

Fig. 3. Panoramic view of the waiting room area in situ study topic

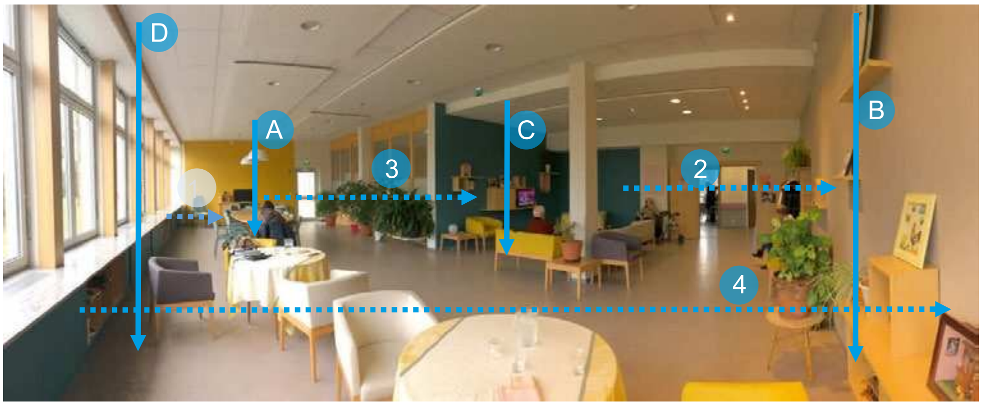

Fig. 4. Reading directions representing the chromatic ranges and combinations of Fig. 5

the environmental factors (colour and light) conducive to the medical management of elderly patients with cognitive disorders. The study was carried out in two phases, a chromatic survey and a lighting survey.

The chromatic survey using the NCS tools allowed us to identify the different colours that comprise the chromatic palette of the space. We calculated the luminance factor of each colour by using the L*a*b colour model as before, coupled with the computation of the contrast values of the identified ranges. The ranges discussed until now were subject to vertical reading from floor to ceiling, represented by segments A, B, C, and D in Fig. 4. As part of the present study, we used an additional reading dimension, a horizontal reading represented by segments 1, 2, 3, and 4 in Fig. 4. This allowed us to consider chromatic combinations not only in isolation but also in the context of a 360° view space environment.

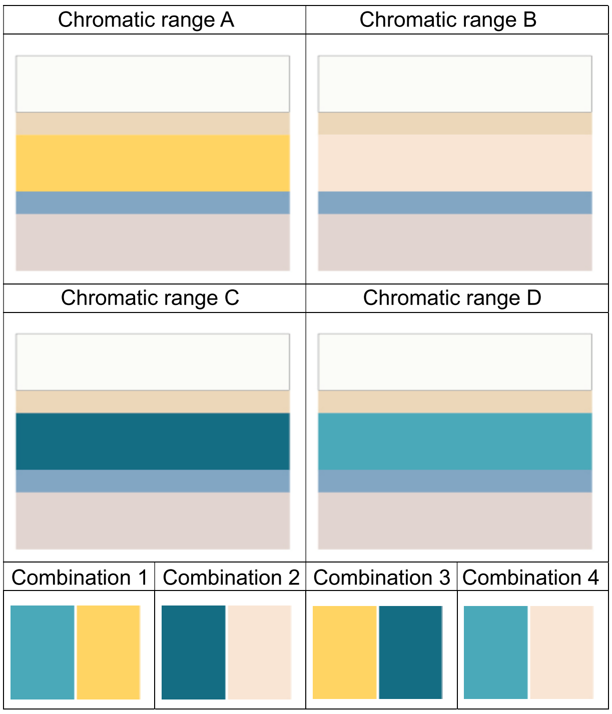

Fig. 5. Chromatic representation of the in situ ranges A, B, C, D and combinations 1, 2, 3, 4

The lighting survey was carried out at markers A, B, and C shown in Fig. 3. An average of the results obtained at these three points was considered in Table 3. In addition, the assessment was made at three different times of the day (morning at 10:00, early afternoon at 14:00, later afternoon at 17:30) to measure the light amplitude.

A colorimeter (Konica Minolta CL-70F) was used to establish the illumination and colour temperature of the ambient light for each of the time markers. These surveys were conducted on March 19 and 20, 2018, under overcast conditions. When we carried out the survey, the artificial lights were turned on, but we did not have the information regarding its technical properties. Unlike the lighting survey, the chromatic colour survey was performed only at a single time point because it is quantitative and non-perceptual data collection, in view of a correlation with a reference frame. We are interested in colour as a quantifiable surface object and not as a perceptual element influenced by temporal elements.

OBSERVATION

The different ranges and chromatic combinations presented in Fig. 5 are the results of the in situ chromatic survey, based on the individual readings of segments A, B, C, and D and 1, 2, 3, and 4 in Fig. 4. They present the combinations that make up the space and generate its general chromatic ambiance.

These colour combinations create a dynamic ambiance. Indeed, the use of complementary colours, such as the yellow accompanied by the two blues, stimulates the eyes. However, the presence of a neu-

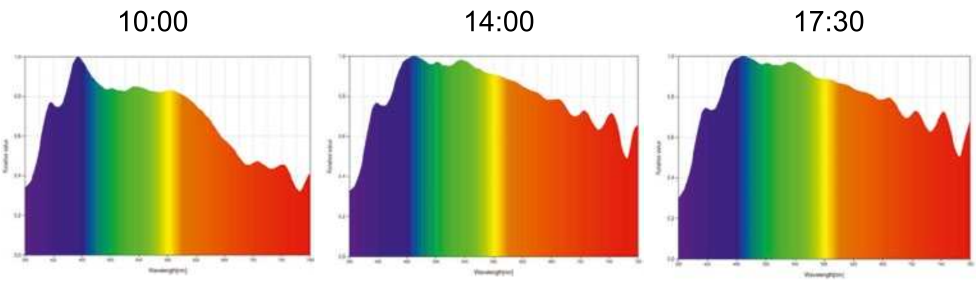

Fig. 6. In situ light spectra

tral shade such as beige helps not to tire the eyes. This combination creates a space that balances stimulation and relaxation of gaze. The succession of complementary colours allows us to create a rhythm and generate a warm atmosphere by using predominantly warm colours supported by colder minor colours. The chromatic distribution allows organizing the space. Every colour that is used helps to create visual cues.

The yellow (chromatic range A, Fig. 5) defines the dining space, the dark blue (chromatic range C, Fig. 5) defines the TV/rest space, and the light blue (chromatic range D, Fig. 5) defines the space of contemplation towards the outside.

This repartitioning allows delineation of the space according to activities and thus, allows the patients to locate themselves more easily according to their needs. Table 2 presents quantitative results such as average luminance factors 0.68 for large areas (wall, floor), 0.77 for small areas (door frame, plinth), and 0.94 for the ceiling, and average contrast rates, 14 % in vertical reading and 32 % in horizontal reading.

Because of these different ranges, it is possible to generate a harmonious and dynamic chromatic environment conducive to visual stimulation and creation of spatial reference points for patients, as noted during our field study.

Table 3 presents the results of the lighting survey showing average illumination levels of 580 lx, which is approximately three times higher than the levels established by the European standard NBN EN12464–1 [21] equivalent to 200 lx.

The above standard is not specific to the elderly but calculated to meet the needs of an average observer. It could be assumed that the minimum value recommended by this standard is not sufficient for the elderly, because the illuminance values collected on site (Table 3) satisfied the visual comfort requirements of the patients there. However, a standard value for illuminance cannot be predicted on the basis of these values and it is difficult to determine whether these values are optimal for the design of a visual environment suitable for the elderly.

The illuminance values presented in Table 3 were observed as a result of LED lighting that supplemented the incoming natural light, owing to the large glazed area which benefits the space. This distribution between natural and artificial lighting is easily identifiable during the day by means of the outline of the spectra presented in Fig. 6, typical of a conjunction between a relatively regular pattern peculiar to natural light and a peak in the blue light characteristic of LED lighting. The latter peak is mostly observed in the morning, which indicates that the natural light is less prominent in the morning than during the rest of the day. Artificial lighting compensates for the low illumination and thus helps to maintain equivalent levels of illuminance throughout the day. In addition, as depicted in the Kruithof diagram in Fig. 7, [22], colour temperatures correlated with all illuminance values appear in the recommended comfort zone. Two of the three colour temperatures are even close to the threshold that can be described as too cold for an average observer. However, as per data collected by us in the field, people prefer more cold lights, which suggest that the illuminance values depicted in the diagram do not satisfy the visual comfort requirements of elderly patients.

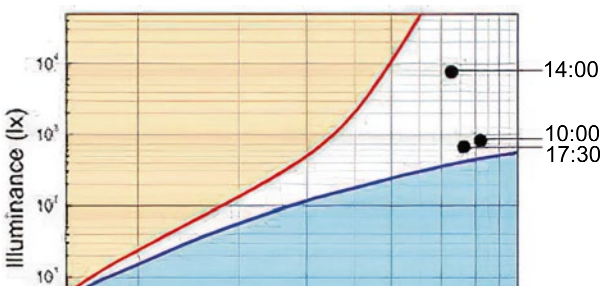

Fig. 7. Kruithof diagram and correlation of in situ illuminance measurements

Table 2. Numerical Values of Ranges A, B, C, and D and Combinations 1, 2, 3, and 4

	NCS codification	L * a * b	Luminance factor	Contrast%	
Vertical reading					
Elements common to all colour ranges					
Ceiling	S0500-N	94*0*2	0.94	7 %	
Door frame	S1010-Y30R	87*4*17	0.87		
Plinth	S2030-R90B	66*-8*-20	0.66	15 %	
Floor	S2505-R	78*4*2	0.78		
Chromatic range A					
Door frame	S1010-Y30R	87*4*17	0.87		10 %
Wall	S1080-Y10R	78*16*91	0.78	15 %	
Plinth	S2030-R90B	66*-8*-20	0.66		
Chromatic range B					
Door frame	S1010-Y30R	87*4*17	0.87		11 %
Wall	S2005-Y80R	77*4*4	0.77	14 %	
Plinth	S2030-R90B	66*-8*-20	0.66		
Chromatic range C					
Door frame	S1010-Y30R	87*4*17	0.87		52 %
Wall	S4040-B10G	42*-21*-21	0.42	36 %	
Plinth	S2030-R90B	66*-8*-20	0.66		
Chromatic range D					
Door frame	S1010-Y30R	87*4*17	0.87		26 %
Wall	S2040-B20G	64*-8*-20	0.64	3 %	
Plinth	S2030-R90B	66*-8*-20	0.66		
Horizontal reading					
Combination 1					
S2040-B20G		64*-26*-17	0.64	18 %	
S1080-Y10R		78*16*91	0.78		
Combination 2					
S4040-B10G		42*-21*-21	0.42	45 %	
S2005-Y80R		77*4*4	0.77		
Combination 3					
S1080-Y10R		78*16*91	0.78	46 %	
S4040-B10G		42*-21*-21	0.42		
Combination 4					
S2040-B20G		64*-26*-17	0.64	17 %	
S2005-Y80R		77*4*4	0.77		

4. RESULTS

The first phase of our study showed us that based on the existing literature it is possible to design chromatic scales suitable for the elderly. In theory, they meet the needs and requirements of the elderly and satisfy their visual comfort if we comply with the levels of contrast and precise luminance indices. We then measured existing on-site chromatic scales using the same method as in the design phase (identification of luminance indices and calculation of contrast levels). However, we observed a difference between the in situ chromatic scales and the theoretical chromatic scales conceived from

Table 3. In Situ Lighting Surveys

	Interior light		Outdoor light	
	Illuminance (lx)	**CCT (K)**	**Illuminance (lx)**	**CCT (K)**
10:00	520	5800	3210	8000
14:00	950	5100	3910	5900
17:30	280	5000	1530	6200

the existing literature. Indeed, the luminance factors and contrast levels observed on site did not all correspond to the values observed during the design phase. Only the average luminance factors of the light colours and the ceiling corresponded. However, the average luminance factor of the dark colours is three times higher and the levels of contrast are on average three times lower than the data obtained during the design phase. But these chromatic scales are still considered satisfactory because they allow visual references to create. Next, we made light readings, which showed a disparity between values that satisfied the visual comfort of the patients and values recommended by existing standards and recommendations. We found that higher illumination and lower colour temperatures were more appropriate for older people. In fact, the average illuminance was three times higher than the current European standard and according to the Kruithof's diagram; two of the three colour temperatures measured moved away from the optimal comfort zone and approached the zone considered too cold.

5. DISCUSSION AND OUTLOOK

This reference system method of design and evaluation allow chromatic ranges adapted to the needs of the elderly affected by visual and/or cognitive pathologies particularly resulting in a loss of spatial orientation to design.

Even if the values obtained during the design phase have been questioned during the in situ evaluation phase, they can guide a designer's work. However, it is important to weigh the indices obtained with respect to the general atmosphere and the context of application in order to avoid generalities. Moreover, even if these chromatic combinations seem to meet the requirements of the elderly users, we must not forget that the choice and preference of colors remain chiefly subjective and personal. Subjectivity then intervenes as a personal and individual manifestation of attraction or repulsion for particular colours, guided by a cultural, social, and historical baggage of an individual, which belongs to the individual alone. Thus, designers compose their colour ranges not only according to established recommendations but also by considering their own preferences dictated by a baggage that belongs only to them. Thus, this methodological approach emphasizes the complementarities between the subjective approach and the measurement-based approach.

To proceed using the referential method can be appropriate in the context of communal spaces, responding then to the representative preference of the majority, but for domestic use, consideration and conception based on individual choice would be favoured. Moreover, even if the colour ranges meet the requirements of the main users – the elderly – we should not overlook the fact that secondary users such as care teams – or more generally, caregivers – also encounter these ranges, which may not meet their preferences and requirements. This raises a question about the adaptability of such chromatic projects. Indeed, as the elderly are not the only users of their environment, should we design the light and colour ambiance only on criteria associated with aging? It would also be interesting to select the colour considering its luminance factor according to a colorimetric standard not only at a single moment but also generally and subject to a daily context, thus undergoing perceptual modifications related especially to the lighting or to the singular perception of the eye of the users. Restoring its moving dimension, changing to colour and no longer static, would play an important role in the overall perception of the chromatic scales, considering chromatic combinations as a system instead of in an isolated and confined manner to the influence of the elements that surround them.

Similarly, only a vertical reading of the chromatic scales removes them from their surroundings, leading to a loss of the overall inclusive reading of the space possible in conjunction of a horizontal chromatic reading. If we add to this background the light dimension of these bright and colourful environments, the qualitative and quantitative dimensions of the lighting is to be taken into account.

Regarding chromatic preferences, it is also important to consider the preferences in terms of lighting and ambient light, here characterized by a low colour temperature and high illumination.

Thus, this systemic approach to creating an ambiance simultaneously considers the chromatic and luminous aspects, thus taking into account not only the effects they can have on one another but also the effects approved by the users, be they primary or secondary. This approach allows drawing the contours of a reference potential or method integrating the qualitative, quantitative, and project uses. Our approach also leads, in view of the results produced, to a reconsideration of the existing norms and recommendations, in favour of a new, more adapted referential, which fully satisfies the visual comfort of the elderly. We can then question the relevance of creating a reference specific to the elderly.

Ambiance is no longer a subject of only the designer but it is also an issue pertinent to its users.

6. CONCLUSION

Suitable lighting and colour environments can be designed by the use of existing repository, although we must critically examine it to produce future repository, taking into account the requirements and physical preferences of users. Such an ambiance provides spatial-temporal landmarks for the elderly, particularly those with cognitive and/or visual disorders that lead to disorientation in space, decrease in their visual field quality and visual acuity, and more generally, a perceptual impairment regarding their environment.

Additionally, the ambiance makes their environment secure by allowing better discrimination of spaces, to bring comfort and autonomy by modifying their living environment in accordance with their habits and daily activities. However, it may not be enough only to answer the accuracy of the frame of reference that allows us to provide a framework for the design of these ambiances, but it is also important to consider the chromatic project as a whole in order to produce a harmonious light and colour ambiance responding to the uses and requirements conveyed by users who occupy the environment, in this case, the elderly. Moreover, it is important to consider what their caregivers can perceive, to generate an environment conducive to the well-being of every user.

Owing to its results, this study demonstrates the importance of designing the visual environment by adapting it to users. In the case of the elderly, the beneficial effects of colour in the design of their surroundings can be observed. The results allow us to define the premises of new standards, conducive to the quality and visual comfort of the elderly. They also present the need to develop a new European standard, similar to existing ones. Development of a specific standard complementary to existing standards will significantly improve the efficiency of current lighting systems to favour greater visual comfort.

Thus, this consideration of the colour and lighting aspects of spaces generates a systemic and trans-disciplinary approach designed for the well-being of people, more particularly, the elderly.

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REALIZATION OF A LABORATORY TUNEABLE COLOUR LIGHT SOURCE

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ABSTRACT

A spectrally tuneable colour light source (TCLS) has been designed and constructed at Physikalisch-Technische Bundesanstalt (PTB), Germany. It consists of an integrating sphere with 24 LEDs which are driven by a computer-controlled power supply. It is intended for producing any visible spectral distribution and to mimic various light sources for use in laboratories as a calibration source. With the help of an integrated spectrometer, a closed loop operation was introduced to improve the performance of the TCLS and to spectrally stabilize its output spectrum. Before practical realization of the TCLS a series of simulations have been made to predict its performance and capability with a number of different target spectrums. During the practical implementation we have encountered difficulties, namely optimization of the output spectrum, dependency of LED spectra on the electric current through the LED and temperature of the LED, non-linearity of LED's luminous flux with respect to electric current through the LED and some difficulties with small synthesis coefficient values, which were all successfully solved.

