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## Editorial Office:

VNISI, Rooms 327 and 334
106 Prospekt Mira, Moscow 129626, Russia
Tel: +7.495.682.26.54
Tel./Fax: +7.495.682.58.46
E-mail: lights-nr@inbox.ru
http://www.sveto-tekhnika.ru



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 four issues, with about 80–140 pages per issue. Each paper is reviewed by recognized world experts.

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# CONTENTS

**VOLUME 25 NUMBER 1 2017**

## LIGHT & ENGINEERING

*Light & Engineering*
*Vol. 25, No. 1, pp. 4-13, 2017*

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# THE ROLE OF BL GROUP HOLDING IN THE DEVELOPMENT OF THE LIGHTING INDUSTRY

George V. Boos

*BL GROUP Holding, Moscow*
*E-mail: first@gboos.ru*

**ABSTRACT**

This article describes the 25-year history of BL GROUP holding and its development from its establishment until the present day.

**Keywords:** SVETOSERVIS, BL GROUP holding, architectural illumination, State prize, Patriarchy medal, automated illumination control system (AICS), uniform light environment, luminaires with light emitting diodes, lighting poles

A quarter of a century is a considerable period of time for reflection upon events and people, which have allowed the development of the small SVETOSERVIS company into the largest national lighting holding in Russia.

Light engineering is a surprising industry of science, engineering and production. People and society depend upon it a great deal. Light is inseparably linked with people's life in all spheres of their activity. Since the beginning of industrialisation, people spend most of their time in closed spaces with artificial light. Their quality of life depends on the quality of illumination. Light can influence the psychological, emotional and physical state of a person. Poor quality illumination influences people depressively. According to photo-therapist Alexander Vunsh, to be in good health, a person must experience the full spectrum of visible radiation, as there is an important connection between illumination and the feeling of comfort. Professionals have been warning of a general lack of expertise concerning high-quality illumination. As part of these discussions, both energy saving narratives, and those calling for improving health impacts and quality of life are becoming more and more audible. German light designer Ingo Maurer perfectly summarised: "Light is a feeling, and feelings should be correct. Bad light makes people unfortunate".

I feel lucky: my parents were light engineers working at the VNISI of S.I. Vavilov. They got me involved in light engineering. I graduated from the Moscow Power Institute electronic engineering department with a degree in light engineering and after army service, worked at the VNISI for several years, where for the first time I considered the imperfection of the established system of developing and reconstructing illumination installations. The system was based on using practical results from various companies, which were not interconnected. Some of them developed and manufactured light devices; others designed lighting installations; some carried out their assembly; and, others still operated them. In the best case, leading companies, such as *Philips*, *Osram*, *General Electric* etc, combined the development and production of the lighting devices with the design of lighting installations using their own equipment. And the remaining steps were, as a rule, performed by others. This approach constantly caused problems, both at the assembly stage, and during operation of the lighting devices: decrease of reliability and service life of the installations themselves, poor illumination quality, growth of labour expenditure at the operation stage and as a consequence, operation cost increase. The absence of a system wide analysis of existing de-

Fig. 1. Workers of Svetoservis Open Company onsite on projects: a – Spasskaya tower of the Moscow Kremlin (V.M. Pyatigorsky and A.S. Bukatov); b – the State historical museum of V.I. Lenin (V.M. Pyatigorsky and N.S. Perov); c – Tsaritsino Manor

vice disadvantages meant that new devices could not be developed and improved to meet consumer requirements.

This observation persuaded me that a system with fully closed cycle needed to be created. From science – to product development and manufacture, and then based of these products – to design of new lighting installations, to their mounting and operation and – to a subsequent analysis, the result of which would be new scientific developments. In other words, a comprehensive illumination approach based on a single foundation was needed. More than 7000 designs were developed based on this approach. And then, in the early nineties, we began to develop a market proposal of a complete illumination service system: from design to operation. The concept turned out to be very topical. We embarked on a wide variety of projects: we illuminated entrances, pavilions, shops, clinics, metro stations and even factories. For example, "Sickle and Hammer", Moscow town-building factory, Oskol metal works, Aircraft production association of Gagarin in Komsomolsk on the river Amur and others.

In 1991, the SVETOSERVIS team, which I had established, united about two dozen young, vigorous and passionate light engineers who were efficient and successful. There were a number of leading experts of the VNISI among them, interested in the implementation of the new operating principle: I. Ya. Kainson, V.M. Pyatigorsky, A.A. Korobko, my father V.G. Boos, V.N. Nakhodnov, M.S. Galinsky, M. Ju. Kaplinskaya, D.A. Halkovsky, E.I. Myasoedova, A.I. Mitin, V.A. Gromadsky. Later on, M.P. Belyakova, P.F. Borzov, A.S. Bukatov, E.A. Vashurkina, V.G. Dektyar, V.I. Infimovsky, T.O. Lukina, G.S. Sokolova, N.N. Sofronov, N.N. Timofeeva, A. Yu. Forov, V.V. Khametova, V.D. Shvachko, E.V. Khozilova joined us, and then V.I. Abramov, V.V. Buyanov, D. Yu. Chepelevsky and others were involved (Fig. 1.).


Fig. 2. Opening of an office of the company in Inzhenernaya street. G.V. Boos is in the foreground

We took on lease a 14-meter room of the VNISI, which soon became too small for us, Fig.2. We began cooperation with all possible lighting product manufacturers, primarily with the Lisma Saransk production association.

It should be said that state of external illumination in Moscow in the 1990s was pitiful. In the evenings the city died out. Yards, streets, squares, avenues, parks – all were dark and unsafe. Building lobbies at best were illuminated with a single dimly flickering bulb, serving all floors. Vandalism prospered. Facing many problems connected with urban illumination, the Moscow government made the decision to transform Moscow into an attractive and comfortable city. A huge contribution to the achievement of this objective was personally made by Ju.M. Luzhkov who was mayor of the capital from 1992 until 2010. Thanks to his support, the first real steps towards the forma-

Fig. 3. Park Pobedy war memorial on Poklonnaya Gora

tion of a balanced light environment, including all types of illumination, were made despite enormous socioeconomic challenges. It was a great start in development of an integrated approach to illumination and primarily, to understanding its necessity for street, landscape, gardening and architectural illumination projects.

The first attempt to change attitudes toward city space illumination was undertaken by the authorities in 1993. The Moscow government planned to implement seventeen projects of architectural illumination, which according to a government order would provide Muscovites with evening illumination by November of that year. But this did not happen: the deadline was missed and the order was not fulfilled. That day I happened to be at a meeting held by a minister of the Moscow government A.S. Matrosov supervising reconstruction and development of unique objects. The debriefing was serious. I came in sight of A.S. Matrosov, and we were charged with completion of fifteen of the seventeen planned projects. The choice was not made on a whim. We just finished an illumination project of the Cathedral of Kazan Divine Mother Icon in Red Square, which was performed in emergency timescales. We were called upon a month before the object commissioning. We fulfilled the task, and the work was of high quality and efficiency, which was recognised by the commissioning authorities.

That period became a serious test for us. The work was complex. Many steps were taken for the first time. The time was limited. It was important to abandon floodlighting under conditions of restrained urban building and to make the move to local and accenting illumination using lighting devices of smaller power in order to avoid blinding and discomfort. At that time in the country, no lighting devices for architectural illumination were manufactured at all. The promised financing, which besides was illusive enough, could not cover the costs of expensive foreign lighting equipment. The first payments for the fifteen completed projects only came through in August of the following year. We bought the Svecha-3 light-signal equipment of the Gusev factory of lighting fixtures. Intended for airfields and fishing ships, these lighting devices were made on the basis of reflector incandescent lamps without their own optics.

Having compiled them with reflector lamps based on torches with high-pressure mercury arc lamps containing iodides and throttle mercury lamps, as well as with ballasts of independent production, we managed to develop, in a very short amount of time, small searchlights for architectural illumination, which were acceptable as a first step.

This juncture became critically important for us. When adopting the Moscow Governmental order of 02.08.1994 «On approval of general layout of light-and-colour decoration of the city and on measures for it implementation», we were selected as the general contractor of this program. The duration of the program amounted to three years.

There are many different companies on the Moscow lighting market now and many ideas. New opportunities of developing city illumination with light-emitting diodes is a relevant topic. But back in the nineties, there was a significant backlog of projects and our role in this initiative was determining. Designers and the whole Svetoservis team continued this very intensive and very interesting work. Moscow theatres, high-rise buildings, railway stations, bridges, underground pavilions, churches and monasteries, statues, sculptural compositions, the embankment of Moskva River and many other city sights were provided for by the programme. The quality and delivery of the work were strictly supervised. We lived hazardously, worked tirelessly and fell behind on sleep. The mass-media branded us light-o-holics. We worked with building owners, considered historical documents and features and performed experimental in situ. The projects of greatest significance had to be discussed at the SVETOSERVIS scientific and technical council, and then at the council of the

Main Artist of Moscow. All projects were coordinated with the Department of heritage protection and MOSKOMARHITEKTURA. We started to work closely with architects of Mosproekt-2, and later on with the teams of Mosproekt-4 and Miscow Architectural Institute. We also continued a close cooperation with the VNISI. We performed equipment mounting in all weather. But the joy of seeing each new project completed overpowered all: the weariness, the constant stress and urgency of the work.

Yu.M. Luzhkov, the Matoy of Moscow at that time turned noticed us, when during the construction of the Poklonnaya Gora war memorial, the designers involved in its illumination suggested to install lighting masts, "as on a football field". As Luzhkov was not a light engineering specialist, he rejected this proposal and initiated the procurement of a new provider to design the architectural illumination. Hence we were invited to take on the project. The concept developed by SVETOSERVIS was more appealing to Luzhkov (Fig. 3).

Another significant event occurred in the autumn of 1994 when Elizabeth II, the Queen of Great Britain and Northern Ireland arrived on a state visit. The tour included an evening excursion within the central part of the city; the queen was accompanied by the mayor. By this time, SVETOSERVIS put in commission more than fifty objects. And it was happened that at the moment exactly, when the cortege was driving through, all the illumination was switched off. The next day a special meeting was convened by order of the mayor at the first mayor deputy B.V. Nikolsky's office. He was responsible for the city ensemble. A result of the meeting was the decision to transfer operation of the all lighting installations to our enterprise.

Working days became longer. Each evening, my colleagues and I went round the all objects, and observed the reaction of Muscovites to the illumination, and adapted future plans. The list of our commissioned objects includes, but is hardly limited to the following: the State academic Bolshoi theatre, high-rise building of the Moscow State University (Fig. 4a,), television tower in Ostankino (Fig. 4b,), well-known Shukhov's tower (Fig. 4c,) which is a unique architectural example of the 20th century Russian avant-guard, the Donskoi monastery, Resurrection church in Kadashi, circus on the Vernadsky prospekt, Mosfilm film studios, transport overpass on Prospect Mira (Fig. 5d,), all pedestrian bridges, the first dynamic illumination of Krymsky bridge, and others. Sometimes we were forced to make non-standard decisions. For example, it was when working on the Poklonnaya Gora, we designed an installation simulating beam interception of aircraft. It was made on the basis of tank searchlights using a rotating machine-tool.


Fig. 4. The first objects of the company: a – high-rise building of the Moscow State University of M.V. Lomonosov; b – television tower in Ostankino; c – traffic overpass in Prospekt Mira street; d – radio tower in Shabolovka street (Shuhov's tower);

Fig. 5. Novodevichy Blessed Virgin-Smolensky monastery

Fig. 6. Catholic Cathedral of the Immaculate Conception of the Blessed Virgin Mary

Projects in churches and monasteries were fascinating. In the first instance, a blessing by the Patriarch was required, which we were able to obtain. The approach to this subject had to be delicate; therefore, we only used static illumination. In total, we have illuminated more than 150 places of worship, including the Cathedral of Christ the Saviour, the Novodevichy (Fig.5) and Novospassky monasteries in Moscow, the Svyato-Troitsky Serafimo-Diveevsky monastery in Diveyevo, the Sofiisky cathedral in Vologda, the Peter and Pavel's cathedral in Kazan. As well as mosques in Moscow and Kogalym, the Catholic Cathedral of that Immaculate Conception of the Blessed Virgin Mary in Moscow (Fig.6), and others. Our work was awarded the silver medal of the Patriarchy.

In 1995 we achieved our first victory at the Russian design exhibition-competition. For the years we participated, our prize-winning projects were very different by architecture, purpose and scale. In total, they numbered more than thirty (Fig. 7). Among the winners were the following porjects: the State museum park Tsaritsino and the Bolshoi theatre, Pashkov's house and planetarium, as well as television towers in Sochi "Dancing in the dark". For the period from 1997 to 2000, we received four international prizes, including European awards for the best brand, best service and best quality, and in 2012 the prize of an international competition: *LUCI/Philips city. people.light Award.*

By the end of 1996, about 300 completed projects had become our brand identity. And in 1997 we were awarded the State prize for architectural illumination of the capital. By this time, the appearance of Moscow had changed, and we had gained a wide range of design experience. Calculators and drawing boards became obsolete. Mobile elevating work platforms, cranes, lorries etc. appeared in the service divisions.

Architectural illumination became a leading direction for Svetoservis, but far from its only focus. Our company was a leader in many fields. We were called upon to design, mount and operate residential illumination in administrative districts of Moscow and in other cities. We undertook a technical audit over the entire territory of Moscow. Based on the findings, we developed regulations of technical operation and created technological cards; we developed a uniform electronic database of the systems of external illumination, which did not exist previously. We also performed a full-scale upgrade of the obsolete and worn-out equipment installing support structures with a modern protecting cover. Adherence to European standards in the design of long length tunnels: Lefortovsky, Gagarinsky and Volokolamsky, was also our initiative. This decision ensured that

Fig. 7. The president of the Russian Federation B.N. Yeltsin hands over to the Technical director of Svetoservis Open Company V.M. Pyatigorsky the State prize of the Russian Federation in the creative arts field for 1996 for forming light-and-colour environment of Moscow

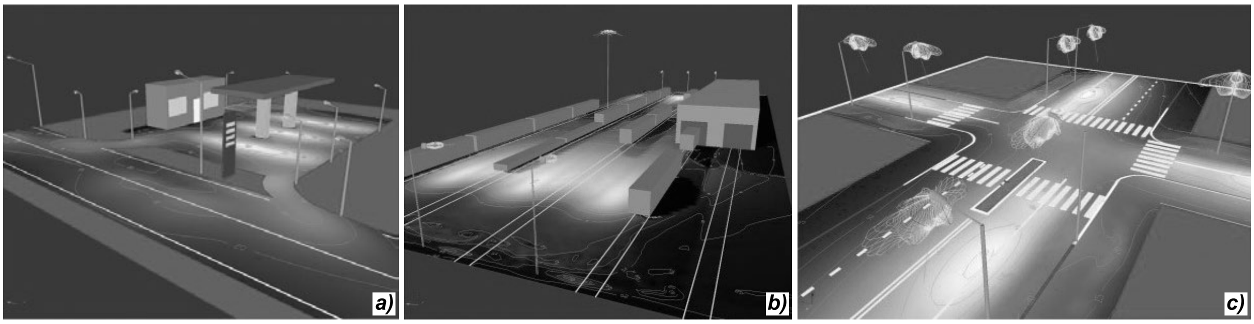


Fig. 8. Light-in-Night projects: a – gas station site with an adjoining road; b – railroad switching unit; c – one-level road crossing

the illumination of the tunnels was designed with due regard for the needs of modern high-speed and intensive traffic; modernising an area where previous illumination standards were set in the 1960s. Today, there are more than thirty such tunnels in our portfolio.

Our enterprise pioneered the creation and application of automated control system of illumination (AICS) in Russia, both for external (unitary), and architectural illumination. We were able to solve problems quickly, whilst delivering a notable energy saving effect and to creating some unexpected colour-dynamics environments.

Bespoke software programs, which we developed for illumination control using the equipment developed and manufactured at our Moscow factory, allow creating dynamic light installations both for everyday tasks ("Smart city», "Smart street», "Smart entrance", "Smart house», "Smart enterprise», "Smart filling station", etc.), and for architectural, exposition, scenic, light-dynamics, as well as for colour-light-dynamic illumination with various special effects.

We are the first and only provider in the history of Russian illumination, to develop concepts of uniform light-and-colour environments for entire cities, such as St.-Petersburg, Sochi, Lipetsk, Perm and others.

As far back as 1993, when the scope of our projects was already increasing, I defined a task of developing a piece of software to calculate and design illumination. The main part of the development fell on the shoulders of A.I. Mitin, A.A. Korobko and then to D. Yu. Chepelevsky.

At the same time, the information culture of the company as a whole changed. A programme for automated design, unique in Russia at the time, was developed. The program significantly increased the work efficiency of designers. An important feature of this program, called *Light-in-Night*, was the introduction of databases of the luminaires, which were manufactured by domestic factories (Fig. 8).

From 2003 we offered the use of this software product to all designers and design companies free of charge. Further, the software was periodically upgraded and improved to keep in line with progress in the illumination field. A convenient user interface and a dialogue mode was created. The package considered all aspects of illumination. To simplify and accelerate the design, templates of a typical solution, a support (pillar) database and an economics section were added.

In spite of the fact that today there are analogous products from abroad available on domestic market, our software package *Light-in-Night* still remains relevant. It completely corresponds to Russian illumination standards and to the road coatings applied in the country. The programme includes a broad database of lighting devices manufactured in Russia and of all lighting installation elements. Therefore, it remains the unique programme of this type certified by the Russian authorities and has tens of thousands regular users. From 2016, the programme became an open platform for all manufacturers who confirmed the quality of their products by results of independent tests.

Returning to the sources and origins, it should be noted that our team initiated a variety of management and structural solutions in order to overcome interdepartmental barriers, with which we were constantly confronted. In particular, concerning transfer of social (budgetary) enterprise networks to the city financial budget. This allowed solving integrally problems both of indoor and external illumination at schools, hospitals, kindergartens and cultural centres.

Fig. 9. Architectural illumination work on the road junction of MKAD and Leningrad highway, Moscow, 2016

In my opinion, another important aspect was that we managed to become the first lighting company with a high production culture. Management culture, regulated performance deadlines, observance of the standards and rules adopted in the industry, hardware, even worker protective clothing and identification logos on the equipment and on the clothing – all of this distinguished us from others and demonstrated accessibility for people (Fig. 9). These methods are widely applied now, but in those years it was unusual. Transparency of the company is the major component of the Holding's policy today as well.

Most of our solutions and innovations were developed as a result of constant feedback with the operating divisions. This was possible due to managing structure of the business. In other words, a closed-loop working cycle was implemented. This was a high-quality tool, stimulating all divisions of the Holding to plan the work with consumer requirements firmly at the forefront of all decision making. For this reason exactly, design solutions, production, and illumination control systems are intended now to increase the quality

Fig. 10. Production process (SVETOTEKHNIKA Likhoslavl factory Open Company, Likhoslavl)

of the lighting equipment and to simplify the service of the lighting installations. All of these points are major factors of our success.

Acquisition of three of Russia's largest factories: the Moscow experimental lighting factory (МОСЗ), which today specialises in the production of control systems, Lihoslavl lighting product factory (ЛЗСИ), which is one of the oldest enterprises of the industry (Fig. 10), and Kadoshkino electro-technical factory (КЭТЗ), was a serious step towards building a powerful association. The construction of the OPORA ENGINEERING factory in 2007 for manufacturing supports and metal structures, finally united all of the available streams of the lighting industry within the company. Since 2008, the Holding has carried its new – BL GROUP, and already at that time it took an absolutely leading position on the Russian lighting product market.


Fig. 11. a – OPORA ENGINEERING Factory Open Company, Tula; b – mounting of lighting installation on a support made at OPORA ENGINEERING Factory Open Company

Fig. 12. Illumination of highways in Moscow

Fig.13. Bridge over Zolotoi Rog bay in Vladivostok

Later on, in 2012, the OPORA ENGINEERING factory branch (Fig. 11) was opened in Samara. WunschLeuchten in Germany (in 2014) and *Boos technical lighting S.L.*in Spain (in 2016) factories were purchased. These steps completed the process of creating a comprehensive industrial, design and operational corporation.

Today in Russia out of each three external illumination lighting devices, two were manufactured at by domestic factories of the Holding. The Holding produces about 30 % of the all illumination support made in the country.

Our equipment is used on the all main roads of the country. The Moscow Ring circular highway (MKAD), the Ring highway round St.-Petersburg (KAD), Moscow to Yaroslavl highway, an overhead road on New-Riga highway, Moscow to Borovsk highway, P-21, M-10, M-20, A-180, A-114, A-128, P-21, P-23 highways and modern toll highways are among them (Fig.12 9). One can see our equipment in city streets across Russia from Kaliningrad to Kamchatka, for example in Vladivostok on the bridge over Zolotoi Rog (Gold Horn) bay (Fig. 13).

And even to Russky island, located to the south of Vladivostok in Peter the Great bay in the sea of Japan, illumination equipment for a guyed bridge was carried from our factories via East Bosphorus strait.

The Holding enterprises annually manufacture and sell over two million luminaires and searchlights for all consumers both for external, and for indoor illumination. As a comparison, all over the Soviet Union no more than 370 thousand luminaires a year were manufactured, and the Holding product stock list today includes more than 4.5 thousand luminaire models. Manufacture of components for lighting devices (ballasts, starting devices and wiring products), including for hothouse irradiators and street luminaires is established. We manufacture more than 1500 million ballasts a year, and so we have practically driven out importers of these products from the Russian market. We provide ballasts for all who manufacture and operate luminaires with HP gas-discharge lamps within the Russia territory and within all former republics of the Soviet Union.

Along with traditional high efficiency light sources, the production of luminaires with light emitting diodes also increases. Their quality indicators are also growing; their range expands and is updated. Each subsequent luminaire model becomes not only more modern, more aesthetically pleaseing but also requires a considerably simplified operation service (Fig. 14). Such luminaires, as “Omega”, “Cordoba”, “Granada”, “Urban”, “Volna” and other recent developments have gained wide popularity.

At the international forum on energy efficiency and energy saving, *ENES,* in 2015, six of our developments were victorious in the competition.