Keywords: LED, tuneable colour light source, spectral power distribution, LabVIEW

1. INTRODUCTION

Tuneable colour light sources (TCLS) are suitable for different purposes and cannot only be used for general lighting purpose but also in laboratories for calibrations. These TCLS are actually multichannel light sources today mostly based on a set of different light emitting diodes (LEDs) which are able to mimic different spectral power distributions (SPD). Some tuneable light sources with different number of LEDs and with adaptable spectrum are already commercially available for applications in lighting, chemistry research and entertainment. The ones for use in general lighting are often only capable to produce white light with different correlated colour temperature [1] and comprise two to four different LEDs. Multichannel LED sources are also used for different chemical tests and measurements. They usually comprise four to eight different monochromatic LEDs with peak wavelengths distributed across the visual part of the spectrum. For stage lighting also multichannel LED light sources (spot lights) are used with single colour LEDs and white light LEDs. Compared with tuneable colour light source for laboratory use and the calibration of photometric instruments, such devices often have a lower number of different LEDs and they do not include spectrometers for real time measurements of the output spectrum. Measurement of output spectrum and "closed loop" operation provides the ability to regulate and stabilize the TCLS calibration source output spectrum, which is a critical property for a source used for calibrations. The ideal TCLS calibration source should be able to simulate any wanted light source with defined spectrum, which then can be used for calibrations of photometric measuring equipment.

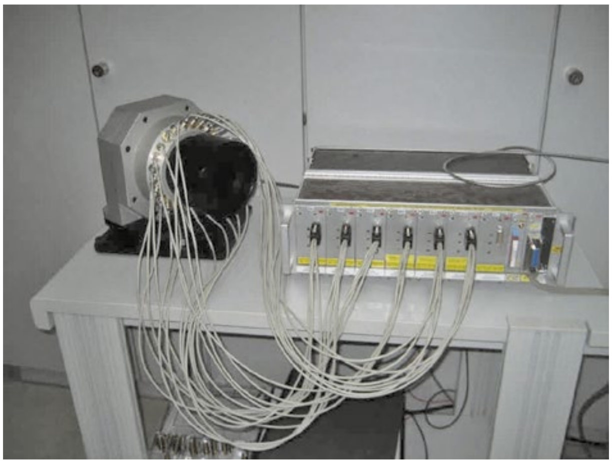

Fig. 1. Tuneable colour light source for calibration purpose: on the left is the sphere with LEDs around the output port; on the right is the 24 channel DC source of power

It is important that the TCLS calibration source produces various SPDs with defined photometric or colorimetric parameters, namely luminance, correlated colour temperature (CCT), colour coordinates (x, y) or colour rendering index (*CRI*). Realization of illuminants with different SPDs by just one light source is making calibration of equipment of different SPDs much easier and more economical. Beside realization of SPDs of real light sources TCLS calibration sources offers also the ability to realize only theoretically defined illuminants.

The TCLS calibration source based on an integration sphere with 24 entry ports for LEDs has been developed at PTB, Germany. The built TCLS calibration source is mainly intended for calibration of different instruments and measuring equipment at various spectra [2]. In this paper we describe the control program we use to control the TCLS calibration source and problems that occurred during development. Most problems resulted from the practical application of the developed optimization method and the properties of real LEDs, which do not change linearly over time and electric current. The paper also shows the performance of the developed TCLS calibration source.

2. CONTROL OF OUTPUT SPECTRUM

The idea of the TCLS calibration source based on larger number of LEDs used to produce any wanted spectrum. The basis of the TCLS calibration source is an integrating sphere equipped with many ports for multiple LEDs installed in a circle around the output port. As the LEDs are baffled and only illuminate the back of the sphere, no direct light can leave the sphere, Fig. 1. LEDs are connected to the multi-channel DC power supply where each individual LED or group of identical LEDs is connected to one of the channels. The DC power supply is connected to the controlling personal computer (PC) via GPIB bus, which enables to control each channel's current separately. The circle of LEDs around the output port of the sphere ends with a spectrometer fibre input port. Also the used spectrometer is connected to the controlling PC via USB. The TCLS calibration source is controlled with a program written in LabVIEW™ environment.

Since the TCLS calibration source is intended as a luminance source with an adjustable spectrum, it is very important that the current of each LED can be set individually. An internal output coefficient K_i, where i is the number of specific LED, is used within the control program to describe the individual settings, which is based on the ratio of the luminous flux at a given current setting with respect to the luminous flux of the LED at its nominal electrical current. The value of K_i is in a range from 0 to 1. In this way, the contribution of each LED to the overall light output of the TCLS calibration source can be described.

The procedure to calculate the needed 24 coefficients K_i for the wanted synthesized spectrum consists of a few steps. The goal of the program is to adapt the output spectrum, which is measured, as close to the target spectrum as possible. In a first step, the wanted spectrum is loaded into the program as "target" spectrum and program tries to find a "best fit" with the premeasured spectra of the LEDs which are installed in the TCLS calibration source. Because the total light output of the TCLS calibration source should be adjustable to be adapted to the wanted luminance without changing in the shape of the spectrum, the target spectrum is normalized to 1. The control program provides the possibility to set the number of LEDs to be used for the synthesis of target spectrum and its nominal currents. After that, the control program starts measuring the spectra of the used LEDs. With the known target spectrum and individual premeasured spectra of the single LEDs, synthesis coefficients are calculated according to shape a synthesized spectrum as close to the target spectrum as possible.

To be able to produce a light source with any wanted spectrum, the TCLS calibration source was equipped with 22 monochromatic LEDs and two

Table 1. Peak WL (nm) and Relative Power of the Chosen 24 LEDs

LED	Peak WL /nm	Relative power	LED	Peak WL /nm	Relative power
1	380	0,042	13	599	0,116
2	388	0,361	14	628	0,648
3	405	0,463	15	654	0,069
4	424	0,900	16	666	0,099
5	431	0,943	17	692	0,086
6	456	0,645	18	707	0,071
7	466	1	19	721	0,058
8	492	0,500	20	739	0,044
9	498	0,341	21	762	0,023
10	513	0,213	22	774	0,018
11	531	0,131	23 (WW)	572	0.0339
12	590	0,390	24 (CW)	451	0.1516

additional white LEDs (warm white LED and cool white LED), whose spectra can be seen in Fig. 2. The LEDs were chosen so that their SPDs are evenly distributed throughout the whole visible part of the light spectrum from 380 nm to 780 nm. Such distribution allows to synthesizing a continuous output spectrum.

The warm white (WW) and cold white (CW) LEDs were added to the set because of a lack of LEDs with appropriate peak wavelength (WL) in the spectral range around 550 nm. The peak wavelengths and relative powers of corresponding LEDs are shown in Table 1 where the white LEDs are represented by the 23rd and 24th LED. Relative outputs (relative powers) at peak wavelength in Table 1 were used for better understanding of different power outputs of LEDs. Spectra of all LEDs are scaled according to the one with the maximum power output. Since LEDs with peak WL from 650 to 780 nm have really low output compared to other LEDs, the total luminous flux output of the TCLS calibration source may be very low for some synthesized spectra with large component of light with longer wavelengths (red part of a visible spectrum).

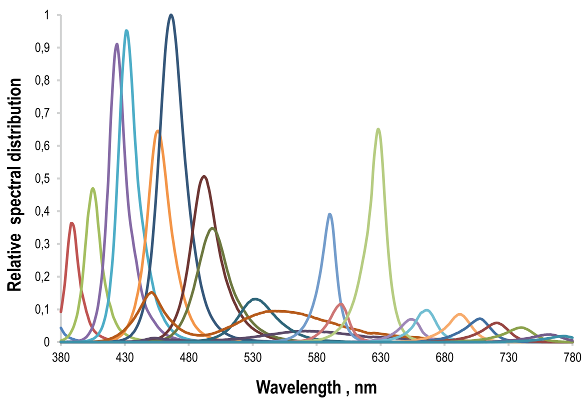

Fig. 2. Spectra of the LEDs set used in the TCLS calibration source, with 22 monochromatic LEDs and 2 white LEDs as measured by the control program of TCLS at their nominal current; spectra are normalized to the spectrum of the most powerful LED

3. OPTIMIZATION METHOD

The optimization process is, in this case, an automated procedure to control the chosen set of LEDs in order to find the ideal combination of LEDs and their respective driving currents to synthesize requested target spectra. A common (synthesized) spectrum of all 24 LEDs is optimized so that the output spectrum at the port of the sphere is as close to the target spectrum as possible. The optimization criterion is based on a sum of the squared differences between the spectrum of the TCLS calibration source and the target spectrum at a single wavelength (with 1 nm step) that needs to be minimized (least squares optimization). The so-called synthesis error can be described by the equation

$$S_{err} = \int \left(b(\lambda) - a(\lambda)\right)^2 d\lambda, \qquad (1)$$

where $a(\lambda)$ is the measured spectrum of the TCLS calibration source and $b(\lambda)$ is the target spectrum. The value of S_{err} can also give us an estimation of the quality of the spectral match of the TCLS calibration source output spectrum with respect to the target spectral distribution.

There are a lot of research papers related to the topic of tuneable colour light sources based on LEDs and how to fit the synthesized spectrum as close to the target spectrum as possible. To satisfy mentioned condition two different approaches are possible, namely through a trial or through an approximation. Fryc et al. [3] proposed a tuneable light source using LEDs where the optimization (fit) of the spectrum was done with a simple but slow iterative procedure, whereas Wu et al. [4] introduced the pruning process where optimization is done by removing LEDs to find an optimal set of LEDs. Most of the methods in papers are based on Gaussian optimization method, which is used to solve non-linear least squares problems with minimizing the sum of squared function values. In our case, we also use Gaussian optimization to minimize the sum of squared differences between the measured synthesized spectrum of the TCLS calibration source and the target spectrum, as it gives the smallest difference between these two spectra. Synthesis coefficients (K_i), which are calculated during the optimization procedure, together form a synthesized spectrum that comes closest to the target spectrum. Unfortunately, basic Gaussian optimization method can return results where some values of K_i become negative. As the synthesis coefficients K_i represent the luminous flux of each LED, where the luminous flux cannot be negative, a synthesized output spectrum cannot be realized with negative coefficients. Therefore, what is needed is a method that takes into account other constraints besides minimizing the sum of the squared differences, namely that calculated values of all coefficients K_i to be positive or equal zero. Lawson and Hanson [5] described a procedure of a non-negative least squares (NNLS) optimization method, which is proved to be an optimal solution for a non-negative problem with certain inequality constrains. Bro and De Jong [6] proposed a fast non-negativity-constrained least-squares algorithm, which is based on the standard NNLS algorithm in [5], whereas Cantarella and Piatek [7] announced a freely available *C* implementation of sparse constrained least-squares problem.

Due to the fact that we can only accept positive values (or values equal to zero) as a suitable solution of Gauss optimization method, we tested the NNLS method which does take into account constrain of the positive (or zero) synthesis coefficient values. Firstly, we tested number of different methods as well as the NNLS method in simulations where we used actual measured spectra of LEDs from the TCLS calibration source. As NNLS method gave the best results for all tested target spectra, we decided to implement it in the LabVIEW™ environment used to control the TCLS calibration source.

The optimization method based on NNLS is defined by statement:

- Minimize $||Ax–b||$, subject to $x \geq 0$

where A is the $m \times n$ matrix with $m \geq n$; b is the m element data vector and x is the n element solution vector; A solution for the equation $Ax \approx b$ must be found, where $x \geq 0$. Entries of the matrix A are the components of the sampled SPDs of the measured LEDs, where n is the number of LEDs and $m=401$ is the size of the sampled SPD vector with 1 nm step in range from 380 nm to 780 nm. The target spectrum is sampled in a vector b with the same size $m=401$ as matrix A.

Lawson and Hanson in [5] described the algorithm in nine steps. The procedure starts with setting all elements of x to zero, creating set Z, containing all indices, and an empty set P. In the main loop the gradient vector w is calculated with the current value of x using the equation

$$w = A^T\left(b - Ax\right). \quad (2)$$

If Z is empty or if all elements of w with indices in Z have values ≤ 0, the solution is found and the procedure terminates. Otherwise in the next step the maximum element of w is moved from set Z to P. If any of the elements have negative values, only a fraction of Z can be accepted as a trial solution. Therefore, in the next step one need to find an index q such that the expression

$$\frac{x_q}{\left(x_q - z_q\right)} \quad (3)$$

is the minimum of all such expressions for negative elements of Z. For this q call the expression for α so, that the linear sum can be calculated (4).

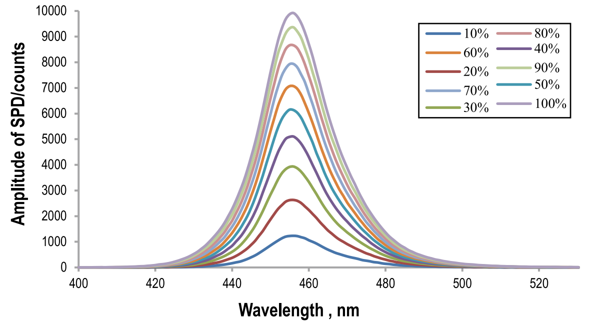

Fig. 3. Dependence of amplitude of the LEDs spectrum for increasing currents. Legend represents the percentage of the nominal current, which was used to measure SPD in the same colour

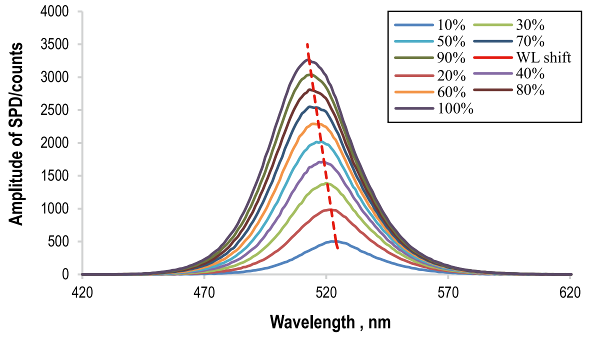

Fig. 4. Example of dependency of LED spectrum amplitude and peak wavelength on increasing current; legend shows the percentage of the nominal current for each SPD and dashed red line marks the shift of peak wavelength

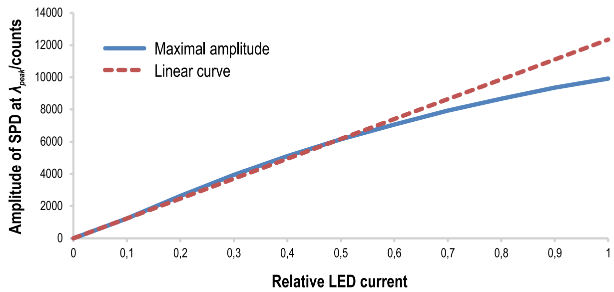

Fig. 5. Amplitude of the LED SPD of at different relative currents with respect to the nominal current; the dotted line shows a linear extrapolation of the initial linear behaviour below 10 % of the nominal LED current

$$x = x + \alpha(z - x). \tag{4}$$

In the final step all indices for which the corresponding elements of x is zero, are moved from set P to Z. These will include x_q, but may also include other elements as well. When the procedure converges, the set P provides a vector of the synthesis coefficients. The procedure is also described in more details in [8].

4. PROBLEMS WITH REALIZATION OF TCLS IN PRACTICE

The main question that arises with the realization of the TCLS calibration source and in particular the optimization procedure in practice is, how calculated luminous flux percentages defined by optimization coefficients K_i can be converted to the required electrical current through the LEDs. The implemented NNLS method uses measured spectra of LEDs for calculation of K_i. Each K_i represents the required amount of luminous flux of one particular LED at its nominal current. Unfortunately, the luminous flux is mostly not linearly dependent on the electrical current through the LED, so K_i cannot be directly used to calculate the required LED current from its nominal one. To calculate the LEDs current properly, the dependence of LED's SPD for increasing driving currents needs to be taken into account. One example of such dependence is given in Fig. 3.

The changes of the LEDs electric current will also affect the p-n junction temperature, which consequently leads to a change in LEDs SPD. Such a change of the SPD will shift the LEDs peak wavelength depending on the individual current and hence, will also change the colour of the emitted light. However, as only a very small peak wavelength shifts of the LEDs used in TCLS calibration source were detected, a procedure that takes such shifts into account was not integrated in our optimization procedure. Instead, an additional feedback control procedure was integrated in the LabVIEW™ program, which, apart from maintaining a stable output of the TCLS calibration source, is also capable to eliminate the relatively small impact of LEDs wavelength shift on final output spectrum. In future, if the used LEDs will be replaced with LEDs providing higher output power which also causes larger wavelength shifts, a procedure within the algorithm for taking such shifts into account will be necessary. An example of LED's peak wavelength shift can be seen in Fig. 4.

To determine the dependency of the LED luminous flux on the electric current more than one measurement of the LED SPD need to be done. The control program of the TCLS calibration source, therefore, uses 10 measurements of each LED at different currents from 10 % of the nominal current (I_{max}) up to 100 % of I_{max} in 10 %-steps. The program starts with the first LED, whose current takes up a preset value of 10 % of I_{max}, and proceeds with the second LED and then the third LED and so forth. After the last LED in the set measurement, the current increases by the value preset of 10 %. The program carries out nine increases of currents and therefore 10 measurements of SPDs of each LED.

If we use the amplitude of the SPD at the peak wavelength as a measure of the LED luminous flux, its dependence on the current through the LED can be shown in a graph similar to the one given in Fig. 5. To include this dependency into the control procedure of TCLS calibration source it needs to be expressed by a mathematical expression. It was found that the current – flux dependency can be approximated by a polynomial curve. In most cases a 3rd order polynomial curve represents the measured dependency with sufficient accuracy.

Using the determined dependence between the luminous flux and the electrical current of the LED, as shown in Fig. 5, the required electric current for the required luminous flux for each LED can be calculated from synthesis coefficients (K_i) previously calculated by the optimization procedure for the target spectrum. However, before correcting the synthesis coefficients K_i it must be checked whether the values of K_i are large enough to ensure the optimal total luminous flux output of the TCLS calibration source. The synthesis coefficients K_i of each LED represent the required LED luminous flux, where the coefficient equals one for the luminous flux at a nominal electrical current. If the value of coefficient is too small, e.g. smaller than 0.05 to 0.1, the LED will typically not turn on due to low forward voltage. To prevent such small values and to ensure the optimal total luminance of the output port of the TCLS calibration source, all LEDs are normalised according to the LED with the largest required luminous flux value to achieve the target spectral distribution. The electric current for the LED with the largest synthesis coefficient K_i is set to its nominal electric current and the currents through the other LEDs are scaled accordingly. At the same time, the target spectral distribution is also scaled by the same value to be able to compare target and output spectrum. If some of synthesis coefficients K_i become smaller than required to turn on the respective LEDs, these LEDs are excluded from the set of used LEDs for this particular target spectrum and the optimization procedure has to be started again to obtain new "best fit" without the excluded LEDs.

Because of temperature fluctuations and aging, the output of the TCLS calibration source, namely the spectra distribution at the sphere output port as well as the SPDs of the individual LEDs, can change with time. In order to diminish the mentioned impacts, an additional regulation procedure was added to the control program. It is a simple iterative optimization process, which tries to minimize the synthesis error S_{err} by small changes in the electrical current through each LED. With this procedure the output of the TCLS calibration source stays stable and it turns out that in some cases S_{err} get even slightly better (smaller). This is mainly a result of the possibility to perform a closed loop feedback control using the implemented spectrometer, which is the major advantage compared to other commercial tuneable colour light sources. In a first step, this additional feedback procedure increases the current through the LEDs one by one for a set value in between 1 % to 5 % of the nominal current. The size of the step can be set in a control program. After the current of a single LED is increased, the output spectrum is measured by the integrated spectrometer and the synthesis error S_{err} is recalculated. If the obtained value of S_{err} is improved, the current change for this LED is kept for future. If value of S_{err} worsened, the current is set to its original value. Then the feedback procedure continues with the next LED. After all LEDs are checked in this way, the feedback procedure starts again with the first LED to try to improve the value of S_{err}. If an increase of the current did not result in better S_{err} in previous round, the current of the LEDs will be decreased by a set value in the next feedback loop. In this way, slight changes of the LED currents in both directions are put into effect to improve the match between the spectral power distribution of the TCLS calibration source and the target spectrum and to keep the TCLS calibration source stable even if the operating conditions and performance of single LEDs of the TCLS calibration source are slightly changing.

Hence, the control program of the developed TCLS calibration source is composed of three sub-routines. After starting the control program, the target spectrum is loaded and the rated currents of installed LEDs are queried. The first subroutine determines the characteristic of the luminous flux with respect to the electrical current of all LEDs. It starts at 10 % of the rated current and continues in 10 % steps up to the 100 % level. After all LED are measured the optimization procedure of the second subroutine starts and calculates synthesis coefficients

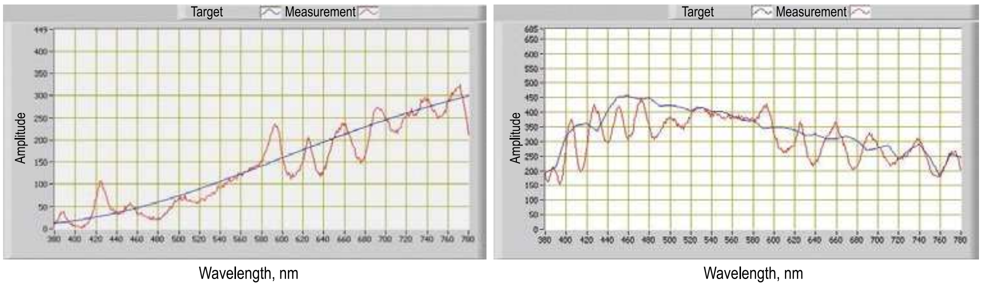

Fig. 6. Target spectrum (blue) and optimized output spectrum (red) for synthesis of Illuminant A (left) and D (right) spectra

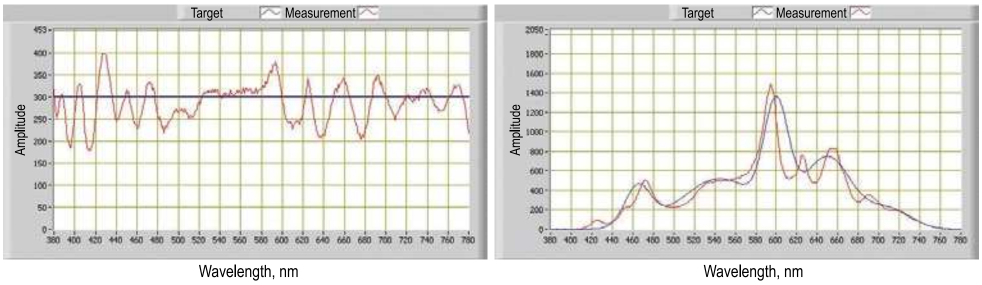

Fig. 7. Target spectrum (blue) and optimized output spectrum (red) for synthesis of EE05 (left) and OLED (right) spectra

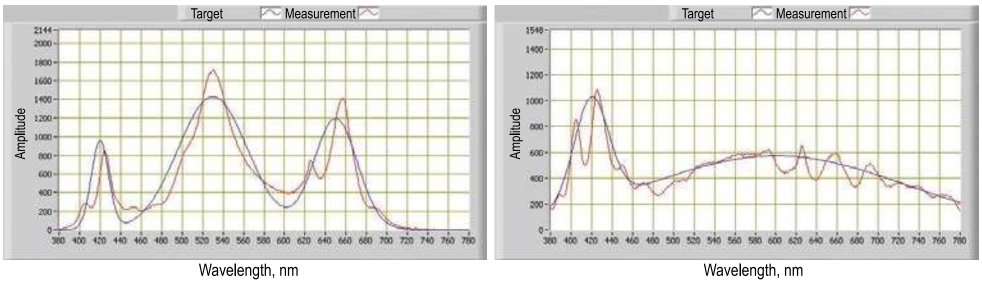

Fig. 8. Target spectrum (blue) and optimized output spectrum (red) for synthesis of RGB (left) and WLED (right) spectra

K_i (i.e. a measure of the required currents for the LEDs) to synthesize the target spectrum. At the end of the optimization process the calculated synthesis coefficients are increased linearly so that the largest becomes 100 %. This is done to achieve the highest possible luminance at the output port of the TCLS calibration source for the requested target spectrum. At the end of this subroutine the synthesis coefficients are transformed into the required LED's electrical currents using the previously measured luminous flux versus electrical current characteristics. Finally, the power supply channels of the TCLS calibration source are set to proper values and turned on. After a warming up period, needed for stabilization of LEDs output, the third subroutine takes over with the feedback control to continuously measuring the output spectral distribution and trying to improve the match to the target spectrum by slightly changing the current through every single LED as described above.

5. RESULTS

The TCLS calibration source is designed to match any spectral distribution in the restricted interval between 380 nm and 780 nm. The matching of the SPDs generated by multiple LEDs to the target spectrum is realized using the optimization method described in the chapter 3. Due to non-linear LED characteristics, calculated synthesis coefficients must be properly adjusted for the conversion into the required currents through the LEDs. To make this possible through mathematical algorithms, a large number of SPDs measurements for LEDs must be performed, which prolongs the time of the entire process. To improve the start-up time all measured SPDs can be saved and used again later, e.g. for other target spectra. The realized spectral distributions of the TCLS calibration source can be different from the target spectrum distribution due to limitations in the optimization procedure as well as due to limitations by the restricted number of LEDs used in TCLS calibration source, their appropriate peak wavelengths and shifts in their radiometric output due to temperature fluctuations or aging, etc.

If setup properly with the used procedure and with the measured and saved LED's SPDs at different currents, the TCLS calibration source provides practically instantly an optimized output spectral distribution at the output port of the sphere. Due to the spectral feedback control mechanism based on periodic measurement of the output spectrum using a spectrometer, the provided spectrum is kept constant during operation. A major advantage using the implemented spectrometer and periodic real time measurements is the possibility and flexibility to replace one or more of the LEDs in the set without any additional calculations or changes within the LabVIEW™ control program. The whole process, starting from the measurement of SPDs of the installed LEDs until the synthesis and control of the output spectrum is automated.

To show the quality of the synthesized spectra some examples with well-known target spectra are provided. Figs. 6 to 8 show results of the optimization and synthesis of six target spectra, namely CIE standard Illuminant A spectrum, CIE standardized daylight D_{65} spectrum equal energy spectrum (EE05), spectrum of generic OLED, spectrum obtained for RGB-LEDs and a spectrum of white LED (WLED). For these examples the set of LEDs described in chapter 2 was used. All spectra shown were measured with the TCLS integrated spectrometer.

5. CONCLUSION

A TCLS calibration source was designed to explore the possibility and use-ability in photometric laboratories for calibration of different instruments and measuring equipment at various spectra. Beside this main task, the developed TCLS calibration source may also assist research for new CIE standard light sources for calibration. Choosing NNLS method for optimization of the TCLS calibration source output spectrum gave good results and show small difference between target spectrum and TCLS calibration source output spectrum, although the number and types of used LEDs was restricted. Due to the integrated spectrometer and iterative procedure described in chapter 4 it was possible to further improve the match of the output spectrum with respect to the target spectrum. There are still noticeable differences between both spectra, as shown in Figs. 6 to 8, which could be improved in the future by using more LEDs for the next generation TCLS calibration source.

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COMPARISON OF DC-DC SEPIC, CUK AND FLYBACK CONVERTERS BASED LED DRIVERS

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ABSTRACT

This paper presents the comparison of LED driver topologies that include SEPIC, CUK and FLYBACK DC-DC converters. Both topologies are designed for 8W power and operated in discontinuous conduction mode (DCM) with 88 kHz switching frequency. Furthermore, inductors of SEPIC and CUK converters are wounded as coupled. Applications are realized by using SG3524 integrated circuit for open loop and PIC16F877 microcontroller for closed loop. Besides, ACS712 current sensor used to limit maximum LED current for closed loop applications. Finally, SEPIC, CUK and FLYBACK DC-DC LED drivers are compared with respect to LED current, LED voltage, input voltage and current. Also, advantages and disadvantages of all topologies are concluded.

Keywords: CUK, FLYBACK, LED driver, SEPIC

1. INTRODUCTION

Using power LEDs in illumination has been so popular lately due to the high efficiency feature with respect to other illumination methods such as fluorescent, incandescent and metal halide bulbs. But, to operate power LEDs with different illumination levels, variable DC power is required. This DC power can be supplied by using DC-DC converters. Basic DC-DC converters are buck, boost and buck-boost converters. In buck-boost converter, output voltage can be lower or higher than input voltage. So, buck-boost DC-DC converter using as a LED driver is more attractive. Furthermore, SEPIC, CUK and FLYBACK DC-DC converters are also buck-boost derived topologies and for low power, it is better to operate those converters in DCM.

In literature, some studies are conducted this topic as follows. Design and analysis of SEPIC, CUK and FLYBACK DC-DC converters are given in [1–8]. In [9, 10], CUK DC-DC converter based LED driver are presented. SEPIC DC-DC converter based LED drivers are also given in [11,12] for road vehicles and general application. In references [13–16], FLYBACK DC-DC converter based LED drivers are also proposed as the single and multi-output drivers. AC-DC and DC-DC converters that are buck, boost, buck-boost, FLYBACK and half bridge are reviewed as a LED driver in [17]. In [18], comparison is made for buck-boost, SEPIC and CUK DC-DC converters based LED drivers. Another comparison is also made in [19] for buck and FLYBACK converter based LED drivers.

In this paper, comparison of SEPIC, CUK and FLYBACK LED driver topologies are presented. Both topologies are connected to DC power supply over an input filter and designed for 8W power with 88 kHz switching frequency. Besides, open loop operation is realized by SG3524 IC and closed loop operation is carried out by PIC16F877, and ACS712 current sensor not to exceed maximum current limit. Furthermore, LED voltage, LED current, input side inductor voltage and current, input voltage and current are measured for all topologies.

The article has the following structure: power LED current-voltage characteristic and electrical circuit model are included in section 2, LED driver

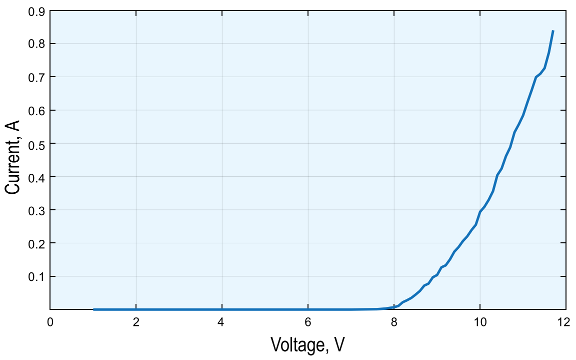

Fig. 1. Voltage-current characteristic of power LED

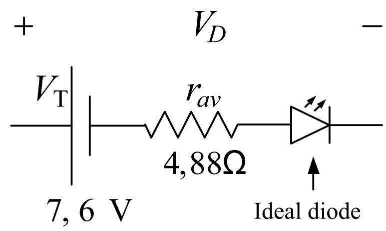

Fig. 2. Electrical equivalent model of power LED

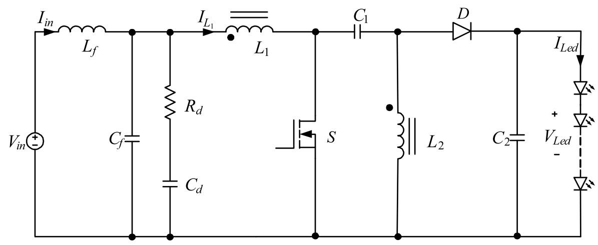

Fig. 3. SEPIC DC-DC Converter

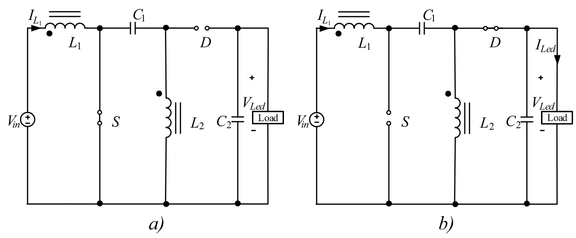

Fig. 4. Switching state: a) on, b) off

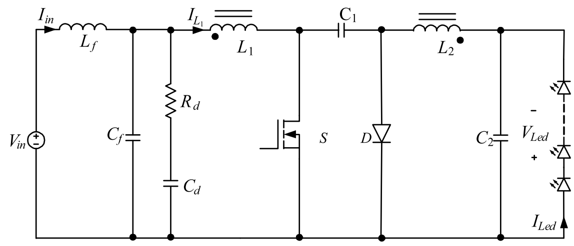

Fig. 5. CUK DC-DC converter

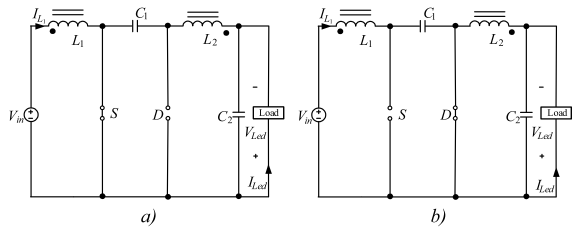

Fig. 6. Switching state: a) on, b) off

topologies applied are introduced in section 3, applications of LED drivers are presented in section 4, measurement results are given in section 5, and conclusions are done in section 6.

2. POWER LED

In this chapter, current-voltage characteristics and electrical circuit model of power LED that are used for this study are derived by using Fluke 15B and Fluke 17B as in [20, 21].

Fig. 1. shows voltage-current characteristic of power LED. The characteristic is obtained by increasing voltage of power LED and plotting voltages versus current. It is seen from the figure that LED voltage and current has exponential relation and LED current increase extremely after LED turns on. Also, LED voltage doesn't change much after and up to 0.8 A current [20, 21].

Electrical circuit model of power LED is derived by using Fig. 1 and presented in Fig. 2. It is understood by this model that threshold voltage and resistance of power LED are 7.6 V and 4.88 Ω respectively as in [20, 21].