Fig. 14. Demonstration of GALAD Urban LED luminaires at the *Light+Building* exhibition, Frankfurt am Main, Germany (March, 2016)

a) b) c)

Fig. 15. Luminaires with light emitting diodes of the *GALAD* trade mark: a – *GALAD Volna LED*; – *GALAD Kassiopeya LED*; b – *GALAD Urban LED*

The Econom luminaire won in two categories. The Kassiopeya LED luminaire was declared best among industrial luminaires with light emitting diodes. The Volna LED luminaire was awarded a diploma. The Urban LED (S) and Urban LED (M) street luminaires with light emitting diodes were declared winners simultaneously in two nominations and in addition were awarded audience choice and jury prizes, which meant the appreciation of both specialists and the consumers (Fig. 15).

There are regional representatives of BL Group in almost every large Russian city. We also work extensively with the CIS countries. Branches of the Holding are located in Kazakhstan, Kyrgyzstan, Armenia and Tajikistan. The operational representative offices of the Holding are in Moscow, Moscow Region, Krasnodar, Sochi, St.-Petersburg, Leningrad oblast, Essentuki, Stavropol Territory and in other regions.

Upgrade and re-equipment of our factories allowed creating enterprises equipped to the highest international standards. By scope and quality of the manufactured products, our factories are within the top 20 % of the ratings of world producers of lighting equipment and within the top ten ratings of the industrial enterprises of Russia. The Holding constantly improves production and service by investing into production equipment, special transport and infrastructure.

For the last ten years only, the investment scope of the Holding amounted to more than eight billion rubles in comparable prices.

Throughout the entire period, we successfully replaced import components with domestic ones, mainly of our own production. Now we have increased the level of our own production components up to 90 % when manufacturing our lighting devices.

One of the latest achievements in the field of new technologies is the development and production of secondary optics for luminaires with light emitting diodes. Until recently, these products were not manufactured in Russia at all. Import optics assembly was complex, and these products were no good for the luminaires they intended to serve under severe operating conditions.

The secondary optics for luminaires with light emitting diodes, which we have developed, provide all necessary types of luminous intensity curves: both round- and axially-symmetric, and asymmetric. The system, which we have developed, does not require glue installation methods, as was the case. This essentially simplifies its technological application and also improves reproduction of the luminaire lighting characteristics


Fig. 16. Illumination of architecture memorials: a – the Bolshoi theatre; b –State history and architectural art and landscape Tsaritsino open-air museum


Fig. 17. International contacts of the Holding: a – heads of Russian divisions of the Holding at WunschLeuchten factory, Germany, 2016. From left to right: A.V. Kireev, M.V. Kryzhov, A.I. Ushakov, Yu.A. Podalinsky, S.V. Koinov, B.B. Danilov, A.A. Privalov, V.S. Rudakov, A. Yu. Shtovhan, A.G. Veryasov, E.G. Mandriko; b –meeting of department of strategic and international project development workers with partners from India: K. Vinkels (fourth from the left) and A.I. Ushakov (third from the right), India, 2016

from one luminaire to another luminaire when manufacturing.

It can be said with confidence, that after these technologies were introduced, we provided a precise alignment of the group optics for light emitting diodes.

The development of luminaires with light emitting diodes in recent years has considerably expanded the opportunities of architectural and external illumination and allowed implementing the idea of multimedia facades for some objects, for example in Novy Arbat street.

In 2014 we became the winners of the Moscow prize in creative arts field for illumination of the "Book type" building in New Arbat street, and in 2015 we were recognised again for the architectural illumination of 22 Moscow bridges.

Currently, the architectural illumination we established previously in Moscow is undergoing an upgrade, and the city becomes more and more light. It is time for architectural illumination to transform new projects using modern technologies; this is a transformation we are implementing ourselves. We are developing new concepts for architectural illumination of the "Stalin's skyscrapers", of the historical Moscow centre and of other main city sights, such as Pashkov's House, the planetarium, the Bolshoi, etc. (Fig. 16a). Many new projects are already delivered, not only in Moscow but also in other cities of Russia.

New illumination concepts of such bright objects as the "Dancing in the dark" towers in Sochi, open-air Tsaritsino museum (Fig. 16b,) and others are also being developed.

Access to foreign markets should be considered a new chapter in the history of the company's development. The Holding company today supplies its products to countries in Central, Western and Eastern Europe, Africa, Asia, India and to former Soviet Union republics. Its design projects are also implemented there (Fig. 17).

Looking at our strategy as a whole, our intentions become obvious. We certainly aim to become lighting company number one all over the world.

As to our social responsibility, we will support Russian domestic lighting as before, encouraging the development of domestic lighting science, domestic lighting education, domestic lighting scientific activity and publishing, as well as veterans of the industry, health protection, culture and children's sports.

***George V. Boos,***
Ph.D. Graduated from the Light and Engineering Chair of the Moscow Power Institute (1986). President of BL GROUP holding. The Head of the Chair "Light and Engineering" of the Moscow Power Institute National Research University, Editorial Board Chairman of Light&Engineering Journal

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# RESULTS AND PROSPECTS OF LIGHT DESIGN DEVELOPMENT IN CITIES OF RUSSIA

Nikolai I. Shchepetkov

*The Moscow Architectural Institute (State Academy), Moscow;*
*E-mail: n_shchepetkov@inbox.ru*

**ABSTRACT**

Some results of the last 23 years of development of light design in Russian cities are summarised. Light design as a whole is considered as a new comprehensive direction of external illumination evolution.

The article uses the example of Moscow and other cities to consider how a new professional field was born, how the theories of light design came to be, how their implementation was experienced and how they adapt to new solutions based on light-emitting diode light sources. The troubled process of city officials attempting to create a methodological basis with standards and references for designers and coordinating bodies are also described.

Additionally, the future of light design development, based on new technologies and a fresh outlook are considered.

**Keywords**: light design, art, light engineering, science, architecture, light environment

To summarise the development of urban light design in Russia, we need to start at a reference point: let it be 1993, when on Moscow was on the threshold of its 850$^{th}$ anniversary celebrations, after a preceding period of desolation. This point was the start of the next major stage of domestic architectural illumination, which is now referred to as light design. After conception in the capital, light design began to appear as a process in other Russian cities, although at different rates, with varying degrees of delay, scope and quality. For some cities (St.-Petersburg, Sochi, Smolensk, Pskov, Kazan, etc.), general light plans were developed. It is difficult today to find a town or settlement of district or even regional level, where illuminated facades or landmark illumination are entirely absent, whether at the expense of the city or of investors. Therefore, the application of light design is definitely growing. On the one hand, despite frequent lack of funding, the process of light design expands due to new and growing levels of public interest. On the other hand, the process often becomes routine, as often happens in architecture, because for most examples of illumination, quantity does not equal quality, and this can discredit the whole field. But if the art of architecture, as viewed in the daytime, is valued and has persisted for centuries, weathering its ups and downs, then the art of light design, which is a second imagined guise of that same architecture, also stands a chance. Capital and major cities can afford to make light design an exciting and a high quality experience with regular spectacular light shows. Smaller towns are limited by festive light decorations, which are determined by local budgets, and occasionally by amateur fireworks. These short-term illuminations are beyond the scope of this article, although in the real world they have a strong effect on spectators influence their perceptions of the subject of our analysis: steady illumination in a city environment.

When considering rapidly developing external illumination, we need to agree whether light design is art or engineering? Obviously, the field stands on the two «whales»: architecture (including urbanism and design) and light engineering (visible radiations as medium existence form, their measurement and production), and their corresponding professional fields. The harmony of architecture is enabled with the «algebra» of light engineering. All types of artificial illumination should be considered under the light design umbrella, with common theories but applied in different proportions: utilitarian (road coating), architectural (building and construction facades, cityscape elements) as well as information light screens (autonomously luminescent elements). All of these types of illumination play a part in city ensembles and optically form their light spaces and light images. Therefore, it is necessary to create these illumination systems together, integrally beginning from the project. Due to the availability of the utilitarian component, in any light situation, light design (as well as architecture) is not art for art's sake similar to painting, sculpture or cinema, in which the creator entirely free.

What is a more important in light design practice: artistry or practicality? Artistry pretensions exist everywhere but they are often groundless. The utilitarian role of illumination is persistent: light from sources other than street lamps in a city environment: from installations of facade and light advertisement illumination, for example, is also useful in navigating the evening city. A light designer, who is only able to draw "beautiful pictures" (i.e. without knowledge of light engineering), is no more, than a visualizer. These pictures are then enhanced for practical use by an engineer; this splintered method of design is used by many design bureaus. But at the same time, an engineer who is not a real specialist in ancient, synthetic and complex architecture and art, cannot be a creator of aesthetic light design. Of course, there are exceptions, which serve to confirm the rules.

So in the history of Western light design, creative parterships were formed (an architect and a light engineer), which developed some famous examples of light architecture: L. Mies van der Rohe and R. Kelly, V. Lukhardt and V. Keller, J. Nuvel and J. Kersale, H. Jan and J. Kersale, Z. Hadid and Van der Heide, T. Ito and K. Mende, etc. But there are also some self-sufficient « light designers with engineering and artistic backgrounds: architects R. Narboni, I. Motoko, L. Klair, A. Gijo, D. Spairs, and M. Major, etc.

The sphere of light design is an architectural environment, either opened (in a landscape) or closed (in an interior), in which it exists and develops. Its fundamental principle is utilitarian function: generating a sufficient level of artificial illumination to support visual work of some complexity. But this physiological minimum was never sufficient for people. As soon as possible they tried to make light superhuman: magnificently transforming the visible environment and making all its objects divinely beautiful. The term «beautiful» is not scientific and not specific, but it has become almost pedestrian: a primary goal of the young branch of light design science has consisted until now in decoding the term. Light design tries to identify the quantitative parameters of illumination accessible for calculation and objective measurements, which can be transferred into a qualitative and subjective language, i.e. into the language of statistically objective visual assessments. These assessments can then be used for design simulation of the light environment parameters so that it can be judged to reliably provide a positive aesthetic environment in reality. Transformation of the lighting parameters into light-composition criteria of an architectural environment is a topical stage of development for this science. For example, it would be important to know at what luminance gradient an object illuminated in the dark along a vertical axis (an obelisk, a tower, a skyscraper) looks static, weighted, and at what luminance gradient it looks dynamic, soaring and dematerialised, certainly with regard to its size and specific situation. Which light spot luminance ratios and surface patterns, which are typical for local façade illumination, effectively destroy it, and which maintain integrity with the daytime image, helped by visual memory and perception constancy. What is the influence of colour light, which is being used more and more widely, on form shaping, emotions in architecture and perceptions of the environment? Of all the architectural forms, an arranged space, which is traditionally viewed in the daytime and perceived as a homogeneous structure within physical boundaries, is the most important but least studied category for artificial light. Under artificial illumination, this type of space becomes a heterogeneous light space with completely new objectives and visually perceived qualities, for which it is important to calculate, normalise and design the light environment in the pedestrian areas of a city.

Harmonisation of the light environment parameters, as well as traditional methods of harmonisation of dimensional characteristics in architecture, should be carried out based on proportioning light by its quantitative and qualitative parameters. Visual disintegration of an architectural form under artificial illumination occurs due to the following reasons: excessive luminance or chromatic (or either) contrasts between its elements, light spots unharmonised by angular sizes or configuration (something that painters could teach designers), unadjusted (though to a lesser degree) illumination kinetics of different lighting installations (LI) in each city space, etc. To determine optimum proportions of artificial light concerning a specific architectural and light-space form (with due regard for visual adaptation) is one of the fundamental tasks of scientific research and of the light design theory.

In conclusion: all categories of architectural forms canonized in architectural theory based on a visual assessment under "universal» daylight conditions, should be reconsidered in light design theory, analysed and measured for conditions of artificial illumination and darkness adaptation.

There is a certain backlog in this field, but it is insufficient for light design theory and practice [1, 2]. Therefore, in modern illumination design empiricism prevails, particularly because of a misunderstanding that meeting an illumination standard is an insufficient reason to provide aesthetic quality within the created light environment. However, it seems everything is in our hands. It is time now to state the interconnected theses of this article:

- In Russia, there is no formal training for the profession of light designer, although there is a need for such professionals in practice;
- In some foreign countries specialist training exists and the profession is recognised;
- There are many positive and negative examples of light design in Russian cities, but no one has a comprehensive idea about the state of light design in the country as a whole;
- The science in this field at the moment has only a few enthusiasts, not capable of solving the main theoretical and methodological problems with which the field is currently faced;
- The "Achilles' heel" of modern light design is poor monitoring of LI design and operation;
- It is unlikely that general, average, monthly and long-term goals for this field can be determined by anyone today.

The profession of light designer does not exist in Russia de jure i.e. in terms of certification and degree courses. However, some technical universities are developing initiatives to deliver this type of education (for example, the ITMO University, the Moscow Power Institute National Research University, etc.) [3]: certain subjects are taught, bachelor and master courses and diploma projects are completed. One can only hope that this will deliver benefits. In architectural higher education institutions, this work is usually conducted in architectural environment design faculties, and occasionally within architectural design departments (MArhI, Tyumen and Saratov SABI, Kazan and Tomsk SABU, the Business and design Institute, the National institute of design in Moscow, etc.). The focus in these institutions is usually on the aesthetics of illumination, frequently at the expense of lighting parameters. And the sad fact is that for some incomprehensible reasons, these universities and their teachers are almost never involved by the authorities in the real practical light design projects of their city, which is a loss both to the education process and the city itself. To fully establish the profession, it is necessary to unite the efforts of architectural and engineering institutions in order to develop uniform and similar programmes of study for this new profession, even though this will be complex from the point of view of management. But with modern teaching methods and technologies it is possible, in particular within the Teaching-and-methodical association (UMO) of the Ministry of Education and Science of the Russian Federation.

On the light design scale, Moscow is certainly ahead of the curve, but by artistic effect of illumination it is far behind other cities, like Baku for example [4]. The first time Moscow was surpassed by another city in terms of light design, was at the time of St.-Petersburg's 300$^{th}$ anniversary in 2003. Since then, St.-Petersburg has gradually strengthened its success without any radical revisions. As for Moscow, after a new mayor was appointed in 2010, the use of light emitting diode colour illumination began in 2012, which can be considered as a beginning of the second stage of light design development. Moskomarkhitektura, headed up by the Main artist of the capital I.N. Voskresensky developed in 2007 a comprehensive, uniform, but pretentious concept of creating a light-and-colour environment for the city, which was approved by the city government in 2008. Its resuscitation began in 2011 from absurd tenders for design of this environment along three streets: Novy Arbat with Kutuzovsky prospekt, Tverskaya street with Leningradsky prospekt and Prospekt Mira with Yaroslavskoe highway. The author of this idea was the Department of fuel and energy economy, as the commissioning body. This start, quite worthy of the Ig Nobel prize, was a subject of journal discussion [5] but city authorities as usual ignored it, though this fact probably affected the liberation of certain persons from the positions of the aforementioned department heads.

The commotion, with which the customer dictated to the designers with a necessary introduction of colour light emitting diodes, and perversely treated idea of a new "uniform light-and-colour environment", led to disputable results. Novy Arbat got a really original image, and the creators received the Prize of Moscow. And Tverskaya being the first large-scale urban light ensemble in Russian practice (1997–98), was disfigured: almost all light devices (LD) with discharge lamps disappeared off the facades (their arms and cables disappeared with them), and LDs with *RGB* light-emitting diodes of the companies determined by the general contractor appeared. And with them new holes appeared in the facades. After all it would be more reasonable to replace some old LDs with new ones, to add where light was lacking and to remove that which was excessive, if necessary. Qualified specialists were needed for this purpose but the customer did not have them on the project, and the design periods were short. Instead, considerable money was used quickly. Using the new LIs as part of the new-year and Christmas holiday illumination in 2012 gave the public a shock of coloured cacophony on facades, which was inexplicable, vulgar and contrary to any laws of harmony, symbolism and sense. Soon even the city authorities understood this and moved the LDs from *RGB*-mode to a bad white light mode. It is best not to speak of the luminance composition or light pattern architecture. Rare remaining rudiments of the old LIs on some buildings in Tverskaya street look much more convincing than the new ones, and they confirm these sceptic assessments. In 2012, light installations with colour light emitting diodes were also mounted for the first time on facades of some imposing buildings from the Stalin era along the Prospekt Mira. Vulgar red, green, dark blue, and violet light, which the authors of the concept did not intend to use, but the executors of the working design introduced without their knowledge, were not in place for long, only for the test switching period only. As well as in Tverskaya street, Mossvet Company also abandoned this approach. Only one strange fragment of this colour «magnificence» was kept: Dolgov's house (#50) – an architectural heritage example from 18$^{th}$ century, which a graceful classical white-yellow portico is highlighted with violet light from within. This especially irritates due to the spots on the left part of the attic.

In the following years, the commotion and intensity decreased, the tenders were procured more and more imperceptibly, the bidders and winners becoming more and more unknown. Today there is virtual silence on the subjects of how the process is going, what light design challenges are solved and so on. During the first stage (1993–2010) dozens of publications on this subject were published in the Light and Engineering journal, and in other journals; the authors of the projects shared their experience. And today it is as though there is nothing to say.

To navigate the huge expanse of Moscow without a specific target and address is almost impossible; therefore impressions of the city can be sketchy and even casual. From general impressions, it can be concluded that many objects along the capital's streets are illuminated but there are few successful custom-made examples and specially designed light ensembles, while this was the precise purpose of the development and implementation of this concept. For example, the Sadovoe Koltso (ring road): the cornices and crowning parapets of many buildings are brightly highlighted by an amber light, which visually separates them from the facade plane, quite often they are illuminated rather indifferently. We have here a mass non-tectonic solution of the light (luminance) composition of the front facade boundary building. A popular song depicts the Sadovoe ring road metaphorically as a wedding ring, which seems like it could be enacted in the illumination. But the amber cornices did not provide either an ensemble or metaphorical effect, and it is unlikely that observers get the idea.

Nevertheless, to give credit where credit is due, the Sadovoe Koltso, Prospekt Mira and other streets and squares of Moscow do present some original "custom-made" light composition solutions. It is likely that many of them are not connected directly with the city programme. Investors discovered the economic efficiency of architectural illumination more than ten years ago and finance these projects themselves. The image of the Ostankino television changed dramatically when it was covered with a media light-emitting diode net. Illumination of parts of the Kremlin has been upgraded. Previously, Moscow light designers did not have access to the Kremlin as it is a federal building, rather than part of the city government. It is the most important urban light ensemble not only in Moscow but for all of Russia, which is restored today. And questions have already arisen concerning the appropriateness of the light composition hierarchy of its elements relative to the implemented illumination fragments.

In recent years, with the reconstruction of two Stalin era skyscraper hotels «Ukraina» and «Leningradskaya», their external architectural illumination installations were improved. Their historical light composition solution was retained and made more complete and expressive, replacing old LDs with new ones, increasing of their number and hence the level of illumination, as well as changing their radiation chromaticity.

Illumination of pedestrian streets of Moscow has become a new and capacious subject of modern light design. Here it was possible to brilliantly implement ideas of a comprehensive architectural light environment for users, because the old installations of street illumination were completely dismantled during reconstruction. But alas, the magnificent granite paving did get appropriately magnificent illumination [6]. There are no streets (except for the Krymskaya embankment), where a high quality light ensemble would be implemented with a corresponding pedestrian street atmosphere. Everything is missing something for harmony of street, front façade and light-and-information illumination together with the urban context. The possible pathos of the uniform light and colour environment when illuminating street and square architectural ensembles was reduced to only the illumination of facades in pedestrian areas i.e. to the lantern arrangement.

It has become clear that the long-term monopoly of Svetoservis Company in architectural and other illumination of Moscow was replaced with a tender system of unknown suppliers: six of one was replaced with half a dozen of the other. The results are not better and there is nobody to blame. Except for Moskomarhitektura, the art council of which approves light design projects. But someone else should control the quality of these projects. The council, on which there are no professional light designers, has adopted a "flexible" policy for many years: the projects are approved on a cost basis, and then free of charge. At one point, one colour might be forbidden (dark blue for example), and then suddenly the whole *RGB* palette is permitted. But the most important thing is that the council does not pay attention to the lack of complexity of light design solutions, traditionally considering front façade illumination to be light decoration, which is the main and probably unique artistic task.

The GlavAPU (State Unitary Enterprise), which is a division of Moskomarkhitektura, in recent years has perfected the methodology of city improvement, including light design. In 2014 the GlavAPU together with Svetoproekt Open Company, developed "standards of technical design specifications, concepts of architectural, art and landscape illumination of a city environment, as well as design specification for architectural and artistic illumination of a monoobject" (what a brilliant language!). In 2015 the GlavAPU issued an "Album of typical solutions (standards) for comprehensive improvement of Moscow city outgoing highways", in which there is an "Illumination" section [7]. The "Summary standard of improving Moscow streets" developed in 2016 by Strelka Design Bureau according to a contract agreed with the Moscow Government, creates the impression that light designers are provided with new instructive and supervising materials, presumably based on the research. However, comparison of these seemingly related standards (including illumination) shows the primitiveness of the standardized LI solutions, the discrepancy of some requirements stated in them with federal standards, the absence of a reliable scien-

Fig. 1. St.-Petersburg. Malaya Konyushennaya street (a) and Aleksandrinsky theatre (b)

tific basis or novelty and a general inconsistency among themselves. It is not a quality munual to help practice, because the standards are overloaded with formal, sometimes even with tautological requirements, give no more than an outline of criteria uniformity to accomplish and assess different light design projects. But it is a pity that the governmental committee (Moskomarkhitektura) has dedicated all its efforts and publications to interdepartmental formal management measures and hardly ever tells residents, designers and the scientific community about the light design problems, prospects, successes and assessments, does not participate in discussions, does not respond to different requirements. And if there is a need to report (for example, at a round table conference), everything is presented through rose-tinted glasses. This policy is undemocratic, short-sighted and unproductive.

As mentioned above, light design is spread throughout the country without knowledge of the details and intricacies of the Moscow practice. More or less advanced regional schools of light design are being formed. Some of them serve not only their own and neighbouring regions but also compete across all of Russia, and probably in the CIS republics. Unfortunately, there is little information about this. So, St.-Petersburg steadily and in its own way implements an original programme included in the light general plan (Fig. 1)[1]. Light ensembles of the historical centre with perspectives of the streets and imperial squares, inventive-

[1] All pictures in the article are photos of the author.