3. LED DRIVER

In this chapter, DC-DC SEPIC, CUK and FLYBACK converter based LED drivers are introduced. Both drivers are connected to DC supply over an input filter. All these topologies can be operated buck-boost principle that means output voltage can be lower or higher than input voltage. Furthermore, input filter is used in order to have current with low noise because of the DCM operating condition and high frequency switching. In SEPIC and CUK converter inductors can be wound as coupled, also FLYBACK converter uses high frequency transformer that works as an inductor.

3.1. SEPIC DC-DC Converter

Fig. 3. shows the SEPIC DC-DC converter that is connected to DC supply by using input filter and this converter has two inductors that are wounded as coupled and two capacitors. Besides, output voltage is the same polarity with the input voltage.

In Fig. 4 circuit of SEPIC converter is shown by switching states. To understand operation of SEPIC

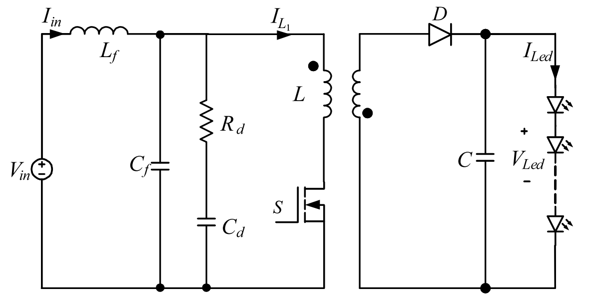

Fig. 7. FLYBACK DC-DC converter

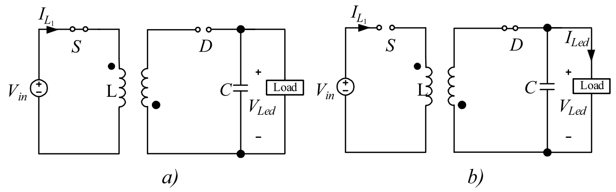

Fig. 8. Switching state: a) on, b) off

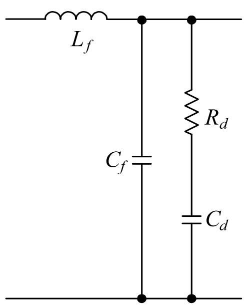

Fig. 9. Input LC series damped filter

converter and design of passive elements, converter should be analyzed with respect to switch on and off position. When S is turned on, L_1 is energized by power source and L_2 is energized by C_1, C_2 feeds the load. When S is turned off, C_1 is charged by power source and L_1, while currents of L_1 and L_2 flowing through D and load, C_2 is also charged [2, 3].

SEPIC converter can supply power to load with lower or higher voltage with respect to input voltage and output voltage is with the same polarity of input voltage. Passive elements in SEPIC converter can be chosen by using equations (1–3) as in [2, 3]. In these equations, L_{1min}, L_{2min} are the maximum inductor values for DCM operation, D is the duty cycle, V_{in} is the input voltage, f_{sw} is the switching frequency, ΔI_L is inductor current ripple, ΔV_{C1} is C_1 voltage ripple, I_{out} is the output current, and V_{ripple} is ripple on C_2.

$$L_{1min}=L_{2min}=D.\frac{V_{in}}{\Delta I_L.f_{sw}}. \quad (1)$$

$$C_2 \geq \frac{I_{out}.D}{V_{ripple}.f_{sw}}. \quad (2)$$

$$C_1=\frac{I_{out}.D}{\Delta V_{C_1}.f_{sw}}. \quad (3)$$

3.2. CUK DC-DC Converter

Fig. 5. shows CUK DC-DC converter circuit that has also two inductors and two capacitors. Furthermore, inductors in CUK converter are also wounded as coupled that means on the same core.

Circuits of CUK converter with respect to switch states are shown in Fig. 6. When S is turned on, L_1 is energized by power source, and C_1 discharges over C_2, load and L_2. When S is turned off, C_1 is charged by power source and L_1, also L_2 currents flows through D, load and C_2 [1, 8].

CUK converter also supplies power with lower or higher voltage with respect to input voltage. However, output voltage polarity of CUK converter is reverse polarity with input voltage.

Passive elements in CUK converter can be chosen by using equations (4, 6) as in SEPIC converter [1, 8]. In these equations, L_{1min}, L_{2min} are the maximum inductor values for DCM operation, D is duty cycle, V_{in} is input voltage, f_{sw} is switching frequency, ΔI_L is inductor current ripple, ΔV_{C1} is C_1 voltage ripple, I_{out} is output current, and V_{ripple} is ripple on C_2.

$$L_{1min}=L_{2min}=D.\frac{V_{in}}{\Delta I_L \cdot f_{sw}}. \quad (4)$$

$$C_2 \geq \frac{I_{out}.D}{V_{ripple} \cdot f_{sw}} \quad (5)$$

$$C_1=\frac{I_{out}.D}{\Delta V_{C_1} \cdot f_{sw}} \quad (6)$$

3.3. FLYBACK DC-DC Converter

Fig. 7. shows the FLYBACK converter circuit that has a high frequency transformer and a capacitor is connected to input supply by input filter. Furthermore, transformer of FLYBACK converter operates as an inductor.

Switch states of FLYBACK converter are shown in Fig. 8. When S is turned on, primary winding of transformer is energized by power source and C feeds load. When S is turned off, energy on primary winding is transferred to secondary winding and over D secondary current flows through load and C [1, 4–7].

Passive elements in FLYBACK converter can be chosen by using equations (7, 8) as in [1, 4–7]. In these equations, L_{mmax} is the maximum magnetization inductance value for DCM operation, D is the duty cycle, R_{Lmin} is the minimum load, f_{sw} is the switching frequency, C_{min} is the minimum output capacitor, V_{cpp} is voltage ripple on C, I_{omax} is the maximum output current, n is the transformer's turn ratio.

$$L_{m(max)} = n^2 R_{Lmin}(1\text{-}D)^2 \Big/ 2.f_{sw}. \quad (7)$$

$$C_{min} = I_{omax}.D \Big/ f_{sw}.V_{cpp}. \quad (8)$$

3.4. Input Filter

Fig. 9. shows the input filter circuit that is used with SEPIC, CUK and FLYBACK converters. This filter is called as LC series damped type input filter. In this paper, all of the converters are operated in DCM mode therefore, without using an input filter, supply current will be discontinuous. In order to have continuous supply current and to reduce high frequency noise LC series damped type input filter is used.

Passive elements in input filter can be chosen by using equations (9–12) as in [22, 23]. In these equations, f_f is the cutoff frequency of filter, L_f is filter inductor, C_f is filter capacitor, R_0 is the characteristic impedance of un-damped filter, R_d is the damping resistance, C_d is the damping capacitor, a is ratio between C_d and C_f. After calculations, values of L_f, C_f, R_d and C_d are found as 160µH, 10µF, 2.47Ω and 40µF respectively and used in all LED drivers.

$$f_f = 1 \Big/ 2\pi\sqrt{L_f C_f}. \quad (9)$$

$$R_0 = \sqrt{L_f \big/ C_f}. \quad (10)$$

$$R_d = R_0 \sqrt{(2+a)(4+3a) \big/ 2a^2(4+a)}. \quad (11)$$

$$a = C_d \big/ C_f. \quad (12)$$

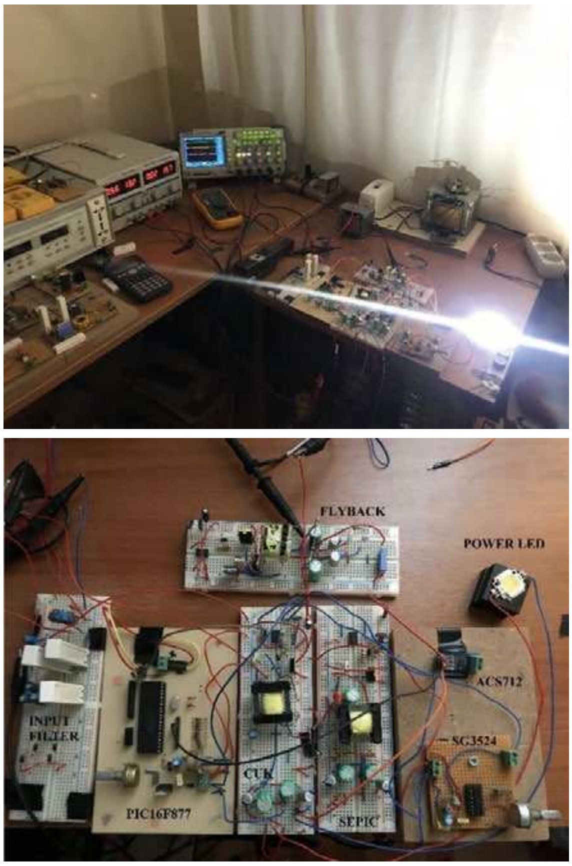

Fig. 10. Experimental setup

4. APPLICATION

In this chapter, applications of SEPIC, CUK and FLYBACK LED drivers are realized. Fig. 10. shows the experimental setup. Both converters are connected to input supply over LC input filter. Furthermore, as a load COB power LED having characteristics in Fig. 1 is connected. In applications, TPS2024B oscilloscope, A622 current probe, FLUKE15B, 17B multi-meters are used. Open and closed loop applications are conducted by SG3524 IC and PIC16F877 microcontroller.

4.1. SEPIC DC-DC CONVERTER

In Fig. 11, application circuit of SEPIC based LED driver is shown. It is understood that open loop operation is realized by SG3524 IC and closed operation by PIC16F877 and ACS712. Besides, IRFZ44N MOSFET, TC4427 MOSFET driver, Schottky diode 1N5822 are included in the application circuit. Furthermore, L_1, L_2 are 18 µH, C_1 is the 10 µF and C_2 is 460 µF [2,3, 24–29].

The duty cycle can be changed by the potentiometer connected to SG3524, PIC16F877 and PWM

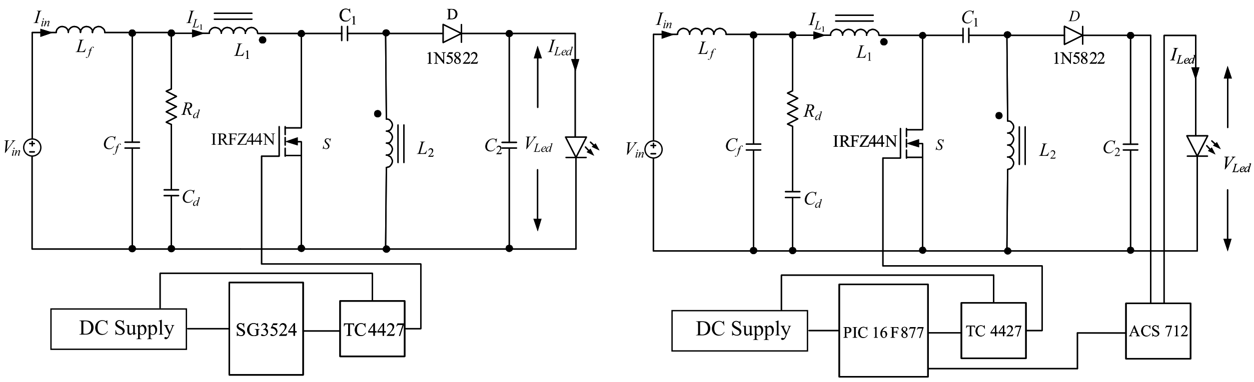

Fig. 11. Application circuit of SEPIC converter

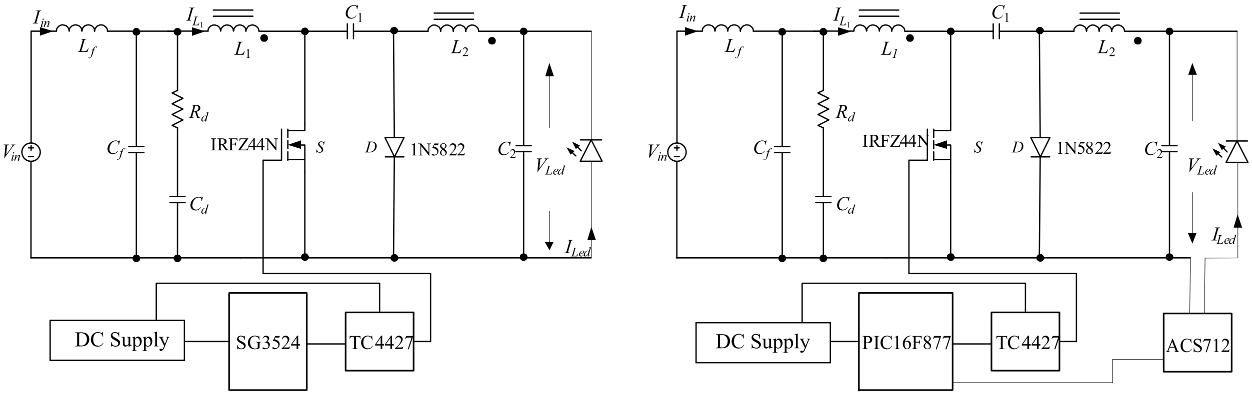

Fig. 12. Application circuit CUK converter

frequency is set to 88 kHz. To reduce high frequency noise and avoid discontinuous supply current *LC* filter is used. Besides, passive elements are used after calculations in equations (1–3).

4.2. CUK DC-DC Converter

Fig. 12. shows the application circuit of CUK converter based LED driver. This application is also realized by open and closed loop algorithm. Furthermore, SG3524 IC or PIC16F877 used for PWM signals, IRFZ44N MOSFET, TC4427 MOSFET driver, Schottky diode 1N5822 are used in the application circuit. Furthermore, L_1, L_2 are 18 µH, C_1 is 10 µF and C_2 is 460 µF [8, 24–29].

The duty cycle can also be changed by the potentiometer connected to SG3524 or PIC16F877 and PWM frequency is again used as 88 kHz. By using equations (4–6), passive elements are chosen.

4.3. FLYBACK DC-DC Converter

Fig. 13 shows the application circuit of FLYBACK converter based LED driver. This application is also realized by open and closed loop algorithm. Furthermore, SG3524 IC or PIC16F877 is used for PWM signals and IRFZ44N MOSFET, TC4427 MOSFET driver, Schottky diode 1N5822 are used in the application circuit. Also, primary and secondary windings of transformer are 18 µH and *C* is equal to 460 µF [4–7, 24–29].

The duty cycle can also be changed by the potentiometer connected to SG3524, PIC16F877 and PWM frequency is again used as 88 kHz. By using equations (7–9), passive elements are chosen.

5. MEASUREMENT RESULTS

LED voltages (V_{LED}), LED currents (I_{LED}), input voltages (V_{in}), input currents (I_{in}), PWM signals, current and voltage of input side inductors (V_{L1}), (I_{L1}) are measured by using TPS2024B oscilloscope and A622 current probe for each LED drivers.

5.1. SEPIC DC-DC Converter

In Fig.14, SEPIC DC-DC Converter characteristics are shown which are getting with help from 1 to 4 oscilloscope channels respectively. LED voltage (V_{LED}), input side inductor voltage (V_{L1}) and current

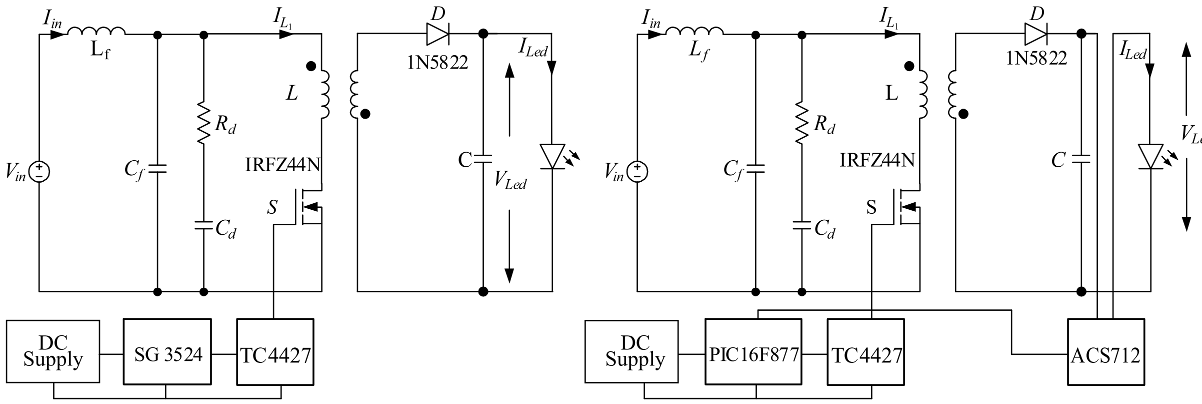

Fig. 13. Application circuit FLYBACK converter

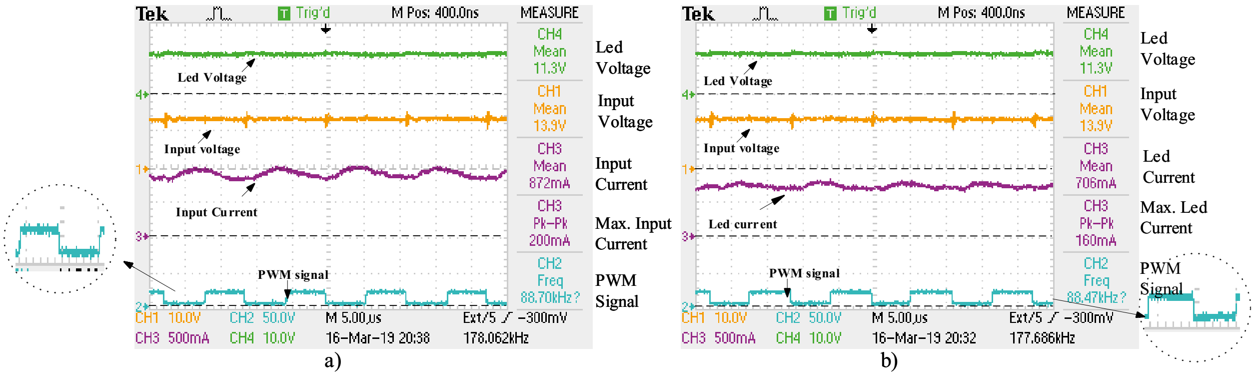

Fig. 14. SEPIC converter: a – LED voltage (V_{LED}), input voltage (V_{in}) and current (I_{in}), PWM signal; b – LED voltage (V_{LED}), input voltage (V_{in}), LED current (I_{LED}), PWM signal

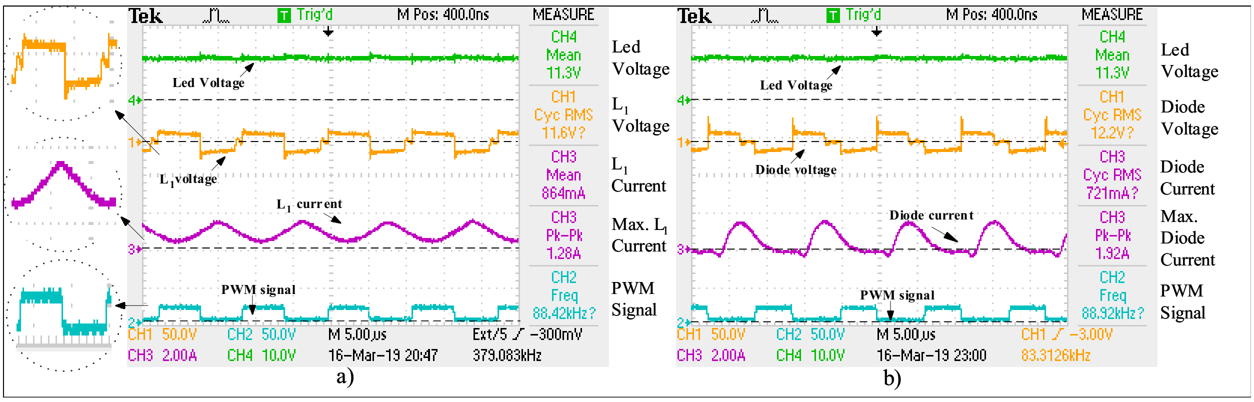

Fig. 15. SEPIC converter: a – LED voltage (V_{LED}), input side inductor voltage (V_{L1}) and current (I_{L1}), PWM signal; b – SEPIC converter input voltage (V_{in}), diode voltage and current, PWM signal

(I_{L1}), PWM signal and LED voltage (V_{LED}), diode voltage and diode current, PWM signal are shown in Fig. 15 a, b respectively. Although, L_1 current (I_{L1}) shown in Fig. 15a is continuous, in DCM operation of SEPIC converter L_1 current swings from a constant current level instead of zero as in [30]. So, diode current shown in Fig. 15 b proves the DCM operation, diode current decreases to zero and increase from zero current. As a result, it is understood that SEPIC converter is operated in DCM with 11.3V LED voltage.

5.2. CUK DC-DC converter

In Fig. 16 CUK DC-DC converter characteristics are presented: a – LED voltage (V_{LED}), input voltage (V_{in}), input current (I_{in}), PWM signal and in b – LED voltage (V_{LED}), input voltage (V_{in}), LED

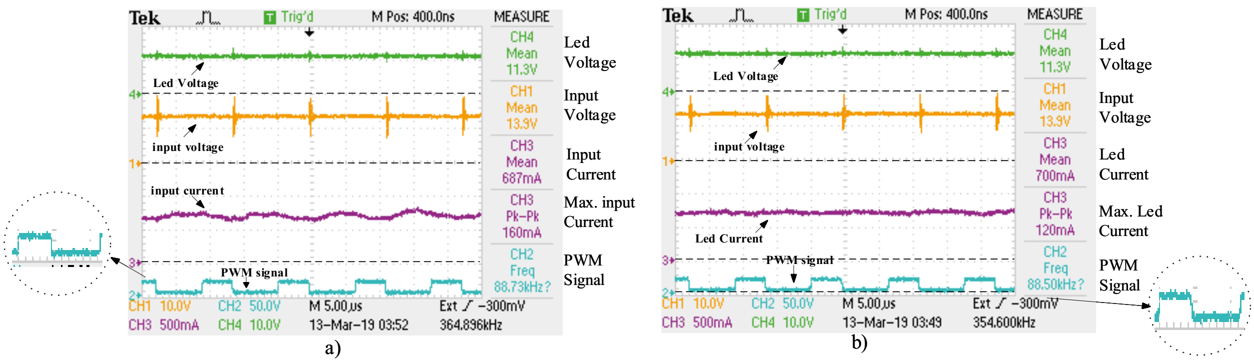

Fig. 16. CUK converter, LED voltage (V_{LED}), input voltage (V_{in}) and current (I_{in}), PWM signal –a; CUK converter, LED voltage (V_{LED}), input voltage (V_{in}), LED current (I_{LED}), PWM signal – b

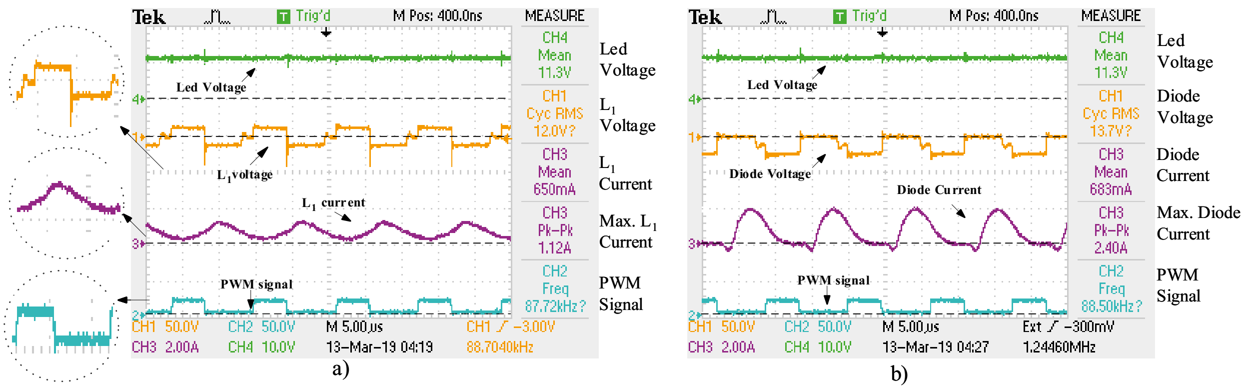

Fig. 17. CUK converter, LED voltage (V_{LED}), input side inductor voltage (V_{L1}) and current (I_{L1}), PWM signal – a; CUK converter input voltage (V_{in}), diode voltage and current, PWM signal – b

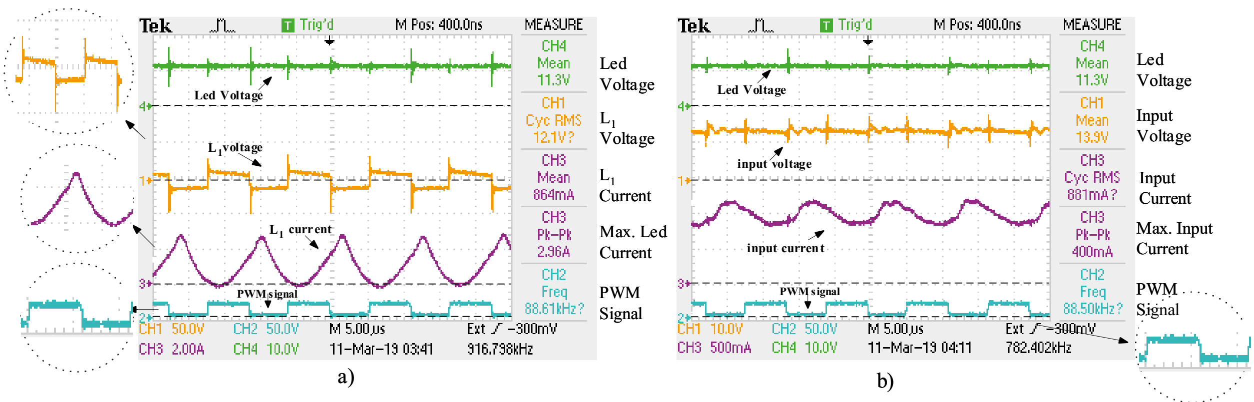

Fig. 18. FLYBACK converter, LED voltage (V_{LED}), primary voltage (V_{L1}) and current (I_{L1}), PWM signal- a; FLYBACK converter, LED voltage (V_{LED}), input voltage and current, PWM signal – b

current (I_{LED}), PWM signal are shown by 1 to 4 oscilloscope channels respectively. It is seen that by using input filter continuous supply current is obtained and efficiency is around 83 % at 8W output power.

In Fig. 17, LED voltage (V_{LED}), input side inductor voltage (V_{L1}) and current (I_{L1}), PWM signal and LED voltage (V_{LED}), diode voltage and current, PWM signal are shown a) and b) respectively. As described in SEPIC converter, in DCM operation of CUK converter L_1 current swings from a constant current level instead of zero as in [30]. So, diode current shown in Fig. 17 b) proves the DCM operation, diode current decreases to zero and increase from zero current. As a result, it is understood that SEPIC converter is operated in DCM with 11.3V LED voltage.

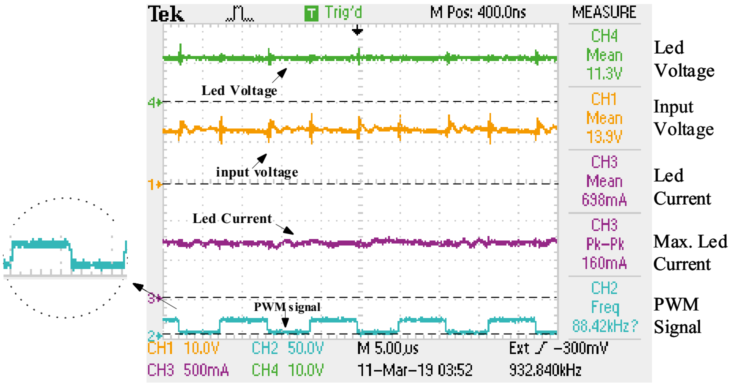

Fig. 19. FLYBACK converter, LED voltage (V_{LED}), input voltage (V_{in}), LED current (I_{LED}), PWM signal

5.3. FLYBACK DC-DC converter

In Fig. 18 FLYBACK DC-DC converter characteristics are shown by 1 to 4 channels, respectively: LED voltage (V_{LED}), primary voltage (V_{L1}) and current (I_{L1}), PWM. It is seen that, FLYBACK converter is operated in DCM with 11.3V LED voltage. In Fig. 18.b LED voltage (V_{LED}), input supply voltage (V_{in}), supply current (I_{in}) and PWM signal is also shown by 1 to 4 channels, respectively. It is seen that by using input filter continuous supply current is obtained.

In Fig. 19 LED voltage (V_{LED}), input voltage (V_{in}), LED current (I_{LED}) and PWM signal are shown. It can be calculated that efficiency is obtained around 65 % at 8W power.

6. CONCLUSIONS

This paper compares DC-DC SEPIC, CUK and FLYBACK converter based LED drivers. All converters are operated at DCM, both open and closed loop applications are conducted. Also, LED current is measured by ACS712 current sensor in order to limit maximum LED current to prevent damage on power LEDs. By means of the applications, LED current, LED voltage, input current, input voltage and input side inductor voltage and current are measured.

By using the same input filter, SEPIC, CUK and FLYBACK LED drivers have 0.1A, 0.08 A and 0.2 A input current oscillations. Also SEPIC LED driver does not disturb input voltage like other drivers. Furthermore, SEPIC, CUK and FLYBACK LED drivers provides current to power LEDs with 80 mA, 60 mA and 80 mA current oscillations, respectively. Besides, power LED voltage is smooth in SEPIC and CUK LED drivers but in FLYBACK LED driver, it has small pulsations. Besides, CUK converter gives better efficiency that SEPIC and FLYBACK converter.

It is observed by the application results, CUK and SEPIC LED drivers have similar characteristics but CUK converter gives better results. On the other hand, SEPIC converter gives the same polarity output voltage with input voltage that is reverse in CUK LED driver. So, if the voltage polarity is matters using SEPIC converter is a better solution. However, FLYBACK LED driver has an electrical isolation because of its high frequency transformer. When isolation is required, FLYBACK LED driver can also be used.

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THE IMPACT OF LIGHT POLARISATION ON LIGHT FIELD OF SCENES WITH MULTIPLE REFLECTIONS

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ABSTRACT

The article describes the role of polarisation in calculation of multiple reflections. A mathematical model of multiple reflections based on the Stokes vector for beam description and Mueller matrices for description of surface properties is presented. On the basis of this model, the global illumination equation is generalised for the polarisation case and is resolved into volume integration. This allows us to obtain an expression for the Monte Carlo method local estimates and to use them for evaluation of light distribution in the scene with consideration of polarisation. The obtained mathematical model was implemented in the software environment using the example of a scene with its surfaces having both diffuse and regular components of reflection. The results presented in the article show that the calculation difference may reach 30 % when polarisation is taken into consideration as compared to standard modelling.

Keywords: polarisation, multiple reflections, local estimates, Monte Carlo method, Mueller matrix, Stokes vector

INTRODUCTION

The development of computers and software over the previous decades has led to the fact that nowadays design of any lighting installation involves modelling light field of illumination scenes, which will be obtained when using the selected lighting devices. Calculation of multiple reflections (MR) of light from the surfaces of the scene being modelled plays a very important role in it.

In lighting engineering, it is common to neglect light polarisation phenomena in calculations. Such neglect does not lead to a significant error in the results when it comes to a small number of reflections from surfaces with mostly diffuse nature of reflection. However, if it is necessary to deal with surfaces where reflection has a significant regular component, the state of polarisation of even completely depolarised light will be changed already after the first reflection, which will affect the nature of further interactions of light with the surfaces of the scene.

It is obvious that the light will be depolarised again after a sufficient number of reflections. Nevertheless, it is still unknown how consideration of polarisation will affect the final result of lighting calculation. The existing estimations indicate that the difference between the results of conventional calculation and those of calculation considering light polarisation may exceed 20 % [1]. Once this assumption is confirmed it will mean the necessity to take the state of polarisation into account for solving applied problems (such as calculation of illuminance in the premises with consideration of MR).

The results of a large number of studies by different authors [2–7], which show the sufficient effect of polarisation on the obtained images of scenes when modelling light distribution using their example, have been published recently. However, these studies do not contain information on how consideration of polarisation affects the obtained values of magnitudes describing the energy performance of light radiation. At the same time, it is these magnitudes that interest most the specialists whose work is related to solving practical problems.

Moreover, the images of scenes presented in the works by the said authors show that the form and location of glares on the scene surfaces change when images are rendered with consideration of polarisation. Therefore, the state of light polarisation ultimately affects not only quantitative but also qualitative characteristics of light distribution created by a given lighting installation.

1. PHOTOMETRIC DESCRIPTION OF LIGHT POLARISATION

To select the method of description of light polarisation, it is necessary to pay attention to the fact that all photometric terms are formulated exceptionally as *observable* values. The nature of these values is determined, in particular, by quadratic characteristics of optical radiation detectors (i.e. response to power), finitude of their dimensions and time constant [8].

In its turn, the electromagnetic field theory uses such values which *are impossible to measure directly by experiment:* amplitude and wave field phase. Therefore, when describing any wave optics experiment, the necessity to transfer to the photometric interpretation of light field is inevitable [9].

In the authors' opinion, it means that the language of polarisation description which is the most corresponding to the processes of radiation measurement by an optical detector includes application of a set of four parameters (or, in other words, the four-dimensional parameter vector) introduced by G.G. Stokes in 1852 in [10]. These parameters describe light such that, if any beams obtained independently of each other have the same values of all four components of the parameter vector, they are optically equivalent and no experiment allows distinguishing them [10].

The works [8, 9, 11] show that for purposes of photometry the Stokes parameters have dimensions of *luminance* which, in its turn, fully characterises radiation. Therefore, the full description of a beam shall include a set of four parameters.

It is possible to determine the components of the Stokes parameter vector based on the electromagnetic theory, like it is done in [11], or experimentally by passing the radiation through a set of polarisation filters [12]. In this case, the said parameters are determined based on reactions J_i of the corresponding optical detectors:

$$L_0 = 2J_0, \quad L_1 = 2(J_0 - J_1),$$
$$L_2 = 2(J_2 - J_0), \quad L_3 = 2(J_3 - J_0), \qquad (1)$$

where $J_i, i \in \overline{0,3}$, are differ the installed polarisation filters:

J_0 is a neutral filter with transmission of 0.5;

J_1 is an analyser, with its optical axis and the direction of radiation distribution determine the coordinate system – a reference plane;

J_2 is an analyser with axis angle of 45° to the reference plane;

J_3 is a complex filter consisting of a quarter-wave plate and an analyser with angle of 45° to the reference plane.