Fig. 2. Tyumen. The building of the Tyumen state architectural building university (a) and Krestovozdvizhensky temple (b)

Fig. 3. Voronezh. The building of regional administration

ly illuminated bridges and light vistas of the embankments of the Neva amaze city residents and visitors with their magnificence and immensity. Kazan effectively expresses its originality using its own light figurative language. Vladivostok [8], Tyumen (Fig. 2), Saratov, Voronezh (Fig. 3), Veliky Novgorod (Fig. 4), Vologda, Astrakhan, Belgorod, Kaliningrad (Fig. 5), and Yakutsk are cities, the artificial illumination of which has been assessed by the author in person, if briefly, in recent years. Each of them has a more or less successful light design solution but there are many less professional, ordinary and "custom-made" objects, which exist outside of the light ensemble concept. Some historical cities of the regional level (salt of the Russian earth): Gorokhovets, Rostov Veliky, Kashira, Dmitrov, Sergiev Posad, Kolomna, Zaraisk and many others could glorify domestic light design and stimulate the more active development of evening tourism if remarkable pieces of architectural heritage would be properly illuminated. Among the above listed cities, Kolomna is distinguished by a number of illuminated objects but here as well the quality of light design is not entirely without fault. In other cities, original and reconstructed kremlins, monasteries, temples and palaces have only security lighting at best. The Architecture and Town-building Committee of the Moscow region has developed light ensemble plans beginning from a development of light general plans for each town. But supervising officials say that a chronic deficiency of budgetary and investment funds interferes with this goal. Troitse-sergiev monastery, as well as the Rostov Kremlin, underwent major restoration in recent years, but, unfortunately, there are no funds for their architectural illumination. LD mounting on architectural sites is rather complex problem and it is better to do it during repair and restoration work, rather than at the end.

Prospects for the development of light design are usually connected with progress in illumination technology: with wider application of light emitting diodes and the introduction of modern illumination control systems. But these are only instruments to address certain challenges, primarily, energy efficiency, resource saving, ecology, etc., and, secondly, to solve problems formed by the light design ideology as an artistic exoression for each specific situation: to create a visually comfortable environment and to make it complete from the artistic point of view. On the whole, it is not a light design question of separate objects, though historically that is where it starts, namely it is a question of an evening city environment as a hierarchy system of various light-space ensembles with individual imaginative expressiveness. And the most urgent task is the provision of a "double" integrated approach to design of this environment and of its situational embodiment. This means LIs must be an organ-


Fig. 4. Veliky Novgorod. The Kremlin (a) and Sofia cathedral (b)


Fig. 5. Kaliningrad. The cathedral (a) with E. Kant's tomb (b)

ic part of the material environment stylistically and physically, and LDs should be incorporated into pavings and lawns, building and construction facades, small architectural forms, supporting walls, ladders, etc. Static installations of utilitarian, architectural (including landscape) and advertising and information illumination functioning conjointly in city spaces, should be calculated and developed together, taking into account the illumination mode, kinetics and chromaticity of each. From the management point of view, this is a complex problem but there are situations when reconstructing pedestrian streets, parks and squares achieves positive results not only economically but socially (Krymskaya embankment in Moscow, *Finsbury Avenue* and *Regents Place* in London [1, p. 231], Nagorny and Primorsky parks in Baku [4], experience of French light designers [9], etc.)

Lack of complexity quite often leads to unpredictable outcomes: in Dmitrov on the square in front of the Kremlin, tens of five-metre tall light columns were installed. They gave a poor light. Then blinding searchlights with HILs for roadway illumination were installed on them, which worsened the visual conditions. At the pedestrian site of Rozhdestvenka street in Moscow, two searchlights directed into the sky recently turned up on two-plafond retro lanterns. Instead of arranging production of double purpose street lanterns with modern optics (autonomous light upwards and downwards), as in boulevard Richard-Lenoir in Paris or in Esplanadi street in Helsinki [1, p. 282], ridiculous solutions are found. The amateur performance of the operated enterprises sometimes turns a light design project into a band aid approach but as a whole the operational quality of architectural illumination installations leaves much to be desired. A new LI with LDs with light emitting diodes on the "Detsky Mir" (Children's world) store facades restored in 2015 repeatedly failed in all sections. Probably, this is a result of the cheap light-emitting diode solution tender purchases.

Despite casual failures, light emitting diodes, including organic, together with computer control have significantly expanded the opportunities for new creative solutions: architecture apparently becomes "reasonable" thanks to media facades and interactive illumination systems, not yet en masse but already implemented singularly in different cities of the world. This trend undoubtedly is the future of light design.

Today light-emitting diodes are more often applied in facade, landscape and advertising illumination than in street illumination, where LDs with light-emitting diodes appear in yards, parks, in local streets, alternative roads and passages. But for the present, it is too soon to remove discharge lamps, because they have advantages and a future. Some manufacturers a making further advancements in this field. One can also hope that the production technology for self-luminous finishing materials based on electroluminescence or photoluminescence, including those using solar energy will also find a practical application. Building facades faced with such materials will absolutely change the city night environment and drastically reduce the required number of street LDs, which now fill and optically form city spaces.

The subject of interior light design, which is also important, wide, complex and interesting, remains outside the scope of this article.

**REFERENCES**

1. Shchepetkov N.I. Light design of a city. Mosow: Arckhitektura-C, 2006, 320 p.

2. Batova A.G. and Shchepetkov N.I. Light and tectonics of order architecture // Svetotekhnika, 2012, # 5, pp. 23–27.

3. To the point of the article of Bystryantseva N.V., Lekus E. Yu., Matveeva N.V. The school of domestic light design: strategy and tactics // Svetotekhnika, 2015, # 4, pp. 65–66 and Karpenko V.E., Lebedkova S.M., Ovcharov A.T., Sanzharov V.B., Silkina M.A., Snetkov V. Ju., Hadzhin A.G., Shchepetkov N.I. // Svetotekhnika, 2015, #5, pp. 60–68.

4. Shchepetkov N.I. Light design evolution in Baku // Svetotekhnika, 2015, #5, pp. 51–58.

5. Shchepetkov N.I. On the concept of creation of uniform light-and-colour environment of Moscow city // Svetotekhnika, 2012, #6, pp. 49–52. Discussion of the questions aroused in the article of A.G. Batov, O.R. Bokova, D.V. Burov, N.V. Bystryantseva, G.I. Garifulina, O.A. Gizinger, A.V. Efimov, Yu.S. Medvedev, M.V. Osikov, E.G. Prilukova, M.A. Silkina, A.K. Solovyov, P.A. Teryoshko and V.G. Chudinova // Svetotekhnika, 2012, #6, pp. 52–61.

6. Matovnikov G.S., Shchepetkov N.I. Illumination of new pedestrian streets of Moscow // Svetotekhnika, 2015, #2, pp. 11–17.

7. Shchepetkov N.I. Concerning the issue of another textbook of the Moskomarkhitektura on the comprehensive improvement and illumination of Moscow // Svetotekhnika. – 2016. – #3, pp. 73–75.

8. Efimov A.V., Karpenko V.E., Shchepetkov N.I. Illumination of embankments of Vladivostok and of the city as a whole // Svetotekhnika, 2016, #5, pp. 62–68.

9. Narboni R. La Lumiere et le Paysage. Creer des paysages nocturnes. Paris: Le Moniteur, 2003.

***Nikolai I. Shchepetkov,***
Professor, Dr. of Architecture, graduated from the Moscow Architect Institute in 1965. At present, he is the Head of the Chair "Architectural physics" of the Moscow Architect Institute, a winner of the State prize of the Russian Federation for architectural illumination of Moscow, and member of the "Light and Engineering" Journal Editorial Board

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# RESEARCH INTO ILLUMINATION OF BUILDINGS AND CONSTRUCTION, CONDUCTED IN ARCHITECTURAL AND CONSTRUCTION EDUCATIONAL AND SCIENTIFIC INSTITUTES: A REVIEW

Alexei K. Solovyov

*MSCU National Research University, Moscow*
*E-mail: agpz@mgsu.ru*

**ABSTRACT**

The article provides a short historical overview of scientific research in building light engineering and natural illumination of buildings, and their design throughout the 20th century. New subjects scientific research are proposed, which can be of interest to engineers, architects and light engineers designing natural and combined illumination of buildings. It is noted that light engineering for buildings is a comprehensive scientific field, which requires synthesis of knowledge from light engineering, construction and architecture, as well as other areas, including the humanities.

**Keywords**: building (construction) light engineering, inner environment, light climate, bactericidal exposure, sunlight, diffuse natural light, light field, cylinder illuminance, illumination dynamics, light openings, glass facades, glazing, heat losses, heat input, light guides, illumination automatic control, energy saving

## 1. A short history of the development of light engineering for buildings from the second half of the 20th century until the present day

In recent years, the interest for design of natural and combined illumination of buildings has grown. Many different companies manufacturing modern glazing have held international conferences dedicated to natural illumination systems of buildings. These conferences involve a considerable number of architects and light engineers. In spite of the fact that International commission on illumination (CIE) focuses primarily on artificial illumination and its corresponding scientific and technical directions, it has a designated joint technical committee (*JTC*) "Visual, Health, and Environmental Benefits of Windows in Buildings during Daylight Hours". This technical committee will include members of Division 3 "Interior environment and lighting design" and of Division 6 "Photobiology and photochemistry" [1]. In the meantime, research exploring illumination health impacts and physiology, as well as the influence of light on human health (for example [2]), are also largely dedicated to artificial illumination or to illumination irrespective of its source. Even as far back as the middle of the 19th century the health benefits of exposure to natural light were already observed by scientists. At first this was attributed to bactericidal influence of sunlight. Later benefits of diffuse natural light also became obvious.

The invention of fluorescent lamps made it possible to raise building illumination levels considerably and tempted the construction of windowless buildings without skylights. In the USA, before the Second World War, even schools were built without windows and skylights, completely abandoning natural light. This trend was particularly apparent in the construction of industrial buildings. However, soon a decrease in labour productivity and increased fatigue of occupants of such buildings forced scientists to search for the causes of these negative outcomes. After a short time, the reasons were found: it was illumination monotony, unavailability of the dynamics inherent in natural light, the lack of a connection with the external environment and a lost sense of time. Manufacturers quickly caught on to the idea. As part of this new trend, in the second half of the 20$^{th}$ century, I was involved in a project to install skylights in the windowless workshops of the Cherepovets steel-rolling factory and at Kherson textile works. Installing light openings into the roofs of single-story workshops at these plants eliminated the illumination monotony.

When describing a connection with external environment, many European scientists considered that only lateral light openings, i.e. windows [3] can provide such a connection. But when the people working in Cherepovets and Kherson were surveyed, after the roof-lights were installed, their responses showed that upper natural illumination systems can also provide a connection with external, because they give an occupant a sense of time and an idea about the weather outside. There is no claustrophobia in big rooms, because inner information is sufficient there. But when it comes to small rooms, in windowless buildings, this factor also adds negative sensations. Besides until now, light spectral composition and its dynamic are not investigated with natural illumination in comparison with the line spectrum in case of fluorescent lamp illumination. There is also a lack of research into the influence of light emitting diode illumination on people.

Fig. 1 shows the Moscow-city ensemble of high-rise buildings. The facades of all these buildings are made of glass. This trend is widespread both in modern architecture in Russia, and abroad. The huge glass covered areas make it possible to use natural light to the greatest extent. But buildings lose more heat through windows in winter than through blind walls. In summer, solar radiation penetrates windows and overheats rooms. This leads to a considerable heat consumption to compensate heat losses in winter and a considerable energy consumption to cool air in summer. However, maximising glass surfaces allows to drastically reduce the need for artificial light in rooms in the daytime, which saves energy.

Energy consumption can be lowered due to design of energy efficient translucent structures, use of sun protection and new energy efficient systems of artificial illumination, for example light emitting diodes, or additional artificial illumination automatic control.

In the USSR, numerous scientists studied natural illumination including those working in the Scientific Research Institute of the Construction physics of Gosstroy of the USSR, now the SRIBPh of the Russian Academy of Architecture and Construction Sciences. In the 1950s, this science school was headed by scientists N.M. Gusev and N.N. Kireev. Professor N.V. Obolensky and team of the Geophysical observatory of the Moscow State University N.P Nikolskaya and T.V. Evnevich played a big part in the development of light engineering for buildings. This period can be considered as the golden age of construction light engineering in the USSR. At that time, numerous post-graduate students of the SRIBPh defended PhDs and began to work in various institutions of higher education in the USSR. In some institutions, schools on light engineering for buildings were formed. For example, at the Tashkent Architectural-Construction Institute, where such school was headed by professor H.N. Nuretdinov; the Makeevsky Construction Institute, now the Donbass Academy of Construction and Architecture (V.A. Egorchenkov); the Magnitogorsk Mining and Smelting Institute, now Magnitogorsk State Technical University (professor V.S. Fedosikhin and S.I. Chikota), the Krasnodar Polytechnical Institute, now the Kuban Technological University (prof. V.T. Ivanchenko), the Tadjik Polytechnical Institute, now University (U.N. Radzhabov and K.H. Hamidov). The department at the Nizhny Novgorod Architectural and construction University headed by D.V. Baharev should be specially noted, where professor L.N. Orlova and other spe-

Fig. 1. A picture of the Moscow-city ensemble

cialists defended their doctorates, as well as the scientific school of the Moscow Construction Institute, now the MSCU National Research University, where under the direction of professor A.N. Kondratenkov, professor A.K. Solovyov and S.V. Stetsky, Ph.D. theses were defended by the heads of the scientific schools listed above, as well as specialists now working in Vietnam, Mongolia, China, Syria, Iraq, Afghanistan, etc.

Unfortunately, during the last 25 years, the growth and development of scientific schools has slowed down. Growth has persisted at the MICI–MSCU, in the Nizhny Novgorod SACU and in the Magnitogorsk STU, where scientific research continues and Ph.D. theses continue to be defended. In recent years, positive trends can again be observed in the development of construction light engineering in the Scientific Research Institute of Construction Physics (SRICPh of the RAACS), where interesting research is being conducted under the direction of I.A. Shmarov and of A.V. Zemtsov, new Ph.D. theses are being defended.

## 2. Current scientific directions pursued by construction light engineering

The main focus of construction light engineering research has always been, and remains, the perfection of natural illumination calculation methods in buildings. Modern computerised application methods allow simulating room natural illumination under various cloud cover conditions and visualising natural illumination within a room. In this field, various computer programs have been developed, some of which imitate natural illumination conditions with a high accuracy [4, 5]. Therefore, there is no problem to simulate a firmament with any cloud cover for research purposes. And hence, there is no need to create expensive installations, such as an artificial firmament. One can experimentally check the research results indoors, or by using a room model under natural firmament after a preliminary calculation of indoor relative illuminance values by means of a computer to simulate similar cloud cover, time of day and season. However, architects and construction engineers need to be able to quickly check natural illumination conditions in rooms during the building design phase, and swiftly change size, configuration and location of light openings. For this purpose, it is desirable to have exact engineering calculation methods for natural illumination inside rooms, which do not require labour intensive input of initial data and can be used efficiently when designing.

A perfection of engineering calculation methods from the elementary (replacing A.M. Danilyuk's graphs with geometrical daylight factor calculation formulas), to an exact formula for calculation of daylight factor from firmament direct light with conchoidal luminance distribution was performed in the MSCI–$5SCU National Research University. The value determined according to A.M. Danilyuk's graph #1, is calculated using the following formula:

$$n_1 = \frac{\cos\alpha_1 - \cos\alpha_2}{2} \cdot 100. \tag{1}$$

The value determined by A.M. Danilyuk's graph #2, is calculated using the following formula:

$$n_2 = \frac{1}{\pi}\left( \begin{array}{l} \dfrac{\bar{\beta}_2 - \bar{\beta}_1}{180°}\pi + \sin\bar{\beta}_2 \cdot \cos\bar{\beta}_2 - \\ -\sin\bar{\beta}_1 \cdot \cos\bar{\beta}_1 \end{array} \right). \tag{2}$$

All the angles can be expressed using the geometrical parameters of the room (Fig. 2).

These are approximate formulas, because they are obtained as a result of separate integrations of A.M. Danilyuk's double integral [6]. A more exact formula is also obtained in the MSCU by means of exact solution of the luminous flux double integral. Out-of-date optical transmission values for light openings are given in the modern Building regulations. In recent years, new light-transmitting materials (E.V. Korkina) and the impact of new window casements, as well as of vertical and horizontal imposts have been investigated at the SRICPh. In Nizhny Novgorod, I.A. Zimnovich also performs such research, following on from D.V. Bakharev.

A perfection of accounting for light reflected from the inner surfaces of a room and from the adjoining ground, balcony, loggia, gallery, etc. surfaces is necessary. This question was developed long ago to be used for the artificial firmament dome experiment. And this had led to considerable inaccuracies and errors. The method

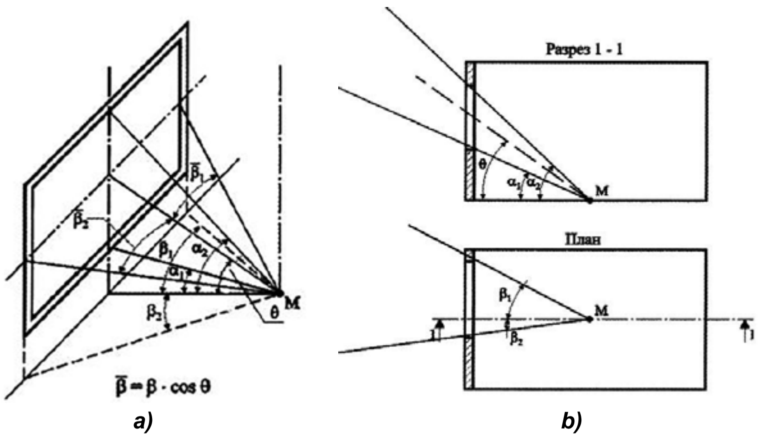


Fig. 2. A diagram of daylight factor component calculation in case of firmament direct light

needs correcting. This problem is addressed by I.A. Zimnovich but at present the work is not finished, leaving a substantial research gap for young researchers to address. For this purpose, advanced computer programs are used, for example *Radiance.* An engineering method similar to that used for the Building Regulations should be the result. The method of accounting light reflected from nearby buildings, including flipping façade reflection, also needs correction. Engineering methods of solving construction light engineering tasks allow the designers to change architectural and structural solutions of buildings, in which construction light engineering tasks are a small part of the questions to be solved. Therefore, they should be simple and effective and restricted in scope and initial input data, most of which represent building geometrical parameters changing in the design process.

Complex problems, such as the calculation of the daylight factor in atriums and in the adjoining rooms needs to be solved separately.

Perfecting the calculation methods also required verification of the main assumptions, which are made when calculating natural illumination characteristics. In 2016, the collaboration between the SRICPh and MSCU NRU on the development of a state standard for non-uniform sky luminance calculations under various cloud conditions was completed [7]. Considering non-uniform sky luminance has two purposes: firstly, to provide comparative calculations of natural illumination in rooms (for example, to compare with the standards). This task requires the development of a standard luminance distribution along the firmament irrespective of the orientation of the light opening, taking into account the typical local light climate.

And it also can be an overcast firmament with ten-point cloud amount, when its luminance changes by a meridian only and does not change by an altitude (conchoidal firmament).

The second task is the determination of energy efficiency of building natural illumination systems, which includes not only calculating the electric energy consumption for artificial illumination but also the energy consumption required to compensate heat losses and eliminate overheating. In view of this, luminance distribution conditions over the sky should be determined under various cloud cover conditions. The standard contains a method for this; however, luminance distribution models should be developed for specific Russian regions. This effort can lead in the future to an important goal of light engineer scientists: a lighting zoning of the Russian territory.

Challenges of natural illumination of buildings cannot be solved without addressing insolation and sun protection problems. Insolation rationing at present is performed in hours. The rationing shows, how long direct solar rays should penetrate to an apartment during different months of a year. And in one – two- and three-room apartments it is enough, that the sun penetrates onto a window sill in one of the living rooms for two hours from the 22nd March to the 22nd September (if the sun is not covered with clouds). These are standard data for Moscow. For other cities, the data can be others. Within central sections of big cities with a high building density, the standard required insolation reduces to 1.5 hours. The insolation standards were developed by the Ministry of Health and Social Development of the Russian Federation. These are Sanitary Regulations and Standards 2.2.1/2.1.1. 1076.03 "Health requirements for insolation and sun protection of inhabited and public buildings". Health specialists explain insolation time rationing by the fact that after two hours under ultra-violet rays, tuberculosis bacteria (bacillus Kochii) in a Petri dish perish. They do not take into consideration the fact that the sunlight spot can be on a window sill of only one room of the apartment and that ultra-violet radiation dramatically decreases when passing through glass. In the West, insolation rationing is based only on psychological reasons. And their standards are not much less tight than in Russia. In the seventies, insolation energy rationing was studied by prof. V.A. Belinsky and other scientists [8]. Today, this research continues at the Kazan architectural-building university. F.R. Halikova under the direction of professor V.N. Kupriyanov continues research into insolation energy rationing.

In Russia, meanwhile not enough attention is given to the needs of an occupant of a room from their light environment under natural illumination conditions. Health specialists, who also experienced a research peak in the second half of the 20th century, investigated and normalised illuminance for various visual work with reference to artificial illumination. Rationing of natural illumination in accordance with the daylight factor is made on the basis of annual equality of natural and artificial illumination quantity indoors. This system was proposed by professor N.N. Kireev instead of the rationing system based on annual equality of effective natural illumination quantity proposed by T.A. Glagoleva. It was based on the Weber–Fechner law and existed to the middle of the 20th century. All experiments were carried out for plain objects on a horizontal surface. Mainly they were written objects and Landolt rings, with no regard to luminance of the obscuring veil.

For distinction of three-dimensional objects in space and for characterization of the general room light conditions, horizontal plane rationing is not suitable. In this case, one should abandon the rationing according to the daylight factor on a horizontal plane and transfer to light field spatial characteristics.

The light field has also been studied for a long time. The founder of this research avenue was A.A. Gershun. Before him, V. Arndt, L. Veber and others considered this idea. Application of the light field theory began in the 1970s by Professor H.N. Nuretdinov in Tashkent and Professor A.K. Solovyov in Moscow in the MSCI NRU. At the MSCU a special scientific school was formed, where six Ph.D. theses were defended on this topic. Eight more Ph.D. theses on natural

Fig. 3. An example of various illumination of a person face

illumination and adjacent subjects were defended in the MSCU.