It should be highlighted that the most important characteristic of the Stokes parameters is the coordinate system in which they are defined or the reference plane; horizontal and vertical positions are defined relative to this plane. The components L_1 and L_2 depend on selection of the plane while L_0 and L_3 don't [12].

For each interaction of light and the environment, the parameters are calculated relative to a new reference plane which is linked with the diffuse point and is obtained by turning the previous plane about a corresponding angle.

Let us assume that the reference plane ζ was obtained by turning the previous plane ζ' about some angle φ relative to the Z axis. Then the following expression is fulfilled for the Stokes vectors $\mathbf{L} = \{L_0, L_1, L_2, L_3\}$ and $\mathbf{L}' = \{L'_0, L'_1, L'_2, L'_3\}$ defined relative to ζ and ζ' [13]:

$$\mathbf{L} = \vec{\mathrm{R}}\,\mathbf{L}', \qquad (2)$$

where $\mathbf{L}'$ is the Stokes vector *before* interaction; $\mathbf{L}$ is the Stokes vector *after* interaction; $\vec{\mathrm{R}}$ is the reference plane rotation matrix or rotator (from the Latin word "rotatio") which is defined as follows [13]:

$$\vec{\mathrm{R}} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\varphi & \sin 2\varphi & 0 \\ 0 & -\sin 2\varphi & \cos 2\varphi & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}. \qquad (3)$$

The sign of φ is defined based on the condition that the coordinate system associated with the beam is right-handed: a positive value of angle φ corresponds to an anti-clockwise turn if looking from the side of positive values of the axis Z.

It is worth noting that the following system of indications is used hereinafter:

$\mathbf{a}$, $\vec{\mathbf{a}}$, $\vec{a}$, $\vec{a}$ is the column vector;

$\bar{\mathbf{a}}$, $\bar{a}$, $\bar{a}$ is the row vector;

$\hat{\mathbf{a}}$, $\hat{a}$, $\hat{a}$ is the unit column vector;

$\vec{\bar{\mathbf{a}}}$, $\vec{\bar{a}}$, $\vec{\bar{a}}$ is the matrix;

$\mathbf{a}\times\mathbf{b}$ is the plane generated by vectors $\mathbf{a}$ and $\mathbf{b}$ with a normal of $\hat{\mathbf{N}} = \frac{[\mathbf{a}\times\mathbf{b}]}{|[\mathbf{a}\times\mathbf{b}]|}$.

2. MATHEMATICAL MODEL OF MULTIPLE REFLECTIONS OF LIGHT WITH CONSIDERATION OF POLARISATION

In order to create a mathematical model considering light polarisation, the authors used the method proposed by G.V. Rosenberg in [11] which is based on use of the Stokes parameter vector for description of the state of a light beam and Mueller matrices for description of light interaction with a substance. Let us review this method in detail.

Distributing in some medium, a beam interacts with substance. In cases when electrodynamics equations are linear and homogeneous, the result of such interaction may be presented in the following form:

$$\mathbf{L}(\mathbf{r},\hat{\mathbf{l}}) = \vec{\bar{\mathrm{R}}}(\hat{\mathbf{l}}'\times\hat{\mathbf{l}},\hat{\mathbf{N}}\times\hat{\mathbf{l}})\cdot \cdot\vec{\bar{\rho}}(\mathbf{r},\hat{\mathbf{l}},\hat{\mathbf{l}}')\vec{\bar{\mathrm{R}}}(\hat{\mathbf{l}}'\times\hat{\mathbf{N}}',\hat{\mathbf{l}}'\times\hat{\mathbf{l}})\,\mathbf{L}(\mathbf{r},\hat{\mathbf{l}}'), \quad (4)$$

where $\vec{\bar{\rho}}(\mathbf{r},\hat{\mathbf{l}},\hat{\mathbf{l}}')$ is the 4×4 Mueller matrix which describes the effect on the beam caused by the substance; $\vec{\bar{\mathrm{R}}}(\hat{\mathbf{l}}'\times\hat{\mathbf{N}}',\hat{\mathbf{l}}'\times\hat{\mathbf{l}})$ is the matrix of the reference plane rotation from $\hat{\mathbf{l}}'\times\hat{\mathbf{N}}'$ to $\hat{\mathbf{l}}'\times\hat{\mathbf{l}}$. The plane $\hat{\mathbf{l}}'\times\hat{\mathbf{N}}'$ is generated by direction of the beam after the *previous* diffusion and normal of the element of the surface on which the *previous* interaction occurred; $\hat{\mathbf{l}}'\times\hat{\mathbf{l}}$ is generated by directions of the beams after *the previous and the current* interactions; $\hat{\mathbf{N}}\times\hat{\mathbf{l}}$ is generated by the direction of the beam after the *current* interaction and the normal of the element of the surface on which the *current* interaction occurred.

The result of a row of transformations will be obtained by applying the corresponding matrix $\vec{\bar{\rho}}$, which is the product of matrices of partial transformations:

$$\vec{\bar{\rho}} = \prod \vec{\bar{\mathrm{R}}}_i\,\vec{\bar{\rho}}_i\,\vec{\bar{\mathrm{R}}}'_i. \quad (5)$$

This work studied only the case of light reflection from scene surfaces with different fraction of Fresnel component. That is why below the construction of Mueller matrices which describe change of the Stokes vector only at the interface of media with different refractive indexes is presented.

Let us assume θ is the angle of incidence, i.e. the angle between the direction $-\hat{\mathbf{l}}'$ and the vector $\hat{\mathbf{N}}$ of normal to the surface (Fig. 1); θ_{reflec} is the angle of reflection; θ_{refrac} is the angle of refraction.

Direction $\hat{\mathbf{l}}$ of the beam reflected from the interface will be determined as:

$$\hat{\mathbf{l}} = \hat{\mathbf{l}}' - 2(\hat{\mathbf{N}},\hat{\mathbf{l}}')\hat{\mathbf{N}}. \quad (6)$$

Generally, for reflection from the border of two dielectric media, the Mueller matrix $\vec{\bar{\rho}}$ has the following form [13]:

$$\vec{\bar{\rho}} = \frac{1}{2}\begin{pmatrix} \rho_\perp+\rho_\parallel & \rho_\perp-\rho_\parallel & 0 & 0 \\ \rho_\perp-\rho_\parallel & \rho_\perp+\rho_\parallel & 0 & 0 \\ 0 & 0 & 2\sqrt{\rho_\perp\rho_\parallel} & 0 \\ 0 & 0 & 0 & 2\sqrt{\rho_\perp\rho_\parallel} \end{pmatrix}, \quad (7)$$

where $\rho_\parallel = \frac{\mathrm{tg}^2(\theta-\theta_{refrac})}{\mathrm{tg}^2(\theta+\theta_{refrac})}$ is the Fresnel reflection coefficient for a beam linearly polarised in the in-

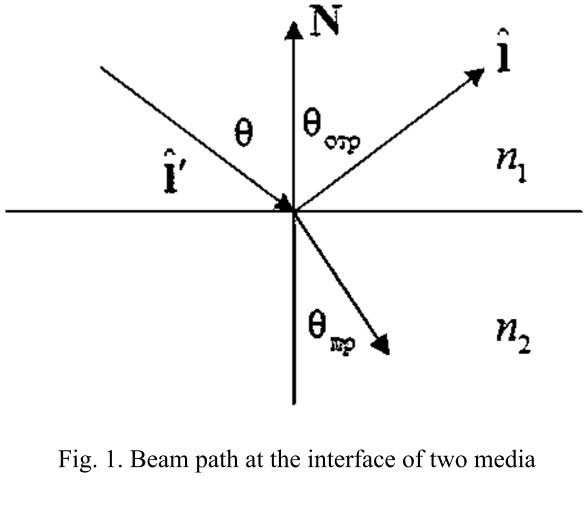

Fig. 1. Beam path at the interface of two media

cidence plane; $\rho_{\perp} = \dfrac{\sin^2(\theta - \theta_{refrac})}{\sin^2(\theta + \theta_{refrac})}$ is the Fresnel reflection coefficient for a beam linearly polarised perpendicularly to the incidence plane.

Both the reflected wave and the refracted wave retain polarisation they had before interaction.

In the particular case of normal incidence $(\theta = 0)$, when the reflection coefficient does not depend on polarisation, the matrix $\vec{\rho}$ will be as follows:

$$\vec{\rho} = \rho \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}. \quad (8)$$

For the Brewster angle $\theta = \theta_B$, with $R_{\|} = 0$, the matrix is equal to:

$$\vec{\rho} = \frac{1}{2}\cos^2 2\theta_B \begin{pmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}, \text{ and}$$

$$\mathbf{L}_{ref} = \frac{1}{2}(L_0 + L_1)\cos^2 2\theta_B \begin{pmatrix} 1 \\ 1 \\ 0 \\ 0 \end{pmatrix}. \quad (9)$$

Drawing an analogy between luminance and the Stokes vector (which is the "vector luminance"), it is possible to obtain the global illumination equation with consideration of polarisation similar to [14, 5].

With consideration of (2) and (4), the relation between the incident radiation and diffused radiation will be defined in the following way:

$$\mathbf{L}(\mathbf{r},\hat{\mathbf{l}}) = \frac{1}{\pi}\int \vec{\mathrm{R}}(\hat{\mathbf{l}}' \times \hat{\mathbf{l}}, \hat{\mathbf{N}} \times \hat{\mathbf{l}})\vec{\rho}(\mathbf{r},\hat{\mathbf{l}},\hat{\mathbf{l}}') \cdot \vec{\mathrm{R}}(\hat{\mathbf{l}}' \times \hat{\mathbf{N}}', \hat{\mathbf{l}}' \times \hat{\mathbf{l}}) \cdot \mathbf{L}(\mathbf{r},\hat{\mathbf{l}}')\,|(\hat{\mathbf{N}},\hat{\mathbf{l}}')|\,d\hat{\mathbf{l}}', \quad (10)$$

where $\hat{\mathbf{l}}'$ is the unit vector of radiation incidence direction; $\hat{\mathbf{l}}$ is the same for diffusion; $\mathbf{r}$ is the radius vector of the diffusion point; $\mathbf{L}(\mathbf{r},\hat{\mathbf{l}})$ is the Stokes vector at point $\mathbf{r}$ along the direction $\hat{\mathbf{l}}$; $\hat{\mathbf{N}}$ is the normal to the surface; $\vec{\mathrm{R}}(\hat{\mathbf{l}}' \times \hat{\mathbf{N}}, \hat{\mathbf{l}}' \times \hat{\mathbf{l}})$ is the matrix of rotation of the reference plane from $\hat{\mathbf{l}}' \times \hat{\mathbf{N}}$ to $\hat{\mathbf{l}}' \times \hat{\mathbf{l}}$; $\vec{\rho}(\mathbf{r},\hat{\mathbf{l}},\hat{\mathbf{l}}')$ is the Mueller matrix at reflection point with the specified directions of incidence and diffusion of radiation.

Let us assume that there is no absorption, diffusion and refraction in the medium between the surfaces of the scene. Then we have the boundary value problem of the radiative transfer equation (RTE):

$$(\nabla, \hat{\mathbf{l}})\,\mathbf{L}(\mathbf{r},\hat{\mathbf{l}}) = 0, \quad (11)$$

with boundary conditions on the diffusing surfaces:

$$\mathbf{L}(\mathbf{r},\hat{\mathbf{l}}) = \frac{1}{\pi}\oint \vec{\mathrm{R}}(\hat{\mathbf{l}}' \times \hat{\mathbf{l}}, \hat{\mathbf{N}} \times \hat{\mathbf{l}})\vec{\rho}(\mathbf{r},\hat{\mathbf{l}},\hat{\mathbf{l}}') \cdot \vec{\mathrm{R}}(\hat{\mathbf{l}}' \times \hat{\mathbf{N}}', \hat{\mathbf{l}}' \times \hat{\mathbf{l}}) \cdot \mathbf{L}(\mathbf{r},\hat{\mathbf{l}}')\,|(\hat{\mathbf{N}},\hat{\mathbf{l}}')|\,d\hat{\mathbf{l}}', \quad (12)$$

and on the radiant surfaces:

$$\mathbf{L}(\mathbf{r},\hat{\mathbf{l}}) = \mathbf{L}_0(\mathbf{r},\hat{\mathbf{l}}). \quad (13)$$

Solving the equation (1) and proceeding to the surface integral, we will obtain:

$$\mathbf{L}(\mathbf{r},\hat{\mathbf{l}}) = \mathbf{L}_0(\mathbf{r},\hat{\mathbf{l}}) + \frac{1}{\pi}\int \vec{\mathrm{R}}(\hat{\mathbf{l}}' \times \hat{\mathbf{l}}, \hat{\mathbf{N}} \times \hat{\mathbf{l}})\vec{\rho}(\mathbf{r},\hat{\mathbf{l}},\hat{\mathbf{l}}') \cdot \vec{\mathrm{R}}(\hat{\mathbf{l}}' \times \hat{\mathbf{N}}', \hat{\mathbf{l}}' \times \hat{\mathbf{l}})\mathbf{L}(\mathbf{r},\hat{\mathbf{l}}') \cdot \frac{|(\hat{\mathbf{N}},\hat{\mathbf{l}}')(\hat{\mathbf{N}}',\hat{\mathbf{l}}')|}{(\mathbf{r}-\mathbf{r}')^2}d^2\mathbf{r}', \quad (14)$$

where $\hat{\mathbf{N}}' = \hat{\mathbf{N}}(\mathbf{r}')$ is the normal to the surface at point $\mathbf{r}'$. The integral is taken through the directly visible part of the scene surface.

The global illumination equation (GIE) for the Stokes vector will be written in the final form if the visibility function $\Theta(\mathbf{r},\mathbf{r}')$ of the element $d^2\mathbf{r}'$ from the point $\mathbf{r}$ is introduced in it:

$$\mathbf{L}(\mathbf{r},\hat{\mathbf{l}}) = \mathbf{L}_0(\mathbf{r},\hat{\mathbf{l}}) + \frac{1}{\pi}\int \vec{\mathrm{R}}(\hat{\mathbf{l}}' \times \hat{\mathbf{l}}, \hat{\mathbf{N}} \times \hat{\mathbf{l}})\vec{\rho}(\mathbf{r},\hat{\mathbf{l}},\hat{\mathbf{l}}') \cdot \vec{\mathrm{R}}(\hat{\mathbf{l}}' \times \hat{\mathbf{N}}', \hat{\mathbf{l}}' \times \hat{\mathbf{l}})\mathbf{L}(\mathbf{r},\hat{\mathbf{l}}') \cdot F(\mathbf{r},\mathbf{r}')\Theta(\mathbf{r},\mathbf{r}')d^2\mathbf{r}', \quad (15)$$

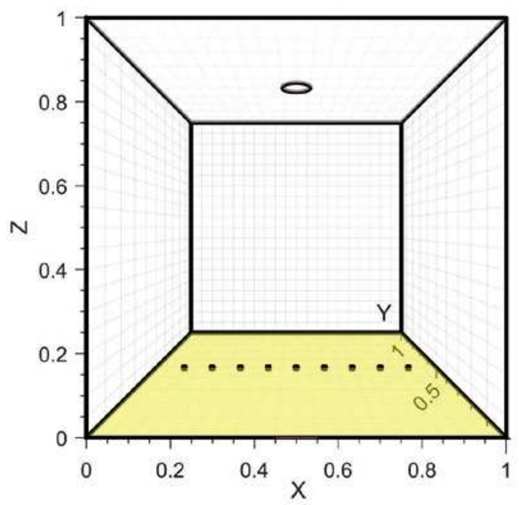

Fig. 2. Scene for modelling multiple reflections

$$F(\mathbf{r},\mathbf{r}') = \frac{|(\hat{\mathbf{N}},\hat{\mathbf{l}}')(\hat{\mathbf{N}}',\hat{\mathbf{l}}')|}{(\mathbf{r}-\mathbf{r}')^2} = \frac{|(\hat{\mathbf{N}},\mathbf{r}-\mathbf{r}')(\hat{\mathbf{N}}',\mathbf{r}-\mathbf{r}')|}{(\mathbf{r}-\mathbf{r}')^4}. \quad (16)$$

3. SOLUTION OF GLOBAL ILLUMINATION EQUATION

Like the standard global illumination equation obtained in [14, 15], generally, the equation (2) does not have an analytical solution. That is why numerical technique shall be used for its solution. The Monte Carlo method (MCM) is the most commonly used technique for this purpose. This approach is based on finding a solution of a problem by estimating its mathematical expectation by means of modelling random values.

Within the framework of this study, a number of programmes, which implemented the method of direct modelling of light distribution without consideration of polarisation, were developed. In the course of the work, this approach demonstrated a number of its well-known disadvantages related to complication of mesh formation and high memory consumption, therefore, it was considered inefficient for solving the problems of modelling multiple reflections with consideration of polarisation.

For solution of GIE with consideration of polarisation, it was proposed to use local estimates of the Monte Carlo Method. This method was first proposed in [16] and is different from direct modelling methods as in this case we estimated not distribution of photons over *all surfaces* of the scene at once but probability of photons getting exactly into *the points of interest to us.* With respect to the considered problem, the method is based on transfer from the *surface* integral to the *volume* integral by introducing the δ-function under the integral, which allows modelling to construct based on the beam.