As a result of the performed research, the required values of light field spatial characteristics were obtained for industries like machine building, metal goods manufacture, textiles, electric lamp production, etc. Engineering methods of light field spatial characteristics calculation were investigated and proposed. However, it is expected to do much in this field. It is also expected to do much in the natural illumination design technique development in buildings using light field spatial characteristics. Such relative characteristics as illuminance daylight cylindrical factor (DCF), daylight spherical factor (DSF) and daylight hemispherical factor (DHSF), as well as relations of light field spatial characteristics to simultaneous horizontal external illuminance were proposed. This makes it possible to use the Building regulations data on building climatology.

A technique of natural illumination design [9] was proposed at a first approximation, but a harmonious and simple design technique has not yet been developed.

A system of natural illumination design by the criterion of a room natural light saturation is being developed in the MSCU by post-graduate student N.A. Muravyova [10]. Such a system is necessary for entrance halls, showrooms, inhabited and administrative rooms and educational audiences. For sales spaces, such research is carried out in the Magnitogorsk State Technical University (S.I. Chikota and A.S. Onshina). Such research should be performed separately for each room type.

In art galleries, light field spatial characteristics should provide a correct simulation of the sculptural objects using a correct combination of the spherical illuminance and light vector. This is clearly seen in the examples of various illumina-

Fig. 4. *RadioLux 111* device


Fig. 5. A tripod for illuminance measurement in museums

tions of a person's face (Fig. 3). There are unique sets of the devices certificated in Germany in the MSCU NRU Construction physics laboratory, which are capable of measuring average spherical, hemispherical, cylindrical and hemicylindrical illuminance (Fig. 4), as well as special tripods and retaining devices to measure light vector and its inclination angles, including in picture plane (Fig. 5).

A separate research area is the development of light field theory for design of natural illumination in rooms. Its founder was the professor of the Nizhny Novgorod State Architectural-Building University D.V. Bakharev. Bakharev named it the "Optical theory of light field". A distinctive feature of this theory is the optical projection of the external environment onto inner surfaces of rooms, on which these projections represent diffused images with reduced luminance. At a point in the inner space, light opening direct light and light reflected by external and inner surfaces, create a non-uniform luminance infinitely small body, which in a simplified form for certain objects can be used to determine average hemispherical, average cylindrical and average hemicylindrical illuminance. However, this theory was not developed to a specific application, because its author died. Perspectives for scientific research in this field still exist.

It should be noticed that in the mid-1970s, due to works of Professor J.B. Aizenberg and G.B. Bukhman, a foundation was laid for a new direction of lighting science and engineering: transportation and space redistribution of artificial light source luminous fluxes and/or direct sunlight and firmament diffuse radiation using hollow long length light guides [11]. This idea is patented in the USSR and in many other countries of the world (for example, the USA patent #3.902.056 of 26.08.1974).

The authors together with V.M. Pyatigorsky and A.A. Korobko developed and implemented in project of natural and artificial illumination of a central hallway of multi story school building using hollow light guides in Sent-Gallen, Switzerland. This project obtained a gold medal at the world ecological exhibition in Bern (more detailed it is stated in J.B. Aizenberg's book "*Hollow Light Guides*": Moscow, Znak, 2009).

As a result of this project, the following requirements for such integrated illumination systems were stipulated:

- It is necessary to use simple sealed heliostats;
- The systems should integrate natural and artificial light;
- The number of the units, in which light optical transformation is carried out, should be as low as possible;
- The heating caused by sunlight and electric lamps should be excluded;
- The gap, through which light penetrates into a room, should be of a minimum size.

Unfortunately, not many structural solutions using hollow light guides were implemented in Russia. From the early 2000s such solutions began to be applied in the US and Western Europe for natural illumination of rooms in which the appropriate type of light opening is not required or impossible. Light guides provide dynamics and spectral composition typical for natural lighting, they provide a connection with the external environment – reflecting the time of day and weather conditions, as well as delivering cost savings for electric illumination. A daylight factor calculation method for rooms with light guides has been developed at the MSCU NRU [12]. An energy consumption estimate technique for illumination of rooms with natural light systems was developed in the SRICPh and further improved at the MSCU NRU.

A comparison between natural illumination system energy efficiency, for example skylights, and light guides shows the efficiency of light guides, mainly due to the considerable reduction of heat losses and heat input from room or into it accordingly [13].

The best known example of the light guide application in Russia is in the rooms of the Customs maritime terminal in St.-Petersburg [14]. At present in Izhevsk, a factory is operating to manufacture hollow tubular light guides (Solargy Open Company), which by quality standards match those light guides produced in Italy by Solar spot and in the US by Solar tube, which are available on the Russian Federation market. With the growth of manufacture, the mass introduction of light guides is beginning in cities of Ural and Siberia. An addition of the provisions on their application to the revised version of the natural and artificial illumination building regulations will undoubtedly promote the further introduction of light guides. This revised version is developed in the SRICPh together with the MSCU NRU. It should be noted that previously the provisions on light guides application for building illumination were included into SanPiN2.2.4.3359–16 «Sanitary-and-epidemiologic requirements to physical factors on workplaces".

The use of light guides is especially effective in combination with additional artificial illumination controlled automatically. This was demonstrated using the calculations of illumination energy consumption in small rooms without sufficient light openings [10]. Calculations of natural illumination with light guides in large rooms have already started but have not been finished. These calculations are subject of further research, especially in conjunction with determining their energy efficiency under conditions of automatically controlled additional artificial illumination.

In general, research of automatically controlled combined illumination are important in the construction light engineering field as they are directly connected with energy saving. This direction began to be developed in the MS CU in the late 1960s (Professor A.N. Kondratenkov). Afterwards, Professor A.K. Solovyov and his post-graduate students worked in this field. At present, in spite of the fact that modern artificial illumination light emitting diode systems provide approximately six-fold energy saving in comparison with incandescent lamps, this subject remains important, especially for big rooms. Furthermore, this solution is a key for light environment comfort. Therefore, builders should liaise with the automatic control system developers, to determine which systems are most effective for different rooms. They also should prompt, where discrete adjustment is more suitable and where continuous adjustment is preferable, as well as where photodetectors must be placed. The main thing is that they should compute in advance the economic and energy effect of such system application depending on the type, size and configuration of natural illumination systems. These studies are connected with determination of light opening energy efficiency, which can serve as a criterion for rationing natural illumination along with artificial and natural illuminations balance. And the energy approach allows selecting normalised daylight factor values with due regard for various subcategories of visual works, which for now is absent from the standards.

### 3. Design focused on the local light climate

This article does not consider works and directions of the construction light engineering field, which are probably developed in other scientific institutions and laboratories of Russia, because publications about them are either absent, or not unknown to the author. So, for example, light engineers who have defended Ph.D. theses in the SRICPh, now work in Samara and Nalchik, graduates of the MSCI–MGSU postgraduate school, work in Mongolia, Vietnam, Iraq and Palestine. In works of these post-graduate students, and now of PhDs works, a specific character of the natural illumination system design in various climate regions of the world is reflected. Climate and light-climate design is an important direction of construction light engineering research. Different regions have many features, which should be taken into consideration when designing natural illumination systems. These features are for example, statistically average luminance distribution over the firmament, the nature of prevailing cloud cover, underlying surface albedo, local wind, thermal, humidity and radiation climate, as well as even psychological features and mentality of the local inhabitants. The main feature of lighting design in construction is an integrated approach. From this point of view, it is similar to the architectural-and-construction design. Therefore, most scientific subjects in construction light engineering are at the junction of such scientific directions designated by the higher certifying commission, as "Heat supply, ventilation, air condition, gas supply and illumination" as well as "Building structures, buildings and constructions". There are provisions concerning both construction, and light engineering in the definitions of both of these scientific specialties. This is a natural development, as modern science should be at the interface of different specialties. And there is a wide and varied field of operation, with many research gaps, for young scientists of architecture and construction high education institutions.

## REFERENCES

1. Knoop, M. Visual, health and environmental benefits of windows// New eyes on existing buildings// 5th VELUX Daulight Symposium. 15–16 May 2013. The Royal Danish Academy of Fine Arts, School of Architecture, Copenhagen.

2. Van den Böld G. Light and health // Svetotekhnika. 2003, # 1, pp. 4–8.

3. Ne'eman, E., Hopkinson, R.G. Critical minimum acceptable window size; a study of window design and provision of a view // Lighting Research and Technology.1970, No. 2, pp. 17–29.

4. Bakharev D.V. Computer calculation of natural illumination / Reference book on light engineering / Editorship of Yu.B. Aizenberg (60 authors). The third revised edition, Moscow: Znak, 2006, Section 18.12, pp. 863–872.

5. Budak V. P, Makarov D.N., Smirnov P.A. Computer programs for lighting calculations of lighting installations // Svetotekhnika. 2004, # 6, pp. 75–79.

6. Obyedkov V.A., Solovyov A.K., et al. Laboratory manual on construction physics / Moscow: Vysshaya Shkola, 1979.

7. Zemtsov V.A., Solovyov A.K., Shmarov I.A. Firmament luminance account ... / Svetotekhnika. 2016, #6, pp.55–61.

8. Belinsky V.A., Semenchenko B.A. A radiation atmosphere model in the ultra-violet spectrum interval/ SRICPh collection. Natural illumination and insolation of buildings. Moscow: Publishing house on the construction literature. 1968.

9. Egorchenkov V.A., Solovyov A.K. Design of natural illumination systems of industrial buildings using spatial characteristics of light environment // Promyshlennoe Stroitelstvo. 1983, #7, pp. 17–19.

10. Muravyova N.A., Solovyov A.K. Researches of cylindrical illuminance distribution nature in rooms with lateral natural illumination // Svetotekhnika. 2015, #6, pp.27–30.

11. Aizenberg Yu.B., Bukhman G.B., Korobko A.A., Pyatigorsky V.M. Some non-implemented optical designs and lighting systems with hollow light guides // Svetotekhnika. 2016, #3, pp. 4–11.

12. Solovyov A.K. Physics of environment. Moscow: ASV Publishing house, 2015.

13. Solovyov A.K., Tusnina O.A. A comparative heat engineering calculation of upper natural illumination systems (Zenith roof-lights and hollow tubular light guides) // Engineering and Construction journal. 2014. #2. pp. 24–35.

14. Kyznetsov A.L., Oseledets E. Yu., Solovyov A.K., Stolyarov M, V. An experience of hollow tubular light guide application for natural illumination in Russia // Svetotekhnika. 2011, #6, pp. 4–11.

***Alexei K. Solovyov,***
Prof., Doctor of Technical Science, graduated from the MISI of V.V. Kuibyshev. At present, he is the Head of the Chair "Architecture of civil and industrial buildings" of the Moscow State Building University, National Research University. A member of the European Academy of Sciences and Arts, a member of editorial board of "Light and Engineering" journal

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# RESEARCH INTO LIGHT SOURCES PRODUCT RANGE, ASSESSMENT OF POWER CONSUMPTION AND ELECTRIC POWER SAVING POTENTIAL IN THE ILLUMINATION SYSTEMS OF RUSSIA

Gennady Ya. Vagin, Oleg Yu. Malafeev, Mikhail V. Martynyuk

*The Nizhegorodsky State Technical University, Nizhniy Novgorod, Russia;*
*E-mail: omail1@mail.ru*

## ABSTRACT

A technique for determining the installed range of light source products throughout Russia, and within all economics sectors is developed. The analysis allows assessing the technological level of the lighting devices used and arranging a constant monitoring of illumination power consumption and energy efficiency in various sectors of the Russian economy.

**Keywords:** scope of the light source market, product range of light sources over economics sectors, power consumption characteristics, electric energy saving potential

## INTRODUCTION

According to [1], up to 14 % of the total amount of electric energy consumed Russia is used for illumination needs of the country. In regulation documents [2,3] and in work [4], measures for introducing energy efficient light sources and luminaires are planned. However, the absence of constant monitoring of illumination power consumption does not allow quick and efficient tracing of how these measures are performing, and responding to a rapidly changing light source market.

The purposes of that research are as follows:

1. To obtain information: how many and what light source types are installed within the territory of the Russian Federation as a whole and within specific consumption sectors;
2. To calculate approximately illumination power consumption both for the whole of the Russian Federation and of the consumption sectors;
3. To calculate approximately illumination current consumption and greenhouse gas emission decrease as a result of switching to energy saving light sources;
4. To form information on the lamp market to assess observance of the Federal Law #261-ФЗ [2].

The work was performed according to project UNPr/GEF/ Ministry of Energy of the Russian Federation "Transformation of the market to promote energy efficient illumination" with participation of specialists of the NSTU and Lighting Business Consulting Open Company.

As the basis for calculation, the following data were used: monitoring data of the illumination system of Russia performed in 2013 – 2014; the Federal State Statistics Service and regional power companies' data; Lighting Business Consulting Open Company reports on the lamp market monitoring in Russia in 2011–2014[1]; interrogatory paper data and administration questionnaire results of more than 70 cities in various regions of the Russian Federations.

[1] Lamp market in Russia in 2011 – 2013. Report on the Lighting Business Consulting Open Company researches.

**Table 1. Average lifetime of lamps depending on the manufacture technology, $T_k$, h [5]**

| IL | HIL | FL | CFL | MAL | HSAL | MHL | LED |
|---|---|---|---|---|---|---|---|
| 1000 | 2000 | 10 000 | 6000 | 10 000 | 12 000 | 10 000 | 20 000 |

**Table 2. Average annual illumination duration for various consumption sectors, $t_q$, h/year [6]**

| Housing | Public | Industrial | Street illumination |
|---|---|---|---|
| 1200 | 3600 | 3950 | 3600 |

The research subjects were all steadily installed light sources in four main economic sectors: industrial, public, housing and external illumination.

**Approach description**

A flow chart of determining light source (LS) market scope over economics sectors is given in Fig. 1.

The market of the all LSs can be divided into $K$ categories ($k = 1 \div K$) by lamp type. At present, there are eight types of lamps: ILs, HILs, CFLs, LEDs, FLs, HSALs, MHLs and MALs. The luminous efficacy of lamp separate type $\eta_k$ is considered identical not dependent on the lamp power.

The total illuminated area can be divided into $Q$ sectors with $S_q$ area of each ($q = 1 \div Q$). In this work, these are four economics sectors.

LS number required to illuminate the $q^{\text{th}}$ economics sector, is calculated according to the expression:

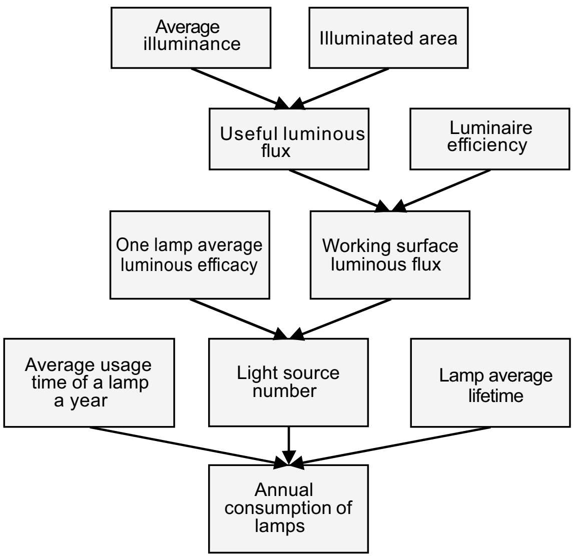


Fig.1 Flow chart of determining LS market scope

$$N_q = \frac{E_q \cdot S_q}{\eta_q}\left(\sum_{k=1}^{K}\omega_{q,k}\cdot\eta_k\cdot P_k\right)^{-1}, \quad (1)$$

where $E_q$ is average illuminance of the $q$th sector, lx; $S_q$ is area of the $q^{\text{th}}$ sector, m$^2$; $\eta_q$ is average efficiency of lighting devices in the $q^{\text{th}}$ sector; $\omega_{q,k}$ is basic ratio between light source number of the $k^{\text{th}}$ type and LS total number in the $q^{\text{th}}$ consumption sector; $\eta_k$ is average luminous efficacy of the $k^{\text{th}}$ category lamps, lm/W; $P_k$ is average LS power for the $k^{\text{th}}$ category, W.

Total LS number over all economics sectors is determined according to the expression:

$$N_\Sigma = \sum_{q=1}^{Q} N_q = \sum_{q=1}^{Q}\left[\frac{E_q \cdot S_q}{\eta_q}\left(\sum_{k=1}^{K}\omega_{q,k}\cdot\eta_k\cdot P_k\right)^{-1}\right]. \quad (2)$$

LS market scope can be determined according to the expression:

$$V = \sum_{q=1}^{Q}\sum_{k=1}^{K}\left(\omega_{q,k}\cdot N_q \cdot \frac{t_q}{T_k}\right), \quad (3)$$

where $T_k$ is lamp lifetime (time between failures) for each type lamps (Table 1); $t_q$ is lamp usage average time for each economics sector within a year (Table 2).

After introducing a concept of the $k^{\text{th}}$ type lamp replacement intensity in the $q^{\text{th}}$ sector we obtain:

$$C_{q,k} = \frac{t_q}{T_k}\left(1 + d_k\right), \quad (4)$$

**Table 3. Lamp premature failure coefficient $d_k$%**

| IL | HIL | FL | CFL | MAL | HSAL | MHL | LED |
|---|---|---|---|---|---|---|---|
| 30 | 5 | 5 | 7,5 | 5 | 2,5 | 2,5 | 15* |

* Such a high premature failure coefficient is caused by the presence on the Russian market of poor quality light emitting diodes.

**Table 4. Average annual specific consumption of lamps in terms of one light point, $C_{q,\,k}$, lamp/year**

| Sector | IL | HIL | FL | CFL | MAL | HSAL | MHL | LED |
|---|---|---|---|---|---|---|---|---|
| Housing | 1.56 | 0.63 | 0.13 | 0.23 | 0.13 | 0.10 | 0.12 | 0.07 |
| Public | 4.68 | 1.89 | 0.38 | 0.69 | 0.38 | 0.31 | 0.37 | 0.21 |
| Industrial | 5.14 | 2.07 | 0.41 | 0.76 | 0.41 | 0.34 | 0.40 | 0.23 |
| Street illumination | 4.68 | 1.89 | 0.38 | 0.69 | 0.38 | 0.31 | 0.37 | 0,21 |

**Table 5. Structural distribution of LSs over consumption sectors in 2013, $\omega_{q,k}$ %**

| Sector | IL | HIL | FL | CFL | MAL | HSAL | MHL | LED |
|---|---|---|---|---|---|---|---|---|
| Housing | 51.5 | 9.4 | < 0.1 | 35.4 | < 0.1 | < 0.1 | < 0.1 | 3.3 |
| Public | < 0.1 | 1 | 73.5 | 14 | < 0.1 | < 0.1 | < 0.1 | 11.1 |
| Industrial | 25.7 | 0.1 | 32.7 | 11 | 22.7 | 3.7 | 4 | < 0.1 |
| Street illumination | < 0.1 | < 0.1 | < 0.1 | < 0.1 | 40.2 | 48.3 | 6.2 | 4.9 |

where $d_k$ is the coefficient of premature failure of each lamp type (it is used based on expert assessments, Table 3), and then expression (3) becomes as follows:

$$V = \sum_{q=1}^{Q} N_q \sum_{k=1}^{K} \left( C_{q,k} \cdot \omega_{q,k} \right). \tag{5}$$

$C_{q,k}$ values, determined in accordance with (4), are given in Table 4.

In Table 5, LS structural distribution over economics sectors is given in percentage obtained on the basis of energy inspections of these sectors.

LS market scope of each type can be determined by its expression as the following equation in a matrix form:

$$V_{1xK} = \boldsymbol{N}_{1xQ} \cdot CW_{QxK}, \tag{6}$$

where $N_{1xQ}$ is matrix of LS number in each economics sector; $CW_{QxK}$ is matrix of reducing total LS number in the $q^{\text{th}}$ sector to the $k^{th}$ type LS number consumed in the $q^{\text{th}}$ sector.

Expression (6) represents a system of linear equations. As $Q < K$ (4 < 8), the equation system is over determined and cannot have a rigorous solution. For such equation systems, least square method (LSM) can be applied, which allows finding vector $N_{1xQ}$ providing a root-mean-square deviation between ($\boldsymbol{N}_{1xQ} \cdot CW_{QxK}$) and $V_{1xK}$ according to the expression:

$$N_{1xQ} = V_{1xK} \cdot \left( CW_{QxK} \right)^T \cdot \\ \cdot \left[ CW_{QxK} \cdot \left( CW_{QxK} \right)^T \right]^{-1}, \tag{7}$$

where $T$ is transposing sign.

As $V_{1xK}$, the lamp market scope data in Russia in 2013 are used (Table 6) [7].

### Results of assessing light point number in the consumption sectors

LS distribution assessment $\boldsymbol{N}_{1xQ}$ over the economics sectors according to expression (7) and market scope by lamp types $V_{1xK}$ calculated according to expression (6) can have big errors, because $w_{q,k}$ values (Table 5) are given as percentages.

**Table 6. Lamp market scope in Russia in 2013, $V_k$, mln. pieces. [7]**

| IL | HIL | FL | CFL | MAL | HSAL | MHL | LED |
|---|---|---|---|---|---|---|---|
| 436.4 | 53 | 121.7 | 124.5 | 8.7 | 2.4 | 1.5 | 53.9 |

**Table 7. LS distribution assessment over the consumption sectors in 2013, $N_q$, million pieces.**

| Housing | Public | Industrial | Street illumination |
|---|---|---|---|
| 547.4 | 458.6 | 66.6 | 9.5 |

Therefore, one should select vector $N_{QxK}$ in such a way that it would provide a minimum relative error, instead of absolute. For this purpose, expression (7) should be changed as follows:

$$N_{1xQ} = 1_{1xK} \cdot \left(CWV_{QxK}\right)^T \cdot \left[CWV_{QxK} \cdot \left(CWV_{QxK}\right)^T\right]^{-1}, \quad (8)$$

where $1_{1xK}$ is a unity matrix; $CWV_{QxK}$ is a matrix obtained from matrices $CW_{QxK}$ according to the expression:

$$CWV_{i,j} = \frac{CW_{i,j}}{V_j}, \forall i = 1 \div Q, j = 1 \div K. \quad (9)$$

LS number distribution over the economics sectors obtained on the basis of formula (8) is given in Table 7.