Local estimates are widely spread for solution of problems related to radiation transmission in turbid media. When it comes to modelling light distribution during design of lighting installations, this method came into use quite recently and was described, in particular, in [17]. In the same work, it is shown that local estimations allowing to conduct physically adequate modelling of GIE and allow us to estimate all points of interest based on one beam, which increases efficiency of calculations averagely by (80–90) times, as exemplified by solution of the Sobolev problem, [17]. In view of this, application of MCM local estimates for calculations of multiple reflections with consideration of polarisation appears to be even more promising if it is taken into account that it is necessary to perform more operations at each step of the algorithm as compared to standard modelling.

However, the equation (2) is not convenient for application of statistical modelling due to the fact that the required function under the integral stands at point $\mathbf{r}'$ but is determined at point $\mathbf{r}$. To be able to use local estimates, it is necessary to transform this equation. It is also necessary to take into consideration that $\mathbf{r}'$ and $\hat{\mathbf{l}}'$ are not independent and are related to each other in the following way:

$$\hat{\mathbf{l}}' = \frac{\mathbf{r}-\mathbf{r}'}{|\mathbf{r}-\mathbf{r}'|}. \quad (17)$$

Then the equation (2) takes on the following form:

$$\mathbf{L}(\mathbf{r},\hat{\mathbf{l}}) = \mathbf{L}_0(\mathbf{r},\hat{\mathbf{l}}) + \frac{1}{\pi}\int \vec{\mathrm{R}}(\hat{\mathbf{l}}'\times\hat{\mathbf{l}},\hat{\mathbf{N}}\times\hat{\mathbf{l}})\vec{\rho}(\mathbf{r},\hat{\mathbf{l}},\hat{\mathbf{l}}')\cdot \vec{\mathrm{R}}(\hat{\mathbf{l}}'\times\hat{\mathbf{N}}',\hat{\mathbf{l}}'\times\hat{\mathbf{l}})\mathbf{L}(\mathbf{r},\hat{\mathbf{l}}')\delta(\hat{\mathbf{l}}-\hat{\mathbf{l}}')\cdot F(\mathbf{r},\mathbf{r}')\Theta(\mathbf{r},\mathbf{r}')d^3\mathbf{r}'. \quad (18)$$

GIE for the Stokes vector contains the δ-function which complicates modelling by the Monte Carlo Method estimates. This aspect may be eliminated by means of spatial integration. As a result, the estimate will take on the following form:

$$\mathbf{I}_{\varphi} = M\sum_{n=0}^{\infty}\vec{\mathrm{k}}(\mathbf{r},\mathbf{r}')\mathbf{Q}_n \text{ or}$$

$$\begin{pmatrix} I_{\varphi 0} \\ I_{\varphi 1} \\ I_{\varphi 2} \\ I_{\varphi 3} \end{pmatrix} = M\sum_{n=0}^{\infty} \vec{\mathrm{k}}(\mathbf{r},\mathbf{r}') \begin{pmatrix} Q_{n0} \\ Q_{n1} \\ Q_{n2} \\ Q_{n3} \end{pmatrix}, \tag{19}$$

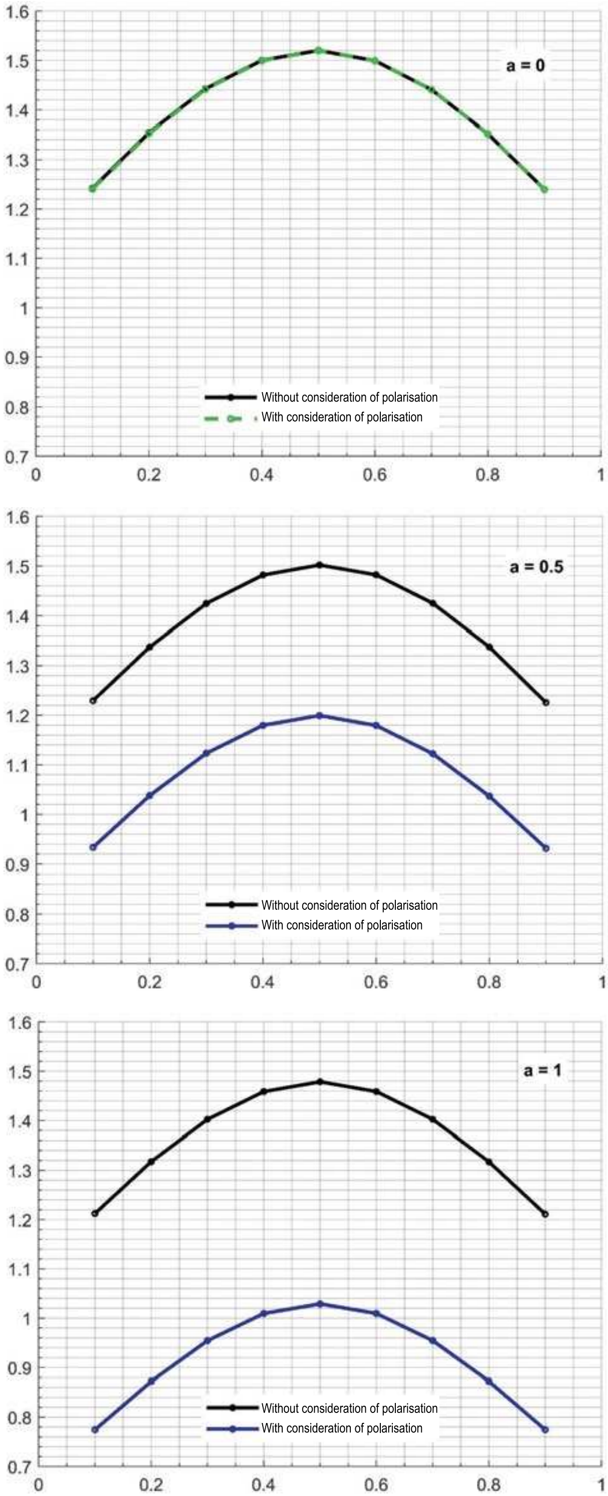

Fig. 3. Distribution of illuminance with different values of *a*

$$\vec{\mathrm{k}}(\mathbf{r},\mathbf{r}') = \vec{\mathrm{R}}(\hat{\mathbf{l}}' \times \hat{\mathbf{l}}, \hat{\mathbf{N}} \times \hat{\mathbf{l}})\vec{\rho}(\mathbf{r},\hat{\mathbf{l}},\hat{\mathbf{l}}') \cdot$$
$$\cdot \vec{\mathrm{R}}(\hat{\mathbf{l}}' \times \hat{\mathbf{N}}', \hat{\mathbf{l}}' \times \hat{\mathbf{l}})F(\mathbf{r},\mathbf{r}')\Theta(\mathbf{r},\mathbf{r}'), \tag{20}$$

where $\mathbf{Q}_n$ is the vector weight of the beam with its components corresponding to the components of the Stokes vector, M is the mean operator.

The expression (19) is called the local estimate of the Monte Carlo method and allows illuminance to estimate at a point of interest $\mathbf{r}$ of space in which multiple reflections are being modelled.

4. IMPLEMENTATION OF THE MATHEMATICAL MODEL AND THE RESULTS

The method of solution of GIE with consideration of polarisation by means of local estimates of the Monte Carlo method proposed above was implemented in MATLAB. A "room" with dimensions of 1×1×1 was selected as a scene for modelling multiple reflections; in the middle of its "ceiling", a disc-shaped lambertian source with radius of 0.05 is installed. On the "floor" of the room, at which nine points illuminance is estimated, are located (Fig. 2).

As the reflection matrix, the sum of two matrices was used:

$$\vec{\rho} = a\vec{\rho}_{\text{ô}} + (1-a)\vec{\rho}_{\text{ë}}, \tag{21}$$

where $\vec{\rho}_{\text{ô}}$ is the Mueller matrix (for Fresnel reflection in the case under consideration); $\vec{\rho}_{\text{ë}}$ is the matrix of lambertian reflection; a is the fraction of Fresnel reflection $(0 < a < 1)$. The matrix $\vec{\rho}_{\text{ë}}$ is the zero matrix with the only non-zero $\rho_{\text{ë},11}$ element, which is equal to the reflection coefficient.

Let us expand on the numerical algorithm which was used in the research programme for modelling interaction of the beam and the surface. Practical implementation of the above approach appears to be a non-trivial problem due to appearing of the δ-function in the indicatrix expression in the case of Fresnel reflection. Its availability gives rise to impossibility of playout of a new direction of a beam after interaction with the Fresnel surface and thus negates efficiency of local estimates.

To bypass this problem, the following algorithm is used. After the beam gets into the surface, the random parameter α, uniformly distributed over the interval (0, 1). is played out. Then, if $\alpha < a$, the new direction of the beam is calculated using formula

(6); otherwise, the beam is played out in accordance with the diffusion law. In accordance with the selected variant of interaction, Fresnel or lambertial reflection matrix is used.

The following parameters of surface were set as input variables: the reflection coefficient is 0.5, the refraction coefficient is 1.5, the parameters *a* varied from 0 to 1. The graphs in Fig. 3 demonstrate distributions of illuminance on the surface of the "floor" obtained both with and without consideration of polarisation with different values of the parameter *a*.

5. CONCLUSION

The above results show that consideration of polarisation significantly affects the values of illuminating parameters obtained while calculation. In case of $a = 0,6$, the difference between values exceeds 20 %, whereas in the limiting case it exceeds 30 %. Therefore, consideration of polarisation is required for solution of a number of lighting engineering problems related to modelling light distribution.

It is necessary to note that the above described mathematical model of multiple reflections of light with consideration of polarisation stays within the framework of standard photometric terms but is generalised for the case of polarisation. Significant difference from the standard model is that luminance is transformed from scalar value into vector value and the reflection coefficient becomes a matrix. Also it becomes necessary to take rotation of the reference plane after each interaction of light with substance into account.

As a result of the work, the global illumination equation was obtained for the polarisation case. This allows us to use the same methods which will consider the state of light polarisation after a certain modification. For instance, the expression for local estimate of MCM with consideration of polarisation was obtained. This method appears to be the most promising one nowadays since it allows simultaneous estimation at all points of interest of the scene based on just one beam and accelerates calculation averagely by (80–90) times as compared to direct modelling methods.

The following stages of research in this area may involve development of a more detailed model of light diffusion on surfaces of the studied scene and in the under-surface layer of the medium as well as its experimental verification.

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SUN LOAD ANALYSIS AND TESTING ON AUTOMOTIVE FRONT LIGHTING PRODUCTS

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ABSTRACT

The purpose of this research is to reach good correlation between sun load simulation and solar focusing test for exterior automotive lighting products. Light coming from sun is highly collimated (parallel rays) and focusable from lenses with concave structure. Focusing incidence leads to a hot spot on lens surrounding plastic parts which may cause melting failures at high temperature zones. Sun load simulation is performing to eliminate risk of discoloration, deformation, out gassing, coating failures and fire with prolonged exposure from field. Irradiance values in W/m^2 defined in simulation as heat source depending of an angle of incidence of the sun radiation. At first step, simulation is performing with 5 degree intervals to define the critical zones then intervals decreased to 2 degree to detect the critical azimuth and inclination angles. Critical azimuth and inclination angles is checking with ray trace analysis to check the bouncing of sun rays and possible solution to eliminate focuses with design solutions. After numerical analysis to release and validate the automotive lighting products regarding the sun load test, measurement with first parts is necessary. Measurement is performing for all critical angles which have been detected at simulation with thermal camera under ultra high-collimation solar simulator. Measured temperatures are settled according to environment conditions and correlation is checking with simulations.

Keywords: sun load, automotive lighting, hot spot, burning glass, Computational Fluid Dynamics (CFD) Thermal Analysis

1. INTRODUCTION

Sunlight is known to melt materials in the case of focusing. Sunlight damage experiments were carried out with the help of a simple magnifying glass and results described as a burning glass effect. Unlike other light sources, the sun rays can be highly focused by the lenses due to the parallelism (Fig. 1.a) [1]. In parallel with the increase number of lenses and plastic materials usage in automotive sector, many new types of burning glass fault type have begun to be observed. The light emitting diode (LED) and high-intensity discharge (HID) bulbs, which are used in the application of high-tech automotive lighting products, require the use of short focal points in terms of appropriate light distribution [2,3]. This necessity causes unwanted focuses on the plastic aesthetic parts, which are used around the lenses. As a result of these focuses, discoloration, deformation, out gassing, and burns occur as a consequence of long-term loads on the parts.

Depending on the angles of the incoming rays, the focuses may occur on the front or back of the lenses (Fig 1.b). For this reason, the lenses used in automotive lighting products must be checked against the effects of sun load.

2. MATERIAL AND METHOD

In the studies, different types of the projectors (Fig. 2) and shell reflector (Fig. 3), which are frequently used to hide the light source in the new lighting products, have been examined.

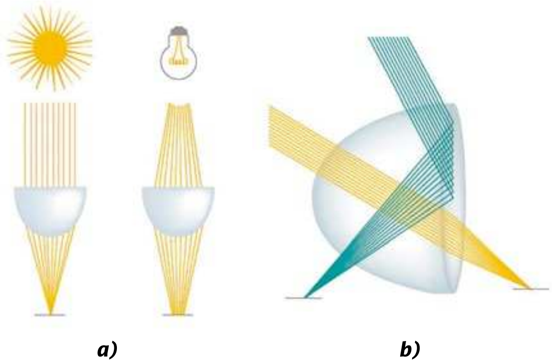

Fig. 1. Sunlight focusing (a) & front and rear surface focusing (b)

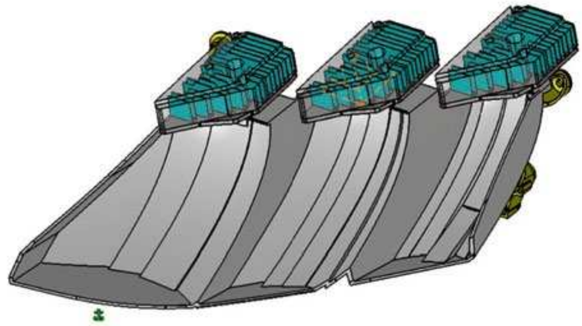

Fig 3. Shell Reflector

The focuses may occur on the aesthetic parts around the projector lenses or shell reflectors. The focusing point varies depending on the interior design of the lighting product and the part characteristics (coating, surface angles, etc.).

At the first step lighting project work shown in Fig. 4, cover panel, tubus and HID frame has been examined without aluminium coating and raw materials are chosen as black. In the front lighting project work shown in Fig. 5, the black separator part has been examined which is designed aesthetically to cover shell reflector.

Fig 2. Projector types

In accordance with the requirements of the parts requested by the customer, components have been identified that may pose a risk when subjected to the sun load in design reviews. In the first place thermal analysis; critical angle definition, ray trace analysis carried out respectively, which is followed by the final thermal simulation with the change of temperature to control the maximum operating conditions. The critical angles determined in the analysis results have been tested by the established mechanism and correlation between analysis and test has been performed.

2.1. Theoretical study

Direct solar radiation (assuming fresh air) based on the theory of optical air mass (AM) has been defined.

$$E_{direct} = E_0 \cdot 0.76^{AM^{0.618}}, \quad (1)$$

where E_0 =1353 W/m^2 is the solar constant, $AM \geq \sim 0.5$ is the optical air mass.

The air mass, which is based on Kasten and Young [4], depends on a height of h above sea level and the zenith angle of γ with earth radius equal to 6378 km and h_{atm} = 8.7 km

The latitude has been taken as 0° (21 March or 21 September) and the zenith angle has been accept-

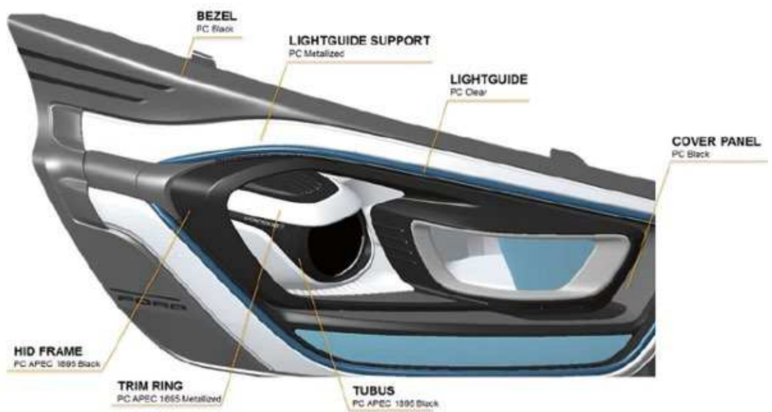

Fig 4. Project study with projector

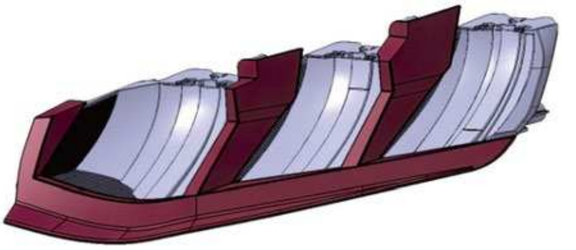

Fig 5. Project study with the shell reflector

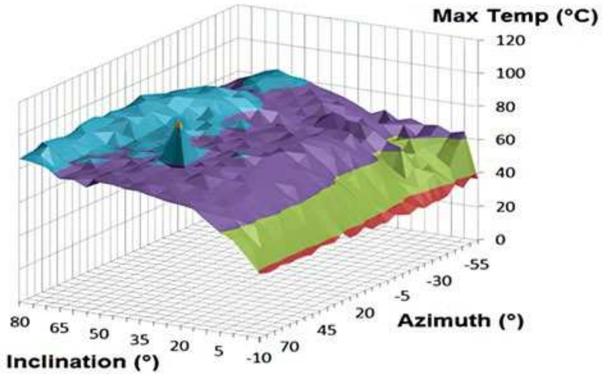

Fig. 6. The 5 degrees angles scan results

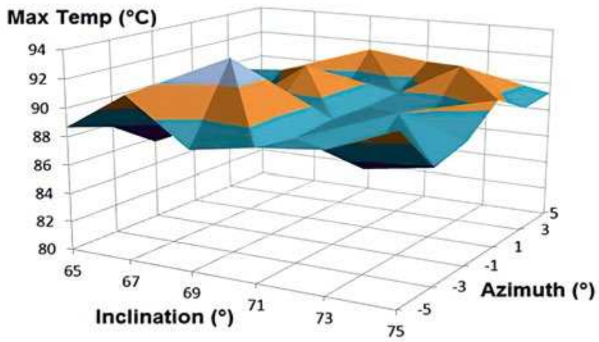

Fig. 7.The 2 degrees angles scan results

ed at 0 ° – 90°. The devices used in solar load measurements have been placed at a height of h = 2 km above sea level and calculated based on the data at this height. Depending on the angle, the radiation values have been calculated and used as input for thermal analysis.

The numerical simulation was performed under steady-state conditions and the air flow was assumed as laminar. The numerical solution includes all heat transfer nodes. The governing equations including continuity, momentum, and energy equations for steady-state conditions of air flow with free convection effects can be written by using equations (3–7). The equation 8 is solved numerically for solid regions without heat generation. The related equations cannot be compressed in the Cartesian coordinate system and can be written by using the Boussinesq approach for steady-state flow as follows:

$$\partial u/\partial x+\partial v/\partial y+\partial w/\partial z=0, \quad (2)$$

$$u\cdot\partial u/\partial x + v\cdot\partial u/\partial y + w\cdot\partial u/\partial z= -1/\rho\cdot\partial p/\partial x + \upsilon(\partial^2u/\partial x^2 + \partial^2u/\partial y^2 + \partial^2u/\partial z^2), \quad (3)$$

$$u\cdot\partial v/\partial x + v\cdot \partial v/\partial y + w\, \partial v/\partial z= -1/\rho\cdot \partial p/\partial y+\upsilon\cdot(\partial^2v/\partial x^2+\partial^2v/\partial y^2+\partial^2v/\partial z^2), \quad (4)$$

$$u\cdot\partial w/\partial x+v\cdot\partial w/\partial y+w\cdot\partial w/\partial z= -1/\rho\cdot\partial p/\partial z+\upsilon(\partial^2w/\partial x^2+\partial^2w/\partial y^2+\partial^2w/\partial z^2)+g\beta(T-T_\infty), \quad (5)$$

$$u\cdot\partial T/\partial x+v\cdot \partial T/\partial y+w\cdot \partial T/\partial z= \alpha\cdot(\partial^2T/\partial x^2+\partial^2T/\partial y^2 +\partial^2T/\partial z^2), \quad (6)$$

$$\partial^2T/\partial x^2+\partial^2T/\partial y^2 +\partial^2T/\partial z^2+\dot{q}/k=0, \quad (7)$$

where, u, v and w are the velocity (m/s) components, α is the thermal diffusivity (m^2/s), υ is the kinematic viscosity (m^2/s), β is the volume expansion coefficient, g is the acceleration of gravity (m/s^2), T is the temperature (°C), ρ is the density (kg/m^3) of fluid in the computational domain, and k and $\dot{q}$ are the thermal conductivity (W/(m⋅K)). For speed components, non-slip conditions are valid on all wall boundaries and the boundary conditions are as follows:

Speed on all wall boundaries, $u = v = w = 0$ m/s;

Pressure sphere surface, $p = 1$ atm;

Ambient temperature, $T = T_\infty = 23$ °C.

In this study, the Monte-Carlo model preferred like similar studies in the literature because of its numerical stability and precision in the results for the calculation of the heat transfer by radiation [5].

For definition of azimuth and inclination angles general range of scanning for azimuth is –90° to 90° and inclination is –10° to 100° with consideration of car tilt as 10°.

First of all, thermal analysis is performed at 5-degree intervals and the critical angle ranges are determined according to the temperature values on the parts (Fig 6).

Based on 5 degree results new scanning range is defined and used as input for 2-degree analysis to define precise angle detection (Fig 7).

After the precise angle detection taken from the peaks of 2 degree results, thermal analysis are repeated by taking the environmental ambient temperature at 80 °C in order to simulate the maximum operating conditions.

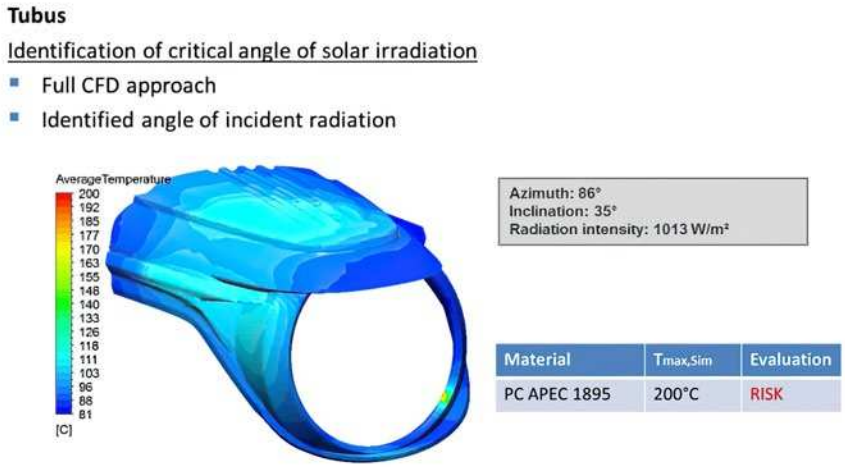

Fig. 8. Tubus thermal analysis results

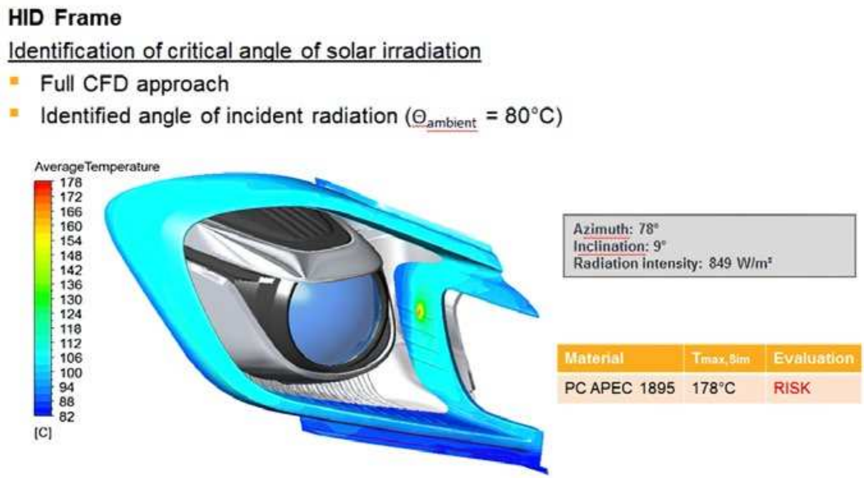

Fig. 9. HID frame thermal analysis results

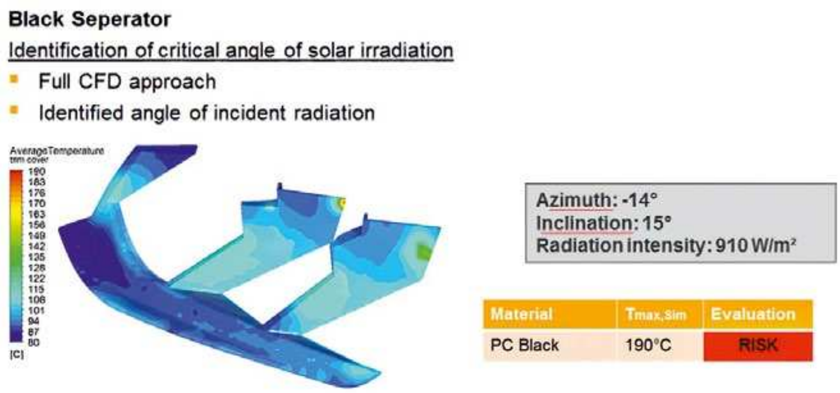

Fig. 10. Black seperator thermal analysis results

3. RESULTS

3.1. Numerical Study

Latest thermal simulations were performed on precised angles which are taken from 2-degree analysis results. Analysis results for all related components given at Table 1.

For tubus part (Fig 8) which is coming from a project, critical angle is defined as azimuth 86° and inclination 35°. Thermal simulation is performed for this precise angle with defined radiation intensity and ambient temperature taken as 80 °C. Vicat softening temperature of the different grades of polycarbonate taken into consideration for risk evaluation [6]. Maximum temperature on tubus was calculated as 200 °C.

For HID frame (Fig 9) critical angle is defined as azimuth 78° and inclination 9°. Maximum temperature on tubus was reached to 178 °C.

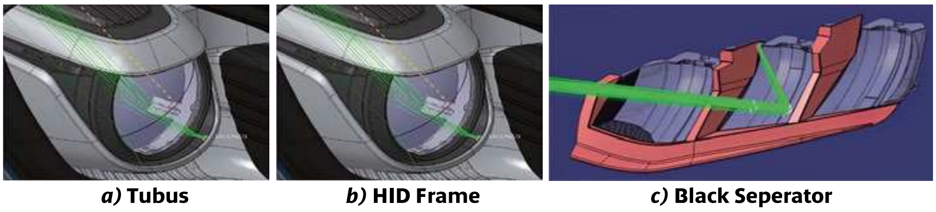

Fig. 11. Hotspot analysis results tubus (a), HID frame (b), black separator (c)

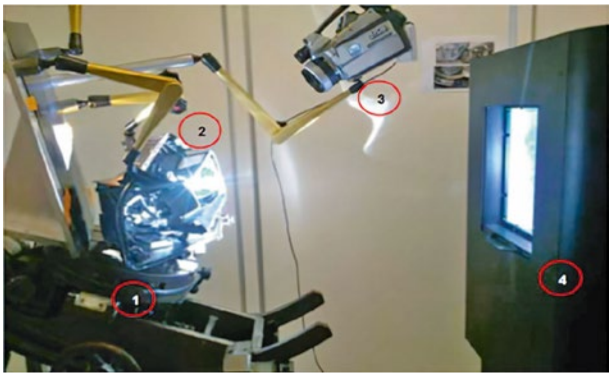

Fig. 12. Front lighting test mechanism (goniometer (1), front lighting (2), thermal camera (3), solar load device (4)

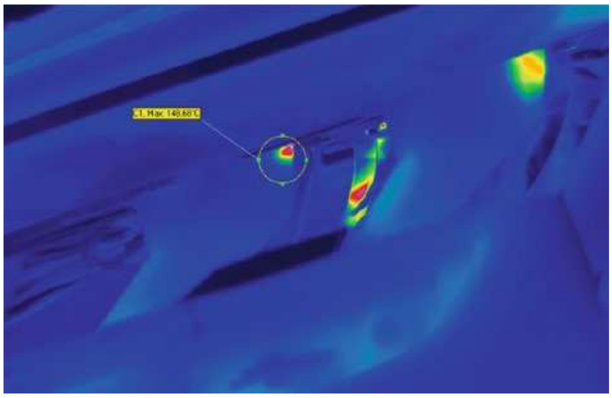

Fig. 13. Thermal camera results of black seperator

For black seperator (Fig 10) critical angle is defined as azimuth –14° and inclination 15°. Maximum temperature on tubus was calculated as 190 °C.

3.2. Optical Study

The optical system is created according to the critical angles found in the result of thermal analysis for the detection of the focusing levels of the solar rays that make up the hotspot. An optical stage is prepared by using the module written by Automotive Lighting Company.

The module lens used in the prepared optical system, peripheral parts (HID frame, tubus, etc.) and the outer lens absolutely must be. A central point is created on the module lens and the axis system is created on this point. This axis system must be exactly the same as the axis of the light source used. By using this axis system, lines are formed according to the critical angles determined later and the axis system is created for the future region of the sun rays. The direction of the destination of the new axis system formed is determined according to the light source and a previously simulated *solar.dis* file (luminous distribution file, belonging to the module) is inserted into this axis system. The optical stage is simulated on the front of the lighting product. The name of this stage is determined as measure screen. The lights coming from the light sources used and the lighting product in a refracted or reflected way hit this stage, and in this way, it's possible to simulate the illumination on the road [7]. The surfaces that are hotspots in the optical system are taken as mandatory and ray traces analysis is initiated by using at least 1million rays. The places of the hotspots on the measurement screen are detected by the back ray traces analysing from which surfaces the rays coming out of the solar light source by refracting from the module lens.The controls carried out as a result of the optical system established according to the angles found as risky in the results of thermal analysis and the focusing levels have been given in Fig 11.

Table 1. Critical Angles

Part Description	Critical angles
Tubus	Az.: 86° Inc.:35°
Black Separator	Az.:-14° Inc.:15°
HID Frame	Az.: 78° Inc.:9°
Cover Panel	Az.: 3° Inc.:69°

3.3. Test Studies

The analysis of the completed samples validated by the test setup prepared at the critical angles. The front lighting product is placed on the goniometer and exposed to the solar load. The goniometer, which can move horizontally and vertically, is brought to the critical angles determined by the analysis and the solar load at this point is adjusted

Table 2. Analysis and Test Results

Part Description	Critical Angles	Sim. Res. (°C)	Test Res. (°C)	Difference Rate (%)
Tubus	Az.: 86° Inc.: 35°	200	194	3,00
Black Seperator	Az.:-14° Inc.:15°	190	188	1,05
HID Frame	Az.: 78° Inc: 9°	178	184	3,37
Cover Panel	Az.: 3° Inc.:69°	129	131	1,55

from the test device and the measurements are performed on the parts, Fig 12.

In Fig. 13 and Fig. 14 thermal measurement results of black separator and HID frame have been given, respectively. Measurements have been performed with thermal camera at ambient temperature 23 °C. According to the thermal camera measurements on black seperator maximum temperature is found as 148,68 °C and on HID frame found as 144,40 °C.

4. DISCUSSION AND EVALUATION

As the tests have been carried out at ambient temperature, the offset values have been added to the test results in order to obtain an ambient temperature of 80 °C depending on the inclination angle determined to be compatible with the analysis results.

In Table 2, the analysis and the test results have been given. The results of the analysis have been compared with the measurements carried out with a thermal camera and the error rates have been examined. The maximum difference rate has been determined on the HID frame part with 3.37 %. Difference rates resulting from plastic parts warpage, assembly and production tolerances may vary in a negative or positive direction. Therefore, according to the temperature values determined after analysis, a minimum security margin of 10 °C is predicted for the softening temperatures of plastic materials, thus preventing the deviations specified to cause damage on the part.

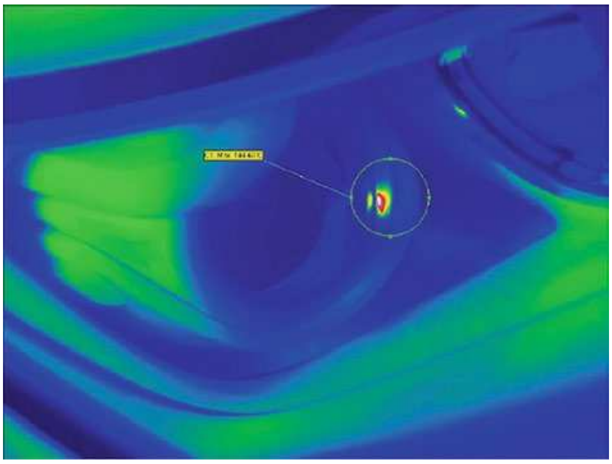

Fig. 14. Thermal camera results of HID frame

5. CONCLUSION

The determined rates of difference are within the 5 % range and the correlation of the analysis and test results have been provided. The selected thermoplastic materials have been prevented from being exposed to colour fading, deformation, gas output and burns generated as a result of long-term loads under the maximum solar load to be exposed in the field. In the subsequent studies, the conduct of studies for different raw material colours, the optimization of the analysis inputs and the correlation with the test results are planned.

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New Publications January 2020
CIE237:2020 Non-Linearity of Optical Detector Systems

This Technical Report gives recommendations for the characterization, selection and application of optical radiation detectors to perform linear measurement conditions. It helps the users to find the causes of non-linear behaviour and to avoid non-linear operation. It discusses detector operating circuits, measurement conditions, detector signal measurements in different modes, and preamplifier measurements. It is shown how to produce a detector system that minimizes measurement uncertainties caused by non-linear operation. Non-linearity test methods and procedures are discussed by which the linearity of detectors and their operating circuits can be determined.

The publication is written in English, with a short summary in French and German. It consists of 35 pages with 18 figures and one table and is readily available from the CIE Webshop or from the National Committees of the CIE.

The price of this publication is EUR108, (Members of a National Committee of the CIE receive a 66,7 % discount on this price).

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