## ILLUMINATION POWER CONSUMPTION ASSESSMENT IN 2013

In Table 8, average LS power obtained according to the power audits and expert assessments data are given.

Using data from Tables 5, 7 and 8, power consumption characteristics were determined over the economics sectors and LS types (Tables 9 and 10) according to the following expressions:

$$N_{q,k} = N_q \cdot w_{q,k}, \quad (10)$$

$$P_{q,k} = N_{q,k} \cdot p_{q,k}, \quad (11)$$

$$W_{q,k} = P_{q,k} \cdot t_q. \quad (12)$$

Thus, electric energy consumption for the purposes of illumination in the Russian Federation territory in 2013 was assessed to be 109 TW·h, which amounted to about 12 % of the general power consumption. The main consumption sources were FLs (29 %), MALs (28 %) and ILs (22 %). Using the data given in Tables 2 and 8, average annual specific power consumption (kW·h) of one LS (Table 11) was calculated.

### Verification of the results

To assess the accuracy of the results in Table 9 by the light point number $N_{q,k}$ and by annual power consumption $W_{q,k}$, a calculation of these criteria based on power consumption data in economics sectors in 2013 [8] is performed. On the basis of knowing illumination electric energy consumption in each economic sector [6], as well as light source average power (Table 8) and time of their use over a year (Table 2), $N_{q,k}$ and $W_{q,k}$ values are calculated (Table 12).

The calculation for external illumination was made based on the data in the illuminated streets, driveways and embankment length in Russia. This

**Table 8. Average lamp power in 2013, $p_{q,k}$, W**

| Sector | IL | HIL | FL | CFL | MAL | HSAL | MHL | LED |
|---|---|---|---|---|---|---|---|---|
| Housing | 60 | 40 | 23 | 14 | 140 | 150 | 81 | 9 |
| Public | 53 | 40 | 23 | 14 | 142 | 149 | 96 | 20 |
| Industrial | 60 | 47 | 40 | 14 | 450 | 165 | 275 | 11 |
| Street illumination | 71 | 83 | 56 | 21 | 275 | 165 | 165 | 40 |

**Table 9. Power consumption general characteristic over the consumption sectors and illumination technologies in 2013**

| Lamp type | Light point number, $N_{q,k}$, million. pieces | Average annual number of use hours, $t_q$, h | Full installed power, $P_{q,k}$, GW | Annual power consumption, $W_{q,k}$, TW·h |
|---|---|---|---|---|
| Housing sector | | | | |
| IL | 282.3 | 1200 | 16.9 | 20.3 |
| HIL | 51.7 | 1200 | 2,1 | 2,5 |
| FL | < 0,5 | 1200 | < 0,01 | < 0,02 |
| CFL | 194,2 | 1200 | 2,7 | 3,3 |
| MAL | < 0,5 | 1200 | < 0,1 | < 0,1 |
| HSAL | < 0,5 | 1200 | < 0,1 | < 0,1 |
| MHL | < 0,5 | 1200 | < 0.04 | < 0.1 |
| LED | 17.0 | 1200 | 0.2 | 0.2 |
| In total | 547.4 | — | 22.1 | 26.5 |
| Public sector | | | | |
| IL | < 0.5 | 3600 | < 0.02 | < 0.1 |
| HIL | 4.7 | 3600 | 0.2 | 0.7 |
| FL | 334.8 | 3600 | 7.7 | 27.7 |
| CFL | 63.6 | 3600 | 0.9 | 3.2 |
| MAL | < 0.5 | 3600 | < 0.1 | < 0.2 |
| HSAL | < 0.5 | 3600 | < 0.1 | < 0.2 |
| MHL | < 0.5 | 3600 | < 0.04 | < 0.2 |
| LED | 53.7 | 3600 | 1.1 | 3.9 |
| In total | 458.6 | — | 10.1 | 36.2 |
| Industrial sector | | | | |
| IL | 17.1 | 3950 | 1.0 | 4.1 |
| HIL | 0.1 | 3950 | < 0.01 | < 0.01 |
| FL | 21.8 | 3950 | 0.9 | 3.4 |
| CFL | 7.3 | 3950 | 0.1 | 0.4 |
| MAL | 15.1 | 3950 | 6.8 | 26.9 |
| HSAL | 2.4 | 3950 | 0.4 | 1.6 |
| MHL | 2.7 | 3950 | 0.7 | 2.9 |
| LED | < 0.01 | 3950 | < 0.01 | < 0.01 |
| In total | 66.6 | — | 9.9 | 39.3 |
| External illumination | | | | |
| IL | 0.01 | 3600 | < 0,01 | < 0.01 |
| HIL | 0.01 | 3600 | < 0.01 | < 0.01 |

| Lamp type | Light point number, $N_{q,k}$, million. pieces | Average annual number of use hours, $t_q$, h | Full installed power, $P_{q,k}$, GW | Annual power consumption, $W_{q,k}$, TW·h |
|---|---|---|---|---|
| FL | 0.01 | 3600 | < 0.01 | < 0.01 |
| CFL | 0.01 | 3600 | < 0.01 | < 0.01 |
| MAL | 3.9 | 3600 | 1.1 | 3.8 |
| HSAL | 4.6 | 3600 | 0.8 | 2.8 |
| MHL | 0.6 | 3600 | 0.1 | 0.4 |
| LED | 0.4 | 3600 | 0.0 | 0.1 |
| In total | 9.5 | — | 1.9 | 7.0 |
| In total throughout the country | 1082.2 | — | 44.0 | 109.0 |

**Table 10. Power consumption general characteristic over illumination technologies in 2013**

| Lamp type | Light point number, $N_{q,k}$, million pieces | Average annual duration $t_q$, h | Full installed power, $P_{q,k}$, GW | Annual power consumption, $W_{q,k}$, TW·h | |
|---|---|---|---|---|---|
| | | | | TW·h | % |
| IL | 300.0 | 1360 | 18.0 | 24.5 | 22 |
| HIL | 56.5 | 1404 | 2.3 | 3.2 | 3 |
| FL | 357.2 | 3617 | 8.6 | 31.2 | 29 |
| CFL | 265.2 | 1852 | 3.7 | 6.9 | 6 |
| MAL | 20.0 | 3799 | 8.0 | 31.0 | 28 |
| HSAL | 8.1 | 3543 | 1.3 | 4.7 | 4 |
| MHL | 4.2 | 3509 | 0.9 | 3.4 | 3 |
| LED | 71.04 | 3026 | 1.2 | 4.1 | 4 |
| In total over the country | 1082.2 | — | 44.0 | 109.0 | 100 |

length amounted to 335 598 km[2]. The distance between street illumination supports is taken to be 40 m. Average luminaire power is taken to be equal to 203 W. The weighted average power is based on the Tables 5 and 8 data.

The difference between Tables 9 and 12 results does not exceed 6 %. This means that the proposed model for determining light point number and annual illumination power consumption is objective and can be used by governmental and non-governmental bodies in order to plan and assess perspective abilities of illumination and of LS market development forecast.

### Forecast of illumination electric energy consumption until 2020

The research performed by the authors show that plans [2, 3] scheduled to introduce energy-effective LSs by 2020 will not be implemented.

[2] Sources of these data are as follows:
– The data of the report "Information research and accumulation to form a project database for copying the street illumination pilot project" UNPr/GEF (www.undp-light.ru/results/16/file/0/235/PROPERTY_25/74/?download=y);
– The data found in the Network (mainly sites of city municipalities and sites of Gorsvet of various cities);
– Interrogatory papers and questionnaire data results;
– The uniform interdepartmental information-and-statistical system (http://www.fedstat.ru/).

**Table 11. Average annual specific power consumption, kW·h**

| Sector | IL | HIL | FL | CFL | MAL | HSAL | MHL | LED |
|---|---|---|---|---|---|---|---|---|
| Housing | 72.0 | 48.0 | 27.6 | 16.8 | 168.0 | 180.0 | 97.2 | 10.8 |
| Public | 190.8 | 144.0 | 82.8 | 50.4 | 511.2 | 536.4 | 345.6 | 72.0 |
| Industrial | 237.0 | 185.6 | 158.0 | 55.3 | 1777.5 | 651.7 | 1086.2 | 43.4 |
| Street illumination | 255.6 | 298.8 | 201.6 | 75.6 | 990.0 | 594.0 | 594.0 | 144.0 |

**Table 12. Results of the power consumption assessment over economics sectors in 2013 used for verifications [6, 8]**

| Sectors of energy consumption | Annual energy consumption over economics sectors, TW·h [8] | Percentage consumption for illumination,%[6] | Annual consumption for illumination, TW·h | Installed power of illumination systems, GW | Light point number, million. pieces |
|---|---|---|---|---|---|
| Mining operation, machine production, electric power, gas and water production and distribution | 564.987 | 5.8 | 32.723 | 11.896 | 57.956 |
| Agricultural and forest sectors | 15.286 | 15 | 2.293 | 0.573 | 5.732 |
| Construction | 12.293 | 2 | 0.246 | 0.049 | 0.492 |
| Transport | 90.378 | 2 | 1.811 | 0.392 | 3.92 |
| Public sector | 127.148 | 25 | 31.787 | 8.830 | 401.351 |
| City and country population | 140.971 | 20 | 28.194 | 23.495 | 587.379 |
| External illumination* | — | — | 6.131 | 1.703 | 8.39 |
| In total over the country | 951.064 | — | 103.1856 | 46.9 | 1065.220 |

* The calculation is made based on the data over the illuminated streets, driveways and embankment length in Russia.

There are many reasons of this failure, but a key factor is the absence of technical regulation non-legislative acts forcing the introduction of such LSs.

In the European Union, directives and regulations are used as non-legislative acts and in Russia these are technical regulations. These documents are necessary both for manufacturers, and for consumers of lighting products. So, approval of three lighting product directives in the European Union (244/2009/EC, 245/2009/EC and 1194/2012/EC) made it possible to lower IL number 2.85 times from 2008 to 2013 and to increase light-emitting diode lamp number 72 times [7].

Removing the 100 W and higher power IL from circulation was introduced in Russia from 2011 [2] but led not to their reduction but to an increase, which is explained by insufficient production scope of domestic CFLs and LEDs, by their high cost and poor quality. From 2011, a complete prohibition on IL purchase for state and municipal needs is also in effect. Governmental order of the Russian Federation of #898 of 8/28/2015, which has taken effect from July 2016, additionally provides for a purchase ban for state and municipal needs of the following inefficient lighting products: haloid-phosphate FLs, MALs and CFLs, luminaires for these lamps and electromagnetic ballasts for FLs.

At present, a discussion is takings place of some measures on technical regulation of the lamp market in the participant countries of the

**Table 13. Dynamics of the LS market development in the Russian Federation (production and import) without technical regulation, million pieces [7]**

| Lamp type | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|---|---|
| IL | 436.4 | 420.5 | 500.0 | 510.0 | 484.5 | 460.3 | 437.3 | 415.4 |
| HIL | 53.0 | 52.3 | 37.6 | 25.0 | 17.0 | 15.3 | 13.8 | 12.4 |
| FL | 121.7 | 88.5 | 80.0 | 64.0 | 38.4 | 28.8 | 21.6 | 16.2 |
| CFL | 124.5 | 105.8 | 58.2 | 36.7 | 17.7 | 4.4 | 3.1 | 2.2 |
| MAL | 8.7 | 6.1 | 2.5 | 1.5 | 0.5 | 0.3 | 0.2 | 0.1 |
| HSAL | 2.4 | 2.2 | 1.4 | 1.0 | 0.8 | 0.6 | 0.4 | 0.2 |
| MHL | 1.5 | 1.4 | 1.0 | 0.7 | 0.5 | 0.3 | 0.2 | 0.2 |
| LED | 53.9 | 123.7 | 99.0 | 122.8 | 167.6 | 209.2 | 240.5 | 264.6 |
| In total | 802.1 | 800.4 | 779.7 | 761.7 | 727.0 | 719.2 | 717.1 | 711.2 |

**Table 14. Dynamics of the LS market development in the Russian Federation (production and import) with technical regulation, million pieces [7]**

| Lamp type | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 г. | 2020 |
|---|---|---|---|---|---|---|---|---|
| IL | 436.4 | 420.5 | 500.0 | 510.0 | 484.5 | 314.9 | 60.0 | 0.0 |
| HIL | 53.0 | 52.3 | 37.6 | 25.0 | 17.0 | 14.5 | 7.2 | 3.0 |
| FL | 121.7 | 88.5 | 80.0 | 64.0 | 38.4 | 19.2 | 9.6 | 4.8 |
| CFL | 124.5 | 105.8 | 58.2 | 36.7 | 17.7 | 50.4 | 24.1 | 11.2 |
| MAL | 8.7 | 6.1 | 2.5 | 1.5 | 0.5 | 0.3 | 0.2 | 0.1 |
| HSAL | 2.4 | 2.2 | 1.4 | 1.0 | 0.8 | 0.6 | 0.4 | 0.1 |
| MHL | 1.5 | 1.4 | 1.0 | 0.7 | 0.5 | 0.3 | 0.2 | 0.1 |
| LED | 53.9 | 123.7 | 99.0 | 122.8 | 167.6 | 309.2 | 374.6 | 421.0 |
| In total | 802.1 | 800.4 | 779.7 | 761.7 | 727.0 | 709.4 | 476.3 | 440.2 |

Eurasian Economic Union, which will provide for the following:

- Removing ILs of 75 W and higher power from circulation from 2018, IL of 60 W and higher power from 2019, and ILs of any power from 2020;
- Banning haloid-phosphate FL from 2018, and also removing MALs, HSALs and MHLs of low efficiency from circulation from 2020;
- Severe reduction of HILs.

Work [7] shows dynamics of the LS markets in the Russian Federation until 2020 (Table 13, 14) for two scenarios of market development:

1) Without the introduction of technical regulation but with due regard for the influence of Governmental order #898 (Table 13);

2) With an introduction of some measures on technical regulation in 2018 (Table 14).

Using expressions (2) – (9), Tables 13 and 14, as well as Fig. 2, an assessment of illumination power consumption dynamics in the Russian Federation until 2020 for these two scenarios of market development was performed (Tables 15, 16). When calculating, an assumption was used that in case of LS replacement, the general luminous flux of all LS remained constant for each year. The replacement was made by means of light emitting diode LSs.

According to the results given in Tables 15 and 16, the annual consumption of all light sources will decrease, with the exclusion of light emitting diodes, the power consumption of which is predicted to be highest of all light sources in 2017.

**Table 15. Assessment of illumination power consumption dynamics in the Russian Federation without technical regulation, TW·h**

| Lamp type | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|---|---|
| IL | 24.5 | 21.2 | 25.2 | 25.7 | 24.4 | 23.2 | 22 | 20.9 |
| HIL | 3.2 | 4.5 | 2.9 | 2.3 | 1.5 | 1.3 | 1.2 | 1 |
| FL | 31.2 | 22.8 | 22.7 | 18.3 | 11.7 | 9.3 | 6.3 | 4.7 |
| CFL | 6.9 | 12.9 | 7.1 | 4.5 | 2.2 | 0.5 | 0.4 | 0.3 |
| MAL | 30.9 | 26.1 | 13.4 | < 0.1 | < 0.1 | < 0.1 | < 0.1 | < 0.1 |
| HSAL | 4.7 | 3.8 | 2.9 | 2.1 | 1.9 | 1.4 | 0.9 | 0.4 |
| MHL | 3.4 | 3.6 | 2.9 | 2.1 | 1.7 | 1 | 0.6 | 0.6 |
| LED | 4.1 | 7.5 | 14.1 | 24.3 | 26.5 | 27.6 | 26.4 | 26.4 |
| In total | 109 | 102.3 | 91.1 | 79.2 | 69.8 | 64.3 | 57.8 | 54.3 |

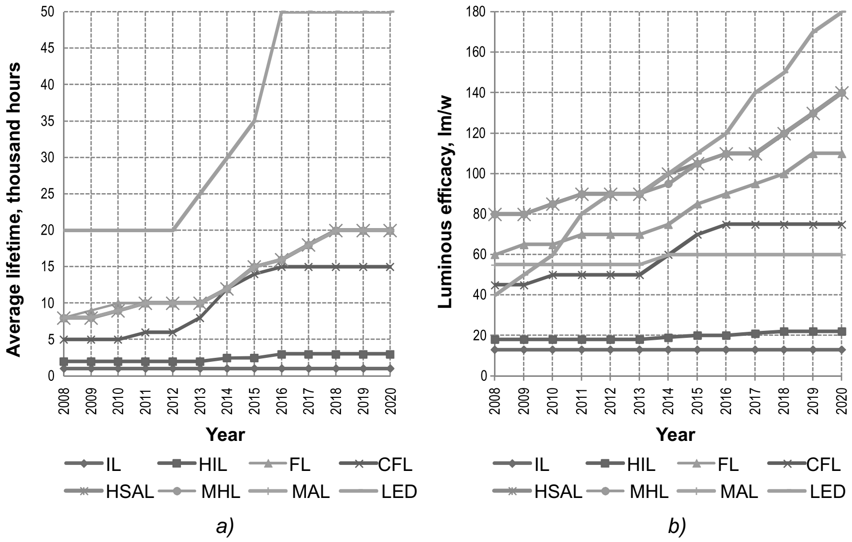


Fig. 2 Forecasting data for LS each manufacture techniques to 2020 [9]:
*a* – average lifetime; b – luminous efficacy

**Assessment of electric power saving potential of illumination**

As in Tables 15 and 16, power consumption assessments are given with considering the replacement of inefficient light sources, the data can be used for assessing potential energy savings. The energy saving potential assessment was determined according to the expression:

$$\Delta W = W_{\Sigma 2013} - W_{\Sigma 2020}, \quad (13)$$

where $W_{\Sigma 2013}$ and $W_{\Sigma 2020}$ is total illumination power consumption in 2013 and 2020 accordingly.

Without the effect of technical regulation on the lighting market, energy saving potential by 2020 will amount to approximately 54.6 TW·h, or 50 % of the illumination consumption in 2013; with the effect of technical regulation accounted for, the saving potential will amount to 75.7 TW·h, or 70 %.

**Calculation of the illumination sector's greenhouse gas associated emission scope**

Calculation of the illumination sector's greenhouse gas associated emission scope is performed according to the technique given in [10]. Emission of greenhouse gases is determined by mul-

**Table 16. Assessment of illumination power consumption dynamics in the Russian Federation with technical regulation, TW·h**

| Lamp type | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|---|---|
| IL | 24.5 | 21.2 | 25.2 | 25.7 | 24.4 | 15.8 | 3 | < 0.1 |
| HIL | 3.2 | 4.5 | 2.9 | 2.3 | 1.5 | 1.2 | 0.6 | 0.3 |
| FL | 31.2 | 22.8 | 22.7 | 18.3 | 11.7 | 6.2 | 2.8 | 1.4 |
| CFL | 6.9 | 12.9 | 7.1 | 4.5 | 2.2 | 6.1 | 2.9 | 1.4 |
| MAL | 30.9 | 26.1 | 13.4 | < 0.1 | < 0.1 | < 0.1 | < 0.1 | < 0.1 |
| HSAL | 4.7 | 3.8 | 2.9 | 2.1 | 1.9 | 1.4 | 0.9 | 0.2 |
| MHL | 3.4 | 3.6 | 2.9 | 2.1 | 1.7 | 1 | 0.6 | 0.3 |
| LED | 4.1 | 7.5 | 14.1 | 24.3 | 26.5 | 27.6 | 28.9 | 29.7 |
| In total | 109 | 102.3 | 91.1 | 79.2 | 69.8 | 59.4 | 39.8 | 33.2 |

**Table 17. Production of electric power by power stations [8,11]**

| Power plants | Electric power production, TW·h | |
|---|---|---|
| | 2013 | 2020 |
| All power plants<br>Including: | 1059 | 1344 ÷ 1561 |
| TPPs | 703 | 873 ÷ 1039 |
| HPPs | 183 | 224 ÷ 240 |
| NPPs | 173 | 247 ÷ 282 |

tiplying fuel consumption by the correspondent coefficients, which depend on the fuel type and on the source category.

Calculation of an average value of carbon dioxide ($CO_2$) annual emission coefficient $K_{ae}$ to the atmosphere across Russia is performed according to the expression:

$$K_{ae} = \{W_{TPP} \cdot (f_{\%,\ \mathrm{oil}} \cdot E_{\mathrm{oil}} + f_{\%,\ \mathrm{gas}} \cdot E_{\mathrm{gas}} + f_{\%,\ \mathrm{coal}} \cdot E_{\mathrm{coal.}}) + W_{\mathrm{HPP}} \cdot E_{\mathrm{HPP}} + W_{\mathrm{NPP}}\ E_{\mathrm{NPP}}\]/W_{\Sigma}, \quad (14)$$

where, $W_{TPP}$, $W_{\mathrm{HPP}}$, $W_{\mathrm{NPP}}$ and $W_{\Sigma}$ is electric power production, TW·h (Table 17); $f_{\%,\ \mathrm{oil}}$, $f_{\%,\ \mathrm{gas}}$ and $f_{\%,\ \mathrm{coal}}$ are portions of primary power resource production,% (Table 18); $E_{\mathrm{oil}}$, $E_{\mathrm{gas}}$, $E_{\mathrm{coal.}}$, $E_{\mathrm{HPP}}$ and $E_{\mathrm{NPP}}$ are coefficients of carbon dioxide ($CO_2$) annual emission to atmosphere, kg/MW.h (Table 19).

In 2013 annual emission of the coefficient value amounted to 264.6 kg/MW.h. By 2020 it will be between 271.5 and 294.7 kg/MW.h.

With illumination purpose electric power annual consumption equal to 109 TW·h in 2013, annual emission of carbon dioxide ($CO_2$) to atmosphere, including transformation and transport system, energy for transforming primary energy amounted to 28.8 million tonnes. With the forecast of illumination purpose electric power annual consumption in 2020 equal to from 33.2 to 54.3 TW·h, annual emission of carbon dioxide ($CO_2$) will be between 9.0 and 16.0 million tonnes. Decrease of carbon dioxide emission by 2020 is assessed from 12.8 to 198 million tons, which amounts to from 45 to 69 % of the annual emission level in 2013.

## CONCLUSIONS

1. An assessment of the installed product range of light sources, both as a whole across the Russian Federation, and within specific sectors of the economy was performed. This allows assessing the technological level of lighting devices

**Table 18. Production of primary energy resources [8,11]**

| Energy resource | Production of primary energy resources, million TFOE | |
|---|---|---|
| | 2013 | 2020 |
| In total Including: | 1880 | 1883 ÷ 2017 |
| Oil | 746 | 718 ÷ 748 |
| natural gas | 770 | 919 ÷ 958 |
| Coal | 237 | 246 ÷ 311 |

**Table 19. Coefficients of annual carbon dioxide emission to atmosphere [12]**

| Primary fuel | Coefficient of annual carbon dioxide emission ($CO_2$) to atmosphere, kg/MW·h |
|---|---|
| Oil fuel | 330 |
| Gas | 227 |
| Coal | 1340 |
| Nuclear energy | 16 |
| HPP | 7 |

used and arranging constant monitoring of energy efficiency of illumination power consumption in various sectors of the Russian economy. It also makes it possible to develop more reasonable plans of introducing energy efficient LSs and their manufacture.

2. An forecast of illumination power consumption in the Russian Federation until 2020 was made, using two scenarios without and with the introduction of technical regulation documents. A potential of energy saving is determined, which is equal to between 54.6 and 75.7 TW·h. This corresponds to 50–70 % of the power consumption for illumination in 2013.

3. In order to accelerate the introduction of energy efficient LSs in the Russian Federation, a speedy enforcement of some measures on the LS market technical regulation is necessary.

## REFERENCES

1. Tsissis Zh, Aizenberg Yu.B., Shevchenko A.S. Formation of Russian lighting market to increase illumination energy efficiency // Svetotekhnika. 2009, 6, pp. 42 – 48.

2. The federal law of November, 23rd, 2009 #261- ФЗ "On energy saving and increase of power efficiency and on amending some legislation acts of the Russian Federation".

3. The state program of energy saving and increase of power efficiency for the period until 2020.

4. Shevchenko A.S. The program of energy-effective illumination promotion in Russia // Svetotekhnika. 2014, #1–2, pp. 112 – 117.

5. Gvozdev S.M., Panfilov D.I., Polyakov V.D., et al.; Editorship of Varfolomeyev L.P. Energy-effective electric illumination: Study guide / Moscow: Publishing house of the Moscow Power Institute, 2013, 288 P.

6. Vagin G. Ya., Sergeev S.F. Saving of power resources in the industry, budgetary enterprises, housing and communal services: Reference and methodical book / N. Novgorod: NSTU, 2007, 280 P.

7. An analysis of the state and perspectives of the lighting product market in the participant countries of the Eurasian economic union (EAEU) / The Program of development of United Nations Organization (UNPr), 2015, 78 P.

8. The Russian statistical year-book. 2013:/Rosstat. Moscow, 2013, 717 P.

9. A report on the researches on the subject: "An analysis of methodical and standard legal basis stimulating implementation of energy saving projects based on power service contracts and preparation of proposals on change or exception of the legislation rules

interfering with a large-scale implementation of energy saving projects on this basis" (final). Moscow, 2013. URL: http://www.undp-light.ru/uploadli / iblock/3ec/3ec1633f0996ab062c9b92940e4bd364.doc (Addressing date: 18.05.2016).

10. Reconsidered directive principles of the national inventories of greenhouse gases – IPCC, 1996. URL: http://www.ipcc-nggip.iges.or.jp/public/gl/russian.html (Addressing date: 18.05.2016).

11. Energy strategy of Russia for the period until 2030. It is approved by an order of the Government of the Russian Federation of the 13th November 2009 #1715-p.

12. The rules and regulations "Energy efficiency of buildings – total consumption of energy and determination of power characteristics" (based on EN15603:2008). Appendix D, Moscow, 2013.

***Gennady Ya. Vagin,***
Dr. of Technical Sciences, Honoured scientist of the Russian Federation, professor of the Chair "Electric power industry, electric power supply and power electronics" of the Nizhny Novgorod State Technical University. An expert of the Analytical centre at the Government of the Russian Federation. Graduated from the Gorky Polytechnical Institute in 1965. His fields of scientific interest include energy saving

***Oleg Yu. Malafeev,***
an assistant of the Chair "Electric power industry, electric power supply and power electronics" of the Nizhny Novgorod State Technical University. Graduated from the Nizhny Novgorod State Technical University in 2010. His fields of scientific interest include energy efficient illumination

***Michail V. Martynyuk,***
Ph.D., senior lecturer of the Chair "Computer science and control systems" of the Nizhny Novgorod State Technical University. Graduated from the Nizhny Novgorod State Technical University in 1999. His fields of scientific interest include energy efficient illumination

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# CAN HIGH DYNAMIC RANGE IMAGES HELP LIGHTING DESIGN ANALYSIS: RESULTS OF A SURVEY

Hongyi Cai and Mariam. I. Saifan

*Department of Civil, Environmental and Architectural Engineering, University of Kansas, USA*
*E-mail: hycai@ku.edu*

## ABSTRACT

This study conducted a questionnaire survey to evaluate the usefulness of an emerging camera- and computer-aided graphic analytic method to help designers improve lighting design analysis. This imaging method uses high dynamic range (HDR) photography to capture millions of luminance values across an interior or exterior space, and then plot HDR luminance and luminance gradient maps in MATLAB for further evaluation of the luminous environment. The questionnaire was taken online by 40 lighting designers in the field without prior experience of using HDR photography. Their anonymous responses were collected online and analyzed. It was found that experienced lighting designers who have empirical design insights gained over years of field practice do not rely on the information revealed on the HDR images. However, the HDR imaging method could be a useful tool for trained beginners to assist in their design practice to evaluate a luminous environment.

**Keywords:** lighting design, imaging method, camera, MATLAB, luminance, questionnaire

## INTRODUCTION

Designing with light is work of both art and science. Designers would think about the space that is being designed in light of their own interpretation for creative ideas, and then search for unique lighting fixtures that will provide sufficient light levels, be energy efficient, and look appealing. The designers often abide by codes, standards, and design practices published by the Illuminating Engineering Society (IES), the International Commission on Illumination (CIE), the Society of Light and Lighting (SLL), the International Association of Lighting Designers (IALD), and local city ordinances. Such design guidelines illustrate to designers how to design with the effect of lights and why a specific design solution is beneficial for human use through the analysis of technologies. On the other hand, lighting design is subjective and can often be an inconsistent but creative practice as a result of the different visions from lighting designers. Often times, designers, lighting specialists, and engineers create a unique luminous environment because they think it looks great. Although the design may meet the requirements of codes and standards, what may be lacking are the relevant principles of visual design and the supporting technologies behind those creative ideas. Such principles and concepts are adopted in lighting design in line with the occupants' visual perception of the luminous environment, and thus are closely related to the spatial luminance distribution across a space.

To interpret the design in light of the visual principles and concepts, the spatial and temporal distributions of luminance-based metrics (e.g., target luminance, background luminance, adaptation luminance, ambient luminance, luminance contrast, luminance gradient) need to be measured in the given building environment. Nonetheless, conventional lighting design is mainly based on the amount of light needed in a space. Illuminance based metrics (e.g., horizontal illuminance, vertical illuminance, task area illuminance, daylight factor, daylight autonomy) are predominant in codes and standards. Since human eyes detect luminance, not illuminance, such illuminance-based metrics cannot be used for interpreting lighting design in visual concepts. To handle this, well-experienced lighting professionals have gained empirical knowledge through many years of lighting practice. Entry-level designers and students lack such empirical knowledge and experience. To make up, they often rely on some design methods to assist in their design practice, such as physical and computer modelling and simulations.

High dynamic range (HDR) photography has the potential to become another design tool in line with the space occupants' vision to help designers capture luminance of indoor and outdoor environments within a large field of view [1,2,3]. HDR photography measures the luminance of target points at pixel level across the entire lighting scene using a single digital camera. With calibrations, HDR photography can capture millions of luminance values at pixel level within the field of view of the camera lens at a single measurement. HDR photography has been validated to capture a greater dynamic range of light between the darkest and lightest areas of a scene [1,4]. It was proven that HDR photography has an error $\leqslant 5$ % for measuring grey surfaces and approximately 10 % for colour surfaces. HDR photography can supplement meter measurement and also provide more information about the environment (e.g., colour, geometry, texture, etc.) that human eyes can see.

On the other hand, the modern lighting profession is transforming from assessing light incident on planes (illuminance) to assessing light arriving in the eyes of space users (luminance)[5]. Thus, recommended light levels for general applications would better deal with human vision and visibility requirements [3,5,6,7]. Corresponding lighting evaluation methods may need to evaluate the seeing process in the real space with design options to interpret the individual differences [7]. HDR photography is a potential technical design tool in line with the space occupants' vision. Real-world luminance can be extracted at pixel level and analyzed from HDR images of interior and exterior luminous environments taken from any viewpoint of space users. As a result, computer-aided lighting evaluation using HDR images might be useful to designers yet not confirmed.

The authors then conducted a literature review to find out if HDR images have been reported useful by lighting designers in the field to assist in lighting design analysis. Many lighting researchers and professionals have used HDR photography for luminance measurement of different types of luminous environments, including day lit scenes [2,8,9,10, 11,12,13,14,15]. However, before 2014, there were rare publications in the literature guiding lighting designers how to use HDR photography and derivative computer-aided imaging technologies to assist in their lighting design practice. At the moment, most lighting designers are still not familiar with HDR photography and derivative lighting analytic methods, which require knowledge of users in both photography and digital imaging and computing.

To help lighting designers, in 2014, the authors introduced a computer-aided graphic analytic method running in MATLAB (a technical computing language for data visualization and analysis) to extract and treat the data from HDR images to help improve lighting analysis [3]. Several case studies were reported in evaluation of interior luminous environments using this computer- and camera-aided lighting analytic tool [3]. It seems, but not yet confirmed by lighting designers, that an HDR image of a project scenario has the potential to help visually express a number of lighting design principles relevant to visual perception that may help understand what type of lighting is needed in a space and the evaluation of its lighting quality like glare assessment [3, 16].

The HDR imaging method has not yet been accepted by lighting designers and used in their design practice. Can this HDR imaging method possibly become a design tool to be used by designers to assist in their lighting design practice? Would lighting designers in the field with various years of experience find the HDR luminance images of great value in their lighting practice? To answer these questions, it is necessary to evaluate the effectiveness of the HDR imaging method at its current format in assisting the design of high quality luminous environments. The authors thus conducted a questionnaire survey to find out whether evaluating HDR imag-


Fig. 1. The two example field measurement scenarios: (a) an illumination laboratory, (b) a lobby with a large glass wall facing east-southeast in a research building [2, Fig.2]

es of a project scenario could potentially help improve lighting design analysis to assist lighting design in practice.

## QUESTIONNAIRE SURVEY

The questionnaire was formed with four closed-ended questions and accompanying HDR images of an electrically lit windowless laboratory (Fig. 1 (a)) and a day lit lobby with a glass wall (Fig. 1 (b)). This illumination laboratory has many ceiling mounted luminaires that are used for teaching and learning of lighting. The field measurement was conducted on April 5 at 4:20 p.m. The day lit lobby in triangular shape is located on the second floor of a research building, which has a big floor-to-ceiling glass wall facing east-southeast without any shades. The lobby was measured on July 9 at 8:00 a.m. on a sunny day.

The HDR images accompanying the questionnaire are shown in Figs. 2–7, including two-dimensional (2D) luminance maps, 2D gradient magnitude maps, 2D gradient direction maps, and three-dimensional (3D) luminance maps. The questionnaire survey was focused on visual perception and evaluation of those HDR images

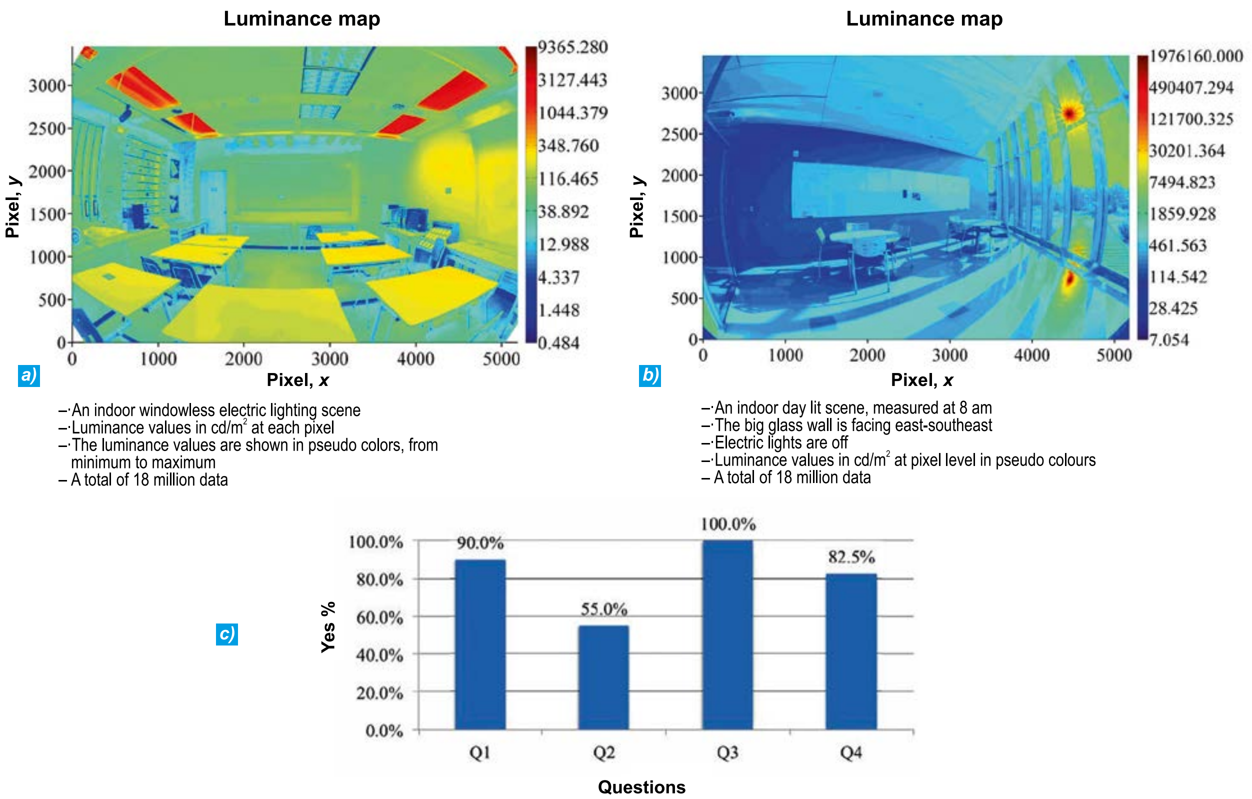



Fig. 2. Survey feedback of "YES" in percentages to those four questions from the 40 lighting designers and six college students with regard to the 2D HDR luminance maps, (a) the luminance map of the electrically lit windowless laboratory in pseudo colour, (b) the luminance map of the day lit lobby in pseudo colour, (c) the survey results on luminance map

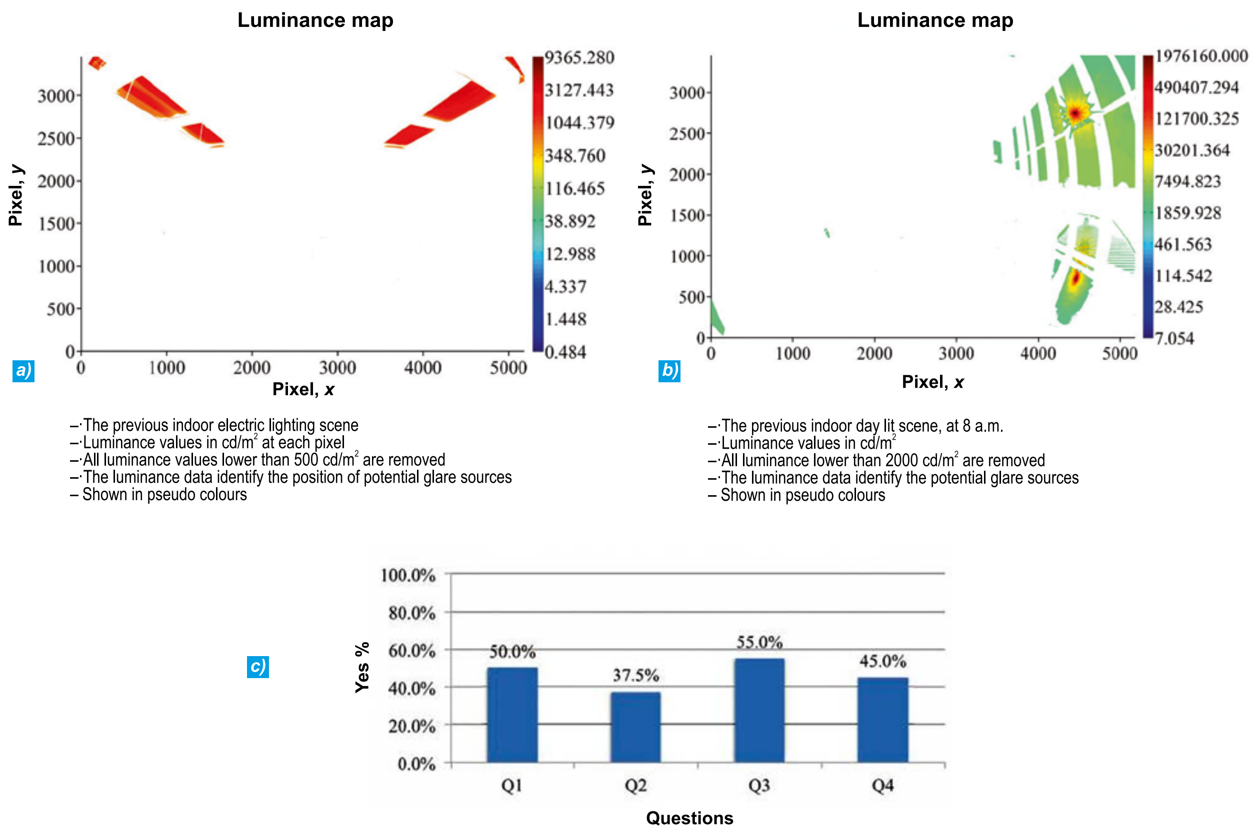



Fig. 3. Survey feedback of "YES" in percentages to those four questions from the 40 lighting designers and the six college students with regard to the 2D HDR luminance map filtered with a lower threshold values, (a) the luminance map of the electrically lit windowless laboratory filtered with a lower threshold values of 500 cd/m$^2$, (b) the luminance map of the day lit lobby filtered with a lower threshold values of 2000 cd/m$^2$, (c) survey results on luminance map filtered with a lower threshold value

without disclosure of the technical details on how they were generated and plotted using the computer- and camera-aided lighting analytic tool. The purpose was to invite more lighting designers, who often lack knowledge in computer programming, digital imaging and computing, to participate and complete the survey in a reasonable short time. Visual assessment of HDR images is actually the last stage of the computer-aided graphic analytic method running in MATLAB [3]. For better understanding of those HDR images (Figs. 2–7) and how they were generated and plotted, readers are recommended to review the authors' previous publication on the computer-aided graphic analytic method [3].

With each type of HDR maps (Figs. 2–7), the same four yes-or-no questions as listed below were asked. Only closed-ended questions were asked in this survey because in general closed-end questions are relatively simple (compared to open-ended questions) and could be answered within a reasonable short time to attract higher response rate from participants, especially those lighting professionals in the field.

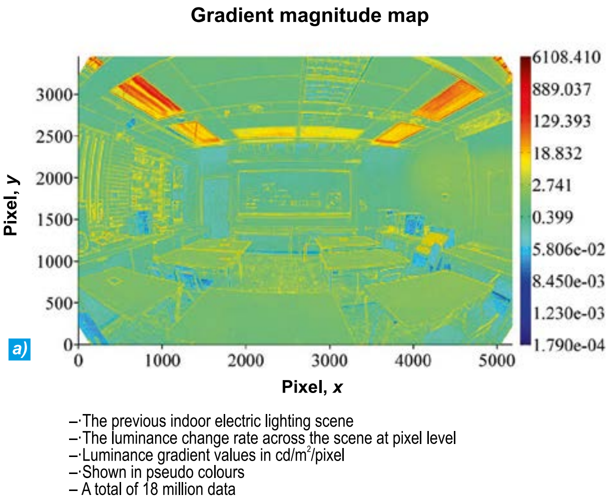
**Q1**: Are these HDR images useful for post-occupancy evaluation or retrofit?

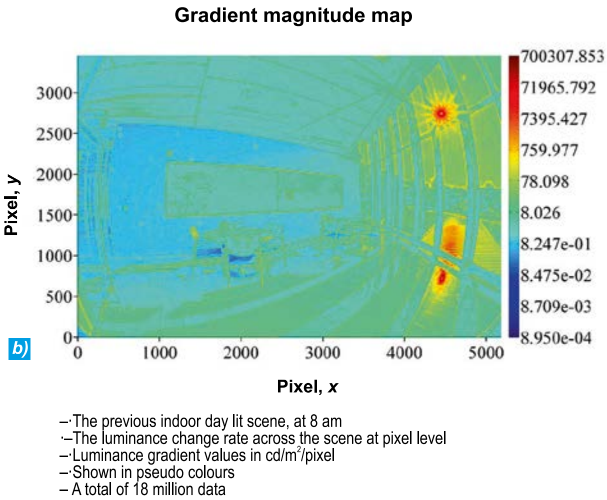
**Q2**: Do these HDR images provide more information than the bare eyes can handle?

**Q3**: If the images above are computer-generated scenes of projects still in design, will they help in lighting design?

**Q4**: Would you be interested in using these HDR images for lighting practice?

The questionnaire was created in Google Docs and a web link to the questionnaire was sent out to all participants. The participation in the online survey was anonymous. The questionnaire was sent out to the lighting professionals who attended the International Association of Lighting Designers (IALD) Enlighten Americas 2013 Conference in Montreal, Canada, and other lighting designers and interior designers in the U.S. Those lighting professionals in the field have different work experience from entry-level to experience in the light-



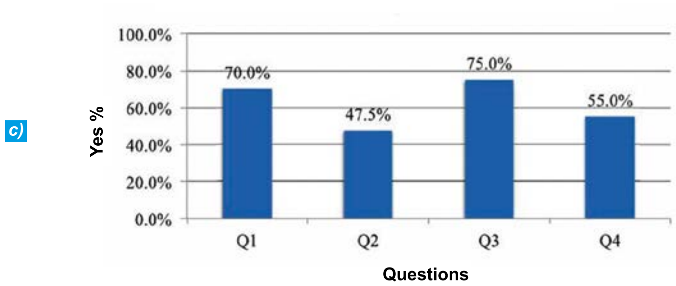




Fig. 4. Survey feedback of "YES" in percentages from the 40 lighting designers and six college students to those four questions with regard to the 2D HDR luminance gradient magnitude maps, (a) the luminance gradient magnitude map of the electrically lit windowless laboratory, (b) the luminance gradient magnitude map of the day lit lobby, (c) survey results on luminance gradient magnitude map

ing design field but little prior experience of using HDR imaging technologies. A total of 40 lighting professionals responded to the survey. The feedback was collected online and analyzed in percentage of how many designers answered YES or NO to each question. The survey results are shown in Figs. 2–7. Below are more details.

Fig. 2 shows the luminance maps in pseudo colours of the two spaces and the survey results of the 40 lighting designers. Each luminance map embodies 18 million luminance values at pixel level. It can be seen from the two HDR images that the luminance in the daylit lobby with a floor-to-ceiling glass wall has a much wider dynamic range (from 7.054 cd/m$^2$ to 1,976,160.000 cd/m$^2$) than the luminance values in the electrically lit windowless laboratory (from 0.484 cd/m$^2$ to 9,365.280 cd/m$^2$). The luminance maps reveal that these two spaces are sufficiently lighted, but may have a problem with glare from the visible sun, the daylit window area, and the electric lights. The questionnaire shows that when the 40 lighting designers looked at the luminance maps, 90 % of them thought that the HDR luminance maps were useful for post-occupancy evaluation or retrofit, 55 % of them thought that the images had more information than the bare eyes could handle, 100 % agreed that the images would help in lighting design of projects still in design, and 82.5 % were interested in using the HDR images for lighting practice.

Fig. 3 reveals the potential lighting hazards of the luminous environment identified at their pixel locations filtered with the lower luminance threshold value 500 cd/m$^2$ for the electrically lit windowless laboratory and 2000 cd/m$^2$ for the day lit lobby. Such threshold luminance levels were adopted based on previous research [13,17,18] on discomfort glare and eyes' adaptation to ambient light. Specifically, in this day lit lobby, glare sources are identified as surfaces having four times the luminance of the average task area luminance, that is, approximately 2000 cd/m$^2$. Fig. 3 also shows the survey results from the 40 lighting professionals of the percentages of participants who answered "YES" to each question. From Fig. 3 (c), it was found that when the lighting designers looked at the filtered luminance maps, 50 %

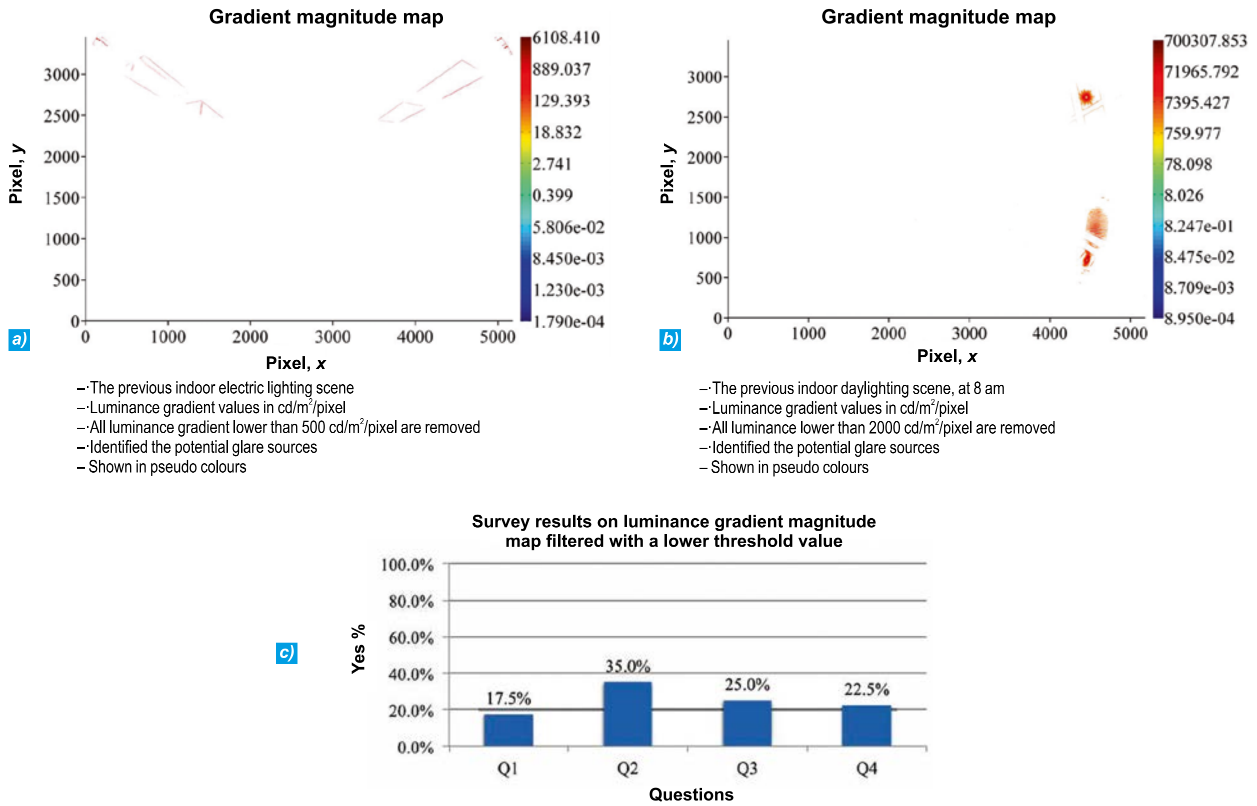



Fig. 5. Survey feedback of "YES" in percentages from the 40 lighting designers and six college students to those four questions with regard to the 2D HDR luminance gradient magnitude maps filtered with lower threshold values, (a) the luminance map of the electrically lit windowless laboratory filtered with 500 cd/m$^2$/pixel for the laboratory, (b) the luminance map of the day lit lobby filtered with 2000 cd/m$^2$/pixel for the day lit lobby, (c) survey results on luminous gradient magnitude map filtered with a lower threshold value

of them thought that the HDR images were useful for post-occupancy evaluation or retrofit, only 37.5 % of them thought that the HDR images had more information than the bare eyes could handle, 55 % of them thought the HDR images might be helpful in designing a new lighting project in computer simulations, and 45 % of them would like to use the filtered HDR luminance maps for lighting practice.

Fig. 4 is the 2D luminance gradient magnitude map. Luminance gradient (G) is defined as the largest change rate (the magnitude) and the polarity of spatial luminance variation on a large surface or across the entire field of view in extraordinarily high resolution [2]. In other words, luminance gradient indicates how fast the luminance changes towards which direction. Fig. 4 renders the magnitude over a large range: from luminance equal to zero per pixel up to luminance 6108.410 cd/m$^2$ per pixel for the windowless laboratory, and for the day lit lobby in the early morning luminance up to 700307 cd/m$^2$ per pixel. Based on Fig. 4, the luminance changed slowly at a rate less than 500 cd/m$^2$/pixel across the walls, floor, ceiling and furniture. The quickest changes occurred at the edges of the light troffers with a maximum gradient level of 6108 cd/m$^2$/pixel. In the day lit lobby, the luminance changed very fast across the glass wall and on the floor with sunlight. The highest luminance gradient occurred in the early morning when the sun was visible to the camera lens. In the deep space away from the window, the light became uniform. The deep interior surfaces had very diffuse light distributions. Based on Fig. 4 (c), when the lighting designers looked at the luminance gradient magnitude map, 70 % of them thought that the HDR images were useful for post-occupancy evaluation or retrofit, yet only 47.5 % thought the luminance gradient magnitude maps provide more information than the bare eyes can handle, 75 % thought that the HDR images would help in computer-aided lighting design of new projects, 55 % of them were interested to use the luminance gradient magnitude maps in their design practice.

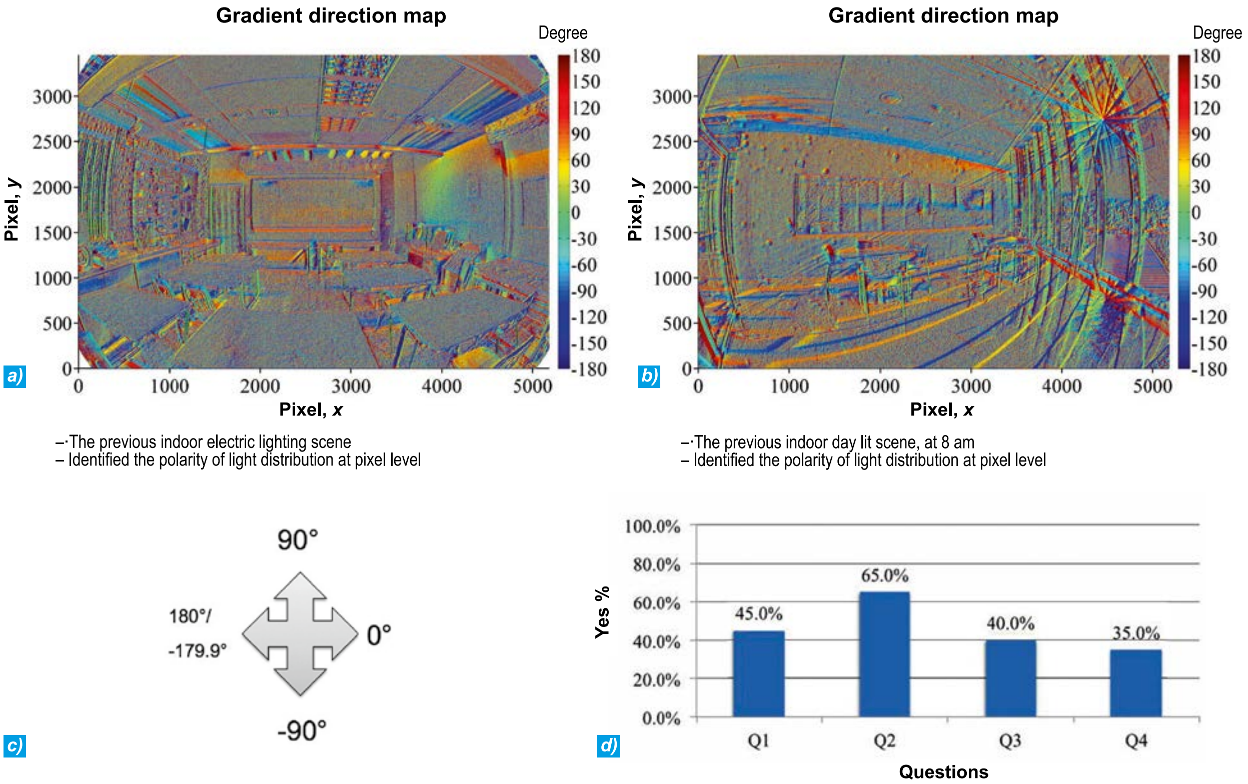



Fig. 6. Survey feedback of "YES" in percentages from the 40 lighting designers and six college students to those four questions with regard to the 2D HDR luminance gradient direction maps (the angle 0° is to the right (the direction of x axis), 90° is up, 180° / –180° is to the left, –90° is down), (a) the luminance gradient direction map of the electrically lit windowless laboratory, (b) the luminance gradient direction map of the day lit lobby, (c) the angle θ measured anticlockwise from the x axis, (d) survey results on luminous gradient direction map

The fast luminance changes lead to excessive light contrast that may cause discomfort glare. Fig. 5 shows extreme light change rates identified using a lower threshold luminance gradient magnitude, e.g., 500 cd/m$^2$/pixel for the laboratory and 2000 cd/m$^2$/pixel for the day lit lobby that are consistent with the lower threshold luminance. Other higher threshold values could also be used for identifying severe lighting hazards in more stringent applications. Based on the results in Fig. 5 (c), when looking at the filtered luminance gradient magnitude maps, only 17.5 % of the lighting designers thought that the images were useful for post-occupancy evaluation or retrofit, 35 % of them thought the HDR images provide more information than the bare eyes can handle, 25 % thought that it would help in lighting design of new project on computers, and only 22.5 % were interested in using that HDR image. Consequently, the filtered luminance gradient magnitude maps were not as useful to those designers as the luminance maps, the filtered luminance maps, or the luminance gradient maps without any filters.

Fig. 6 illustrates luminance gradient direction angle θ towards which the luminance changes at each pixel. The angle θ ranges from –180° to 180°, measured anticlockwise from the x axis, e.g., the angle 0° is to the right (the direction of x axis), 90° is up, 180° / –180° is to the left, –90° is down. Fig. 6 is in colour scale. Warm colours indicate the polarity is up direction, while the cool colours indicate down direction. Based on Fig. 6 (c), when looking at the luminance gradient direction map, 45 % of the lighting designers thought those HDR images were useful for post-occupancy evaluation or retrofit, 65 % of them thought that the images had more information than the bare eyes could handle, 40 % of them agreed the luminance gradient direction maps were useful in computer simulation for new projects, while only 35 % of them were interested in using the luminance gradient direction maps in their practice. Such results, again, reflect the complexity of the luminance gradient as a new design metric proposed [2] and its difficulty to measure by lighting designers in the field without knowledge in HDR imaging technolo-

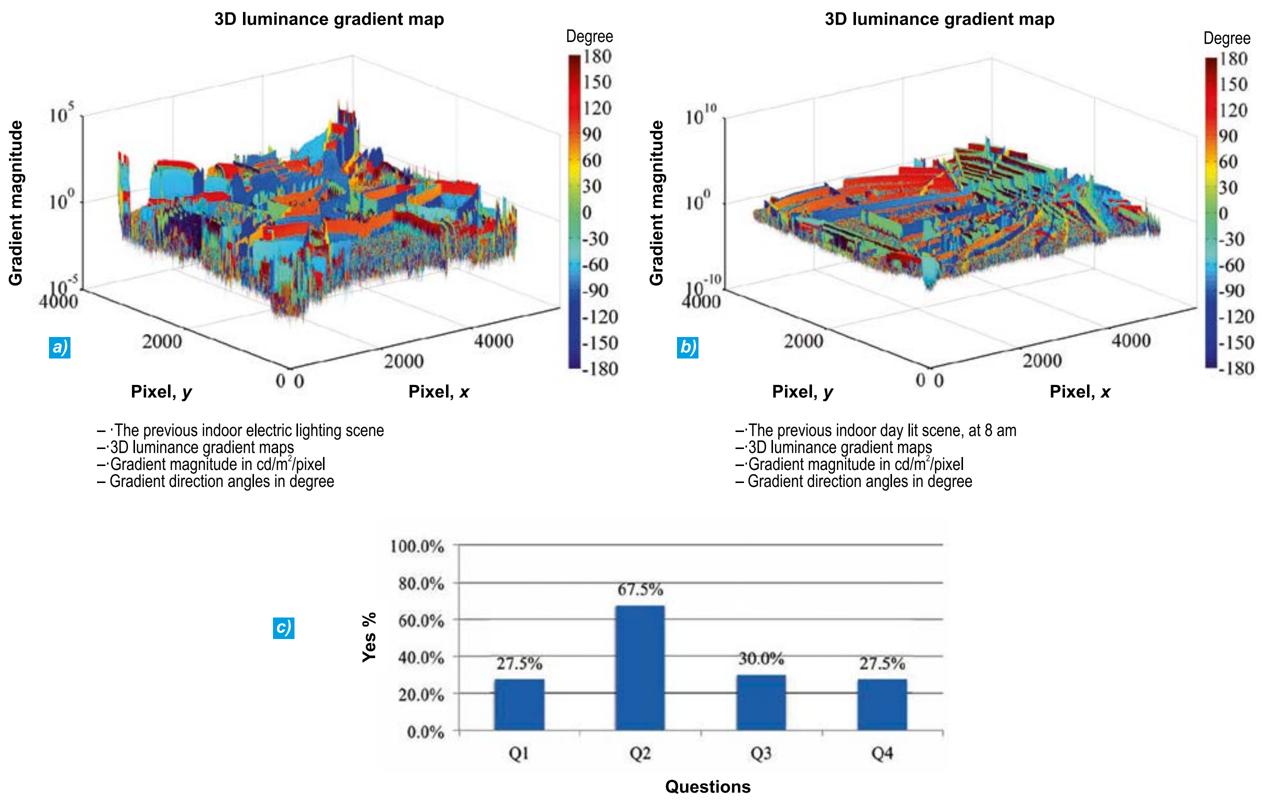



Fig. 7. Survey feedback of "YES" in percentages from the 40 lighting designers and six college students to those four questions with regard to the 3D HDR luminance gradient maps, (a) the 3D luminance gradient map of the electrically lit windowless laboratory, (b) the 3D luminance gradient map of the day lit lobby, (c) survey results on 3D luminance gradient map

gies and advanced computer skills for programming language.

Above luminance gradient magnitude maps and gradient direction maps are two-dimensional plotting. In fact, they could be plotted together in 3D view, as shown in Fig. 7. Unfortunately, in such a 3D graph, front points with large magnitude block other points behind. Thus, the 2D gradient magnitude and direction maps are deemed more straightforward and thus more useful than the 3D graph to locate the luminance and luminance gradient values on the HDR images. However, Fig. 7 was included in the survey to find out if the 3D plotting might still be useful for lighting design, otherwise, they might be erased in future applications. Based on Fig. 7 (c), when looking at the 3D luminance gradient map, only 27.5 % of those lighting professionals thought that the HDR images were useful for post-occupancy evaluation or retrofit, 67.5 % of them still thought the HDR images provided more information than the bare eyes can handle, yet only 30 % of them thought that the images would help in lighting design of new project in computer simulations, and only 27.5 % were interested in using the 3D HDR images. Conclusively, the 3D plotting of luminance gradient was not that useful for lighting designers, thus, could be erased in future applications.

## ANALYSIS OF THE SURVEY RESULTS

Figs. 2–7 (c) show the first-hand data – the percentages of the 40 lighting designers who answered YES to each question. The data were further statistically analyzed for sample means, standard errors, and confidence intervals for population (all lighting designers in the field) at 95 % confidence level. The statistical results are summarized in Table 1.

Based on the results shown in Table 1, at 95 % confidence level the majority (> 50 %) of the general lighting designers in the field who are not familiar with the HDR imaging technology would think the 2D luminance maps and the 2D luminance gradient magnitude maps are useful for post-occupancy evaluation or retrofit, can help lighting design of new projects via computer si-

**Table 1. Statistical results of the questionnaire survey to evaluate if the camera-aided imaging method could be a truly useful tool for lighting designers in the field**

| HDR images | Questions | Sample mean,% | Sample size | Std error,% | Confidence interval at 95 % confidence level,% |
|---|---|---|---|---|---|
| 2D HDR luminance maps | Q1 | 90.0 | 40 | 4.7 % | 80.5–99.5 |
| | Q2 | 55.0 | 40 | 7.9 % | 39.3–70.7 |
| | Q3 | 100.0 | 40 | 0.0 % | 100 |
| | Q4 | 82.5 | 40 | 6.0 % | 70.5–94.5 |
| 2D HDR luminance map filtered with a lower threshold value | Q1 | 50.0 | 40 | 7.9 % | 34.2–65.8 |
| | Q2 | 37.5 | 40 | 7.7 % | 22.2–52.8 |
| | Q3 | 55.0 | 40 | 7.9 % | 39.3–70.7 |
| | Q4 | 45.0 | 40 | 7.9 % | 29.3–60.7 |
| 2D HDR luminance gradient magnitude maps | Q1 | 70.0 | 40 | 7.2 % | 55.5–84.5 |
| | Q2 | 47.5 | 40 | 7.9 % | 31.7–63.3 |
| | Q3 | 75.0 | 40 | 6.8 % | 61.3–88.7 |
| | Q4 | 55.0 | 40 | 7.9 % | 39.3–70.7 |
| 2D HDR luminance gradient magnitude maps filtered with lower threshold values | Q1 | 17.5 | 40 | 6.0 % | 5.5–29.5 |
| | Q2 | 35.0 | 40 | 7.5 % | 19.9–50.1 |
| | Q3 | 25.0 | 40 | 6.8 % | 11.3–38.7 |
| | Q4 | 22.5 | 40 | 6.6 % | 9.3–35.7 |
| 2D HDR luminance gradient direction maps | Q1 | 45.0 | 40 | 7.9 % | 29.3–60.7 |
| | Q2 | 65.0 | 40 | 7.5 % | 49.9–80.1 |
| | Q3 | 40.0 | 40 | 7.7 % | 24.5–55.5 |
| | Q4 | 35.0 | 40 | 7.5 % | 19.9–50.1 |
| 3D HDR luminance gradient maps | Q1 | 27.5 | 40 | 7.1 % | 13.4–41.6 |
| | Q2 | 67.5 | 40 | 7.4 % | 52.7–82.3 |
| | Q3 | 30.0 | 40 | 7.2 % | 15.5–44.5 |
| | Q4 | 27.5 | 40 | 7.1 % | 13.4–41.6 |

mulations, and would be interested in using them in aiding their design practice. Most lighting designers in the field would think the 2D luminance maps provide more information than the bare eyes can handle (with confidence interval of 39.3 % – 70.7 % @ mean of 55.0 %), but the 2D luminance gradient magnitude maps do not (31.7 % – 63.3 % @ mean of 47.5 %). It looks like the 2D luminance maps would be more attractive to designers in the field than the 2D luminance gradient magnitude maps.

Most lighting designers in the field today would think the 2D luminance maps and the 2D luminance gradient magnitude maps filtered with lower threshold values are not useful for post-occupancy evaluation or retrofit, do not provide further help for lighting design beyond what their bare eyes could handle, and are not interested in using these filtered HDR images for lighting practice. Although lighting designers would think the filtered 2D luminance maps may help computer-aided simulation of new projects still in design (39.3 % – 70.7 % @ mean of 55.0 %), the filtered 2D luminance gradient magnitude maps may not (11.3 % – 38.7 % @ mean of 25.0 %).

For the 2D luminance gradient direction maps, most lighting designers in the field would think they can provide more information than what their bare eyes could handle (49.9 % – 80.1 % @ mean of 65.0 %), but are not useful for post-occupancy evaluation or retrofit, do not help computer-aided simulation of new projects, and are not interested in using them in practice. For the 3D luminance gradient map, most lighting designers in the field would think they can provide more information than what their bare eyes could handle, but are not useful for post-occupancy evaluation or retrofit, do not help computer-aided simulation of new projects, and are not interested in using it for lighting practice.

## DISCUSSIONS

Why most experienced lighting designers who routinely work with lighting did not find the camera- and computer-aided design method of great interest? On the other hand, this camera-aided imaging method has potentials for lighting quality evaluation such as glare assessment in a space [3]. We need to take a look at some deep causes. How useful the camera-aided imaging method could be to its potential users depends on (a) the users' need of empirical knowledge of lighting design related to spatial luminance distributions accumulated over years' practice that could be supplemented by the HDR images, and (b) (if there is a lack of empirical knowledge) how easily the HDR images and the following imaging data treatment could be understood and handled by the users, so they are interested to learn.

Most experienced lighting designers in the field are visual and creative. They have empirical knowledge of spatial luminance distributions accumulated over years' practice. Moreover, those 40 lighting professionals were not familiar with the HDR imaging technology. Before the survey, they were not given a chance to learn and practice the technological overwhelming (for designers lacking computing skills) and time-intensive computer-aided data treatment of those HDR images, which may have affected their thorough understanding of the HDR images presented to them at the first time. As a result, a designer may not want to go through all technical steps summarized by Cai [2] to analyze an existing space, which he/she can easily take a look for empirical evaluation.

The opinions of those 40 lighting professionals may not be representative of apprentice lighting designers and college students, who may have knowledge of computing and HDR imaging but little work experience. To find out whether providing training of HDR photography and the camera- and computer-aided imaging method to apprentice lighting designers could help them on using HDR images for lighting design analysis, a follow-up survey was conducted inside college students who have learned and used the camera-aided design tools before. The online link to the questionnaire was emailed to those students after the semester was over to avoid conflicting of interest. A total of six college students responded anonymously online.

It was found that training can help those students understand the camera-aided imaging method and help them accept and explore the use of the luminance maps, the filtered luminance maps with lower threshold values, the luminance gradient magnitude maps, and the luminance gradient direction maps in their design practice, but may not help them accept and use the filtered luminance gradient magnitude maps and the 3D luminance gradient maps in practice.

## CONCLUSIONS

This study explored the use of the camera-aided imaging method proposed by Cai et al. [3] to evaluate lighting in existing spaces for interpreting the lighting quality. This camera-aided imaging method considers the human visual perception that lighting designers should take into account to create a pleasant and high quality lighting design. It was found that most designers in the field would think the luminance map and the luminance gradient magnitude map are helpful, but they would not think the luminance and luminance gradient magnitude maps filtered with lower threshold values could assist in design practice. Most lighting designers in the field would think the luminance gradient direction maps are not useful and the 3D luminance gradient map is also too difficult to use. Conclusively, this camera-aided imaging method may not be that useful for experienced lighting designers. Most likely their years' experience accumulated in a work environment could provide empirical design insights that do not rely on the technical information revealed on the HDR images.

On the other hand, this imaging method may be useful for college students or fresh graduates once trained on how to use the new technologies on design in that they could successfully evaluate a luminous environment in a couple of hours to assist in their lighting design practice without years of experience accumulated in a work environment. Also, great interest in this camera-aided imaging method may be with lighting design instructors who are in constant search of techniques to better link the qualitative and quantitative aspects of lighting for their students. It seems that HDR photography may have the potential as a teaching tool to visually express a number of lighting principles that are normally difficult to explain to students. Future development is needed to overcome the technical barriers on using the camera-aided lighting analytic tool proposed by Cai et al.[3], which in its current format may not be easy to use on a day-to-day basis in the field of light design.

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## REFERENCES

1. Cai, H., Chung, T.M. 2011. Improving the quality of high dynamic range images. Lighting Research and Technology, 43(1), 87–102.

2. Cai, H. 2013. Luminance gradient for evaluating lighting. Lighting Research and Technology. (OnlineFirst). DOI: 10.1177/1477153513512501.

3. Cai, H., Saifan, M.I., Killeen, J.A. 2014. Case Studies of a Camera Aided Imaging Method for Evaluation of Interior Luminous Environments, Indoor and Built Environment. (OnlineFirst). DOI:10.1177/1420326X14534457.

4. Inanici, M.N. 2006. Evaluation of high dynamic range photography as a luminance data acquisition system. Lighting Research and Technology, 38(2), 123–136.

5. Cuttle, C. 2010. Towards the third stage of the lighting profession. Lighting Research and Technology, 42(1), 73–93.

6. Jay, P.A. 2002. Review: subjective criteria for lighting design. Lighting Research and Technology, 34(2), 87–96.

7. Yonemura, G.T. 1981. Criteria for recommending lighting levels. Lighting Research and Technology, 13(3), 113–129.

8. Nazzal, A. 2001. A new daylight glare evaluation method: introduction of the monitoring protocol and calculation method, 33(3), 257–265.

9. Howlett, O.A. 2003. Reflectance characteristics of display screen equipment: application to workplace lighting design. Lighting Research and Technology, 35(4), 285–296.

10. Sarkar, A., Mistrick, R. 2006. A Novel Lighting Control System Integrating High Dynamic Range Imaging and DALI, Leukos, 2(4), 307–322.

11. Wienold, J., Christoffersen, J. 2006. Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. Energy and Buildings, 38(7), 743–757.

12. Howlett, O., Heschong, L., Mchugh, J. 2007. Scoping study for daylight metrics from luminance maps. Leukos, 3(3), 201–215.

13. Tuaycharoen, N., Tregenza, P.R. 2007. View and discomfort glare from windows. Lighting Research and Technology, 39(2), 185–200.

14. Cantin, F. 2010. Daylighting Metrics Based on Illuminance Distribution, Glare, and Directivity. Lighting Research and Technology, 43(3), 291–307.

15. Bellia, L., Spadaa, G., Pedace, A. 2013. Lit environments quality: a software for the analysis of luminance maps obtained with the HDR imaging technique. Energy and Buildings, 67, 143–152.

16. Illuminating Engineering Society of North America (IESNA). 2013. Recommended Practice for Daylighting Buildings. IES RP-5–13. New York, NY: Illuminating Engineering Society.

17. Commission International de l'Eclairage (CIE). 1983. Discomfort Glare in the Interior Working Environment. CIE Publication 055. Paris: CIE.

18. Van Den Wymelenberg, K., Inanici, M., Johnson, P. 2010. The effect of luminance distribution patterns on occupant preference in a daylit office environment. Leukos, 7(2), 103–122.

19. Albrecht, D.C. n.d.. Measuring Color-Systems and Costs. Retrieved May 11, 2011, from http://www.dcdadvancedtech.com/systems%26costs.pdf.

20. Alzoubi, H., Al-Rqaibat, S., Bataineh, R.F. 2010. Pre-versus post-occupancy evaluation of daylight quality in hospitals. Building and Environment, 45(12), 2652–2665.

21. Boyce, P.R., Slater, A.I. 1981. The application of CRF to office lighting design. Lighting Research and Technology, 13(2), 65–79.

22. Cornolly, C., Leung, T.W.W. 1995. Industrial color inspection by video camera. Proceedings 5th International Conference on Image Processing and Its Applications. Conference publication No. 410. IEE1995. July 4–6, 1995, Edinburgh, UK.

23. de Lasarte, M., Vilaseca, M., Pujol-Ramo, J., Arjona, M., Martínez-Verdú, F.M., de Fez, D., Viqueira, V. 2005. Development of a perceptual colorimeter based on a conventional CCD camera with more than three color channels. Proceedings of the 10th Congress of the International Colour Association (AIC'05). International Colour Association, 2005, 1247–1250.

24. Hong, G., Luo, M.R., Rhodes, P.A. 2001. A study of digital camera colorimetric characterization based on polynomial modeling. Color Research and Applications, 26(1), 76–84.

25. Konis, K., Lee, E.S., Clear, R.D. 2011. Visual comfort analysis of innovative interior and exterior shading systems for commercial buildings using high resolution luminance images. Leukos, 17(3): 167–188.

26. Lupton, M.J., Leung, A.S.M., Carter, D.J. 1996. Advances in lighting design methods for non-empty interiors: a review. Lighting Research and Technology, 28(1), 29–41.

27. Martínez-Verdú, F., Pujol-Ramo, J., Capilla-Perea, P.. 2003. Characterization of a digital camera as an absolute tristimulus colorimeter. Journal of Imaging Science and Technology, 47(4): 279–295.

28. Seymour, J. 2009. The technical association of the graphic arts (TAGA). 61st Annual Technical Conference, New Orleans, Louisiana, March 15–18, 2009. Retrieved May 11, 2011, from http://www.gaintest.net/tagaatc09/presentations/2009 %20Session%201 %20Paper%20 05 %20Seymour.pdf.

29. Tobin, K.W., Goddard, J.S., Hunt, M.A., Hylton, K.W., Karnowski, T.P., Simpson, M.L., Richards, R.K., & Treece, D.A. 2000. Proceedings-SPIE The International Society For Optical Engineering, 3966(29): 194–205.

30. Ward, G. 1992. Radiance visual comfort calculation. Retrieved January 10, 2011, from http://radsite.lbl.gov/radiance/refer/Notes/glare.html.

31. Wienold, J. 2010. Daylight glare in offices. Fraunhofer IRB. Retrieved November 14, 2015, from http://publica.fraunhofer.de/eprints/urn: nbn: de:0011-n-1414579.pdf.

32. Wilson, A. (Ed.). 2007. Imaging Systems Tackle Colour Measurement. Vision Systems Design. Retrieved May 23, 2011, from http://www.vision-systems.com/articles/print/volume-12/issue-8/features/product-focus/imaging-systems-tackle-color-measurement.html.

***Dr. Hongyi Cai***
is an assistant professor in Architectural Engineering at the University of Kansas. He received his Ph.D. and M.S. in Architecture with a concentration in lighting from the University of Michigan. In August 2010, Dr. Cai established the University of Kansas Lighting Research Laboratory. His research group has received prestigious international and national awards. In June 2014, Dr. Cai received the Miller Scholar Award in the School of Engineering at the University of Kansas. Before 2010, he was a Research Associate in the Hong Kong Polytechnic University. Dr. Cai also worked in the lighting industry for several years as lighting engineer and designer. Professionally, Dr. Cai is a member of IES (Illumination Engineering Society), IALD (International Association of Lighting Designers), HFES (Human Factors and Ergonomics Society), IDA (International Dark-Sky Association), and IBPSA (International Building Performance Simulation Association)

***Mariam Saifan,***
as a young professional with a master's of science degree in architectural engineering, is passionate about lighting design. She has always loved being creative and has had many diverse experiences in the field of architectural lighting design for an architecture firm. She believes that lighting design is the perfect mix between technology and art, which is why she has chosen it as her career path. A sample of her dedication has been proved through the awards that she has received such as the IALD Trust Scholarship, the IES R.J. Besal Fund, and the IES Young Professionals Scholarship, all for her leadership in lighting design

Fig. 3. Park Pobedy war memorial on Poklonnaya Gora

Fig. 5. Novodevichy Blessed Virgin-Smolensky monastery


Fig. 1. St.-Petersburg. Malaya Konyushennaya street (a) and Aleksandrinsky theatre (b)


Fig. 2. Tyumen. The building of the Tyumen state architectural building university (a) and Krestovozdvizhensky temple (b)

Fig. 3. Voronezh. The building of regional administration

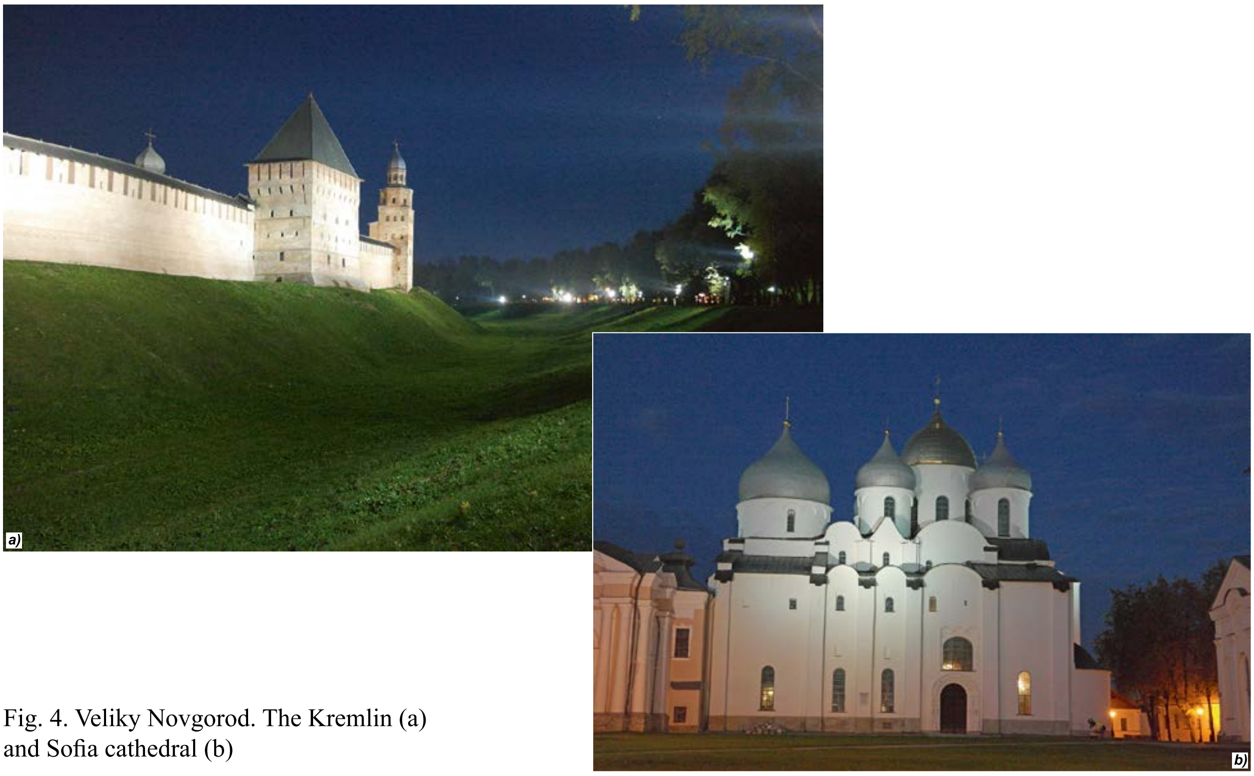


Fig. 4. Veliky Novgorod. The Kremlin (a) and Sofia cathedral (b)


Fig. 5. Kaliningrad. The cathedral (a) with E. Kant's tomb (b)

Fig. 1. General view of polychrome operated LS LEDDCIS with a control panel

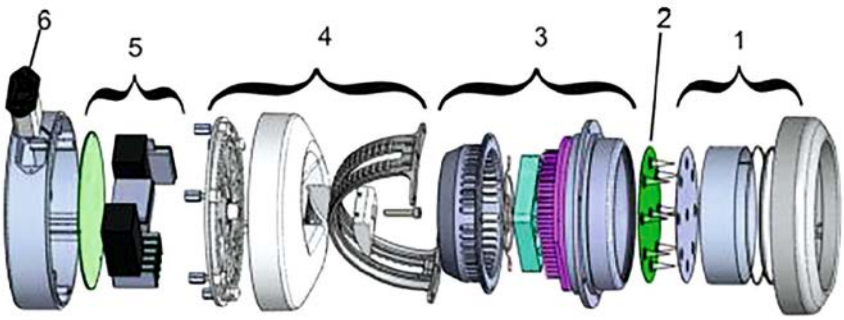


Fig. 4. A schematic view of LS main units. ***1*** – optical system, ***2*** – light-emitting diode module, ***3*** – radiator with a fan, ***4*** – case base with a rotary mechanism, ***5*** – electronic power supply and control unit, ***6*** – network filter

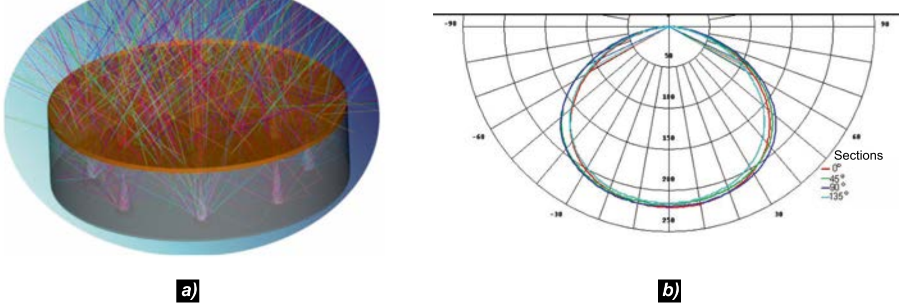


Fig.5. Simulation of optical system using the ray tracing method (a) and the graphic of spatial radiation distribution (b)

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# RESEARCH INTO THE VISUAL ACUITY OF YOUNG PEOPLE, DEPENDING ON ARTIFICIAL ILLUMINATION SPECTRAL COMPOSITION

Alla A. Ryabtseva[1], Anna S. Andryukhina[1], Alina A. Kovrizhkina[1], Victoria A. Lapina[3], Natalia N. Trofimova[2], and Pavel P. Zak[2]

*[1]The Moscow regional research clinical institute of M.F. Vladimirsky SBUE*
*[2]The Institute of Biochemical Physics of N.M. Emanuel of the Russian Academy of Sciences FSBUSE, Moscow.*
*[3]The Physics Institute of B.I. Stepanov of the National Academy of Sciences of Belarus, Minsk, Belarus SSE*
*E-mail: pavelzak@mail.ru*

**ABSTRACT**

The work is dedicated to research of the distinctive sight abilities of people of a young age, depending on the illumination source spectral composition. The researches were performed with two groups of young people: schoolchildren aged between 12 and 14 and students aged between 20 and 24. Visual acuity of the schoolchildren amounted to 1.0 and no more; visual acuity in the students' group was not less than 2.0. The distinctive ability was assessed using error number in distinction of Landolt's rings on the Golovin-Sivtsev's tables. Efficiency of a standard incandescent lamp of $T_c$ = 2500 K, of a warm white light-emitting diode lamp of $T_c$ = 2500 K and of a cold white light-emitting diode lamp of $T_c$ = 6500 K were compared at the same illuminance of 450 $\pm$ 3 lx. It was found that for schoolchildren, when using a cold white light-emitting diode lamp, error number during distinction of Landolt's rings (Table lines 7–9) was 1.5–2 times higher than when using warm white light sources. And the warm white light emitting diode lamp showed slightly better test values than the incandescent lamp. Error number in the student group was minimal. It was random in character and did not depend on the spectrum of the lamp used. It is supposed that the obtained results were caused by the fact that warm white light emitting diode lamps have the narrowest spectral band in the yellow-orange interval. Thus, they form a clearer image on the retina with minimum chromatic aberrations of an eye. The obtained data suggest that it may be better to use warm white illumination sources in school classrooms.

**Keywords:** spectral energy distribution, visual acuity, visual working capacity, light emitting diode illumination, correlated colour temperature, schoolchildren, students

## 1. INTRODUCTION

In recent years, in the lighting and biomedical literature, health impacts of illumination by light emitting diodes (LED) have been widely discussed. Concerns have arisen around the issue of cold white LEDs with a high radiation level in the dark blue spectrum interval and with correlated colour temperature ($T_{cc}$) of above 6000 K. The increased photobiological risk of dark blue light for the retina of the eye is an area of concern. There is also a connection with disturbances of daily rhythms of melatonin generation, which lead to failures in the functioning of metabolic processes [1, 3, 5]. In addition, over the last two years, articles have been published, which suggest that the normal postnatal formation of eye optics in experimental animals (chickens, guinea pigs and monkeys) depended on the spectral composition of the illumination [6–8]. As a whole, before a child's sight is fully developed, it is hypersensitive to the negative properties of the dark blue spectrum interval; it is supposed that daily LED illumination with superfluous dark blue component can have unpredictable delayed consequences for the formation of the visual system and the health of the body. At present, in Russian schools the use of a gentle illumination of neutral white light emitting diodes with $T_{cc}$ no greater than 4000 K is permitted; as a result, there is insufficient research into children's visual working capacity under different types of LED illumination [2]. This study looked at two groups of young people (schoolchildren aged between 12 and 14/ and students aged between 22 and 24) with the aim of addressing this research gap. For the purposes of the study light emitting diode lamps (LEDL) with extreme $T_{cc}$ values were used: from the lowest (2500 K) to the highest (6500 K), in order to assess the importance of illumination spectral composition to provide distinctive ability of eyes.

## 2. METHODS

Paper Golovin-Sivtsev's tables for visual acuity measurements were used in the study. According to the visual acuity measurement international standard confirmed in 1994, Landolt's ring was assessed as the main optotype [9]. The measured variable was the number of errors when recognising Landolt's rings. The study was conducted with schoolchildren aged 12 to 14 (42 participants) and with students aged 22 to 24 (29 participants).

### 2.1. Illumination sources

Visual acuity measurements were made in a darkened ophthalmologic room with Golovin-Sivtsev's table local illumination according to the standard technique from a distance of five metres. Three Rot's devices were used, everyone with its own lamp type: a device with a standard incandescent lamp (IL) of 60 W power and two devices with filament LEDLs of 3 W power of *Madix* Company (China), *MD-NEO-A60* model with a declared rating $T_{cc} = 3000$ K values for warm white LEDLs (WLEDL) and with $T_{cc} =$ 6400 K for cold white LEDLs (CLEDL) equivalent to 60 W power ILs. According to the measurement results obtained by means of two spectrometres (*Avantes 1020*, Nederland and *UPRtec 350*, Taiwan), real $T_{cc}$ of the lamps had values near 2500 K for IL and WLEDL and slightly more than 6500 K for CLEDL. Illuminance of the Tables was at 345 ± 3 lx. And total radiation energy of the all three lamp types within the (400–650) nm wavelength range, appeared to be almost identical with a scatter ± 5 %. Fig. 1 shows the illumination details of the Rot's devices used. As can be seen from the figure, each of lamps used had its own specific spectral character. So IL has a prevailing radiation in the red spectrum interval, which falls on the long-wave $V_\lambda$ part. WLEDL spectrum oc-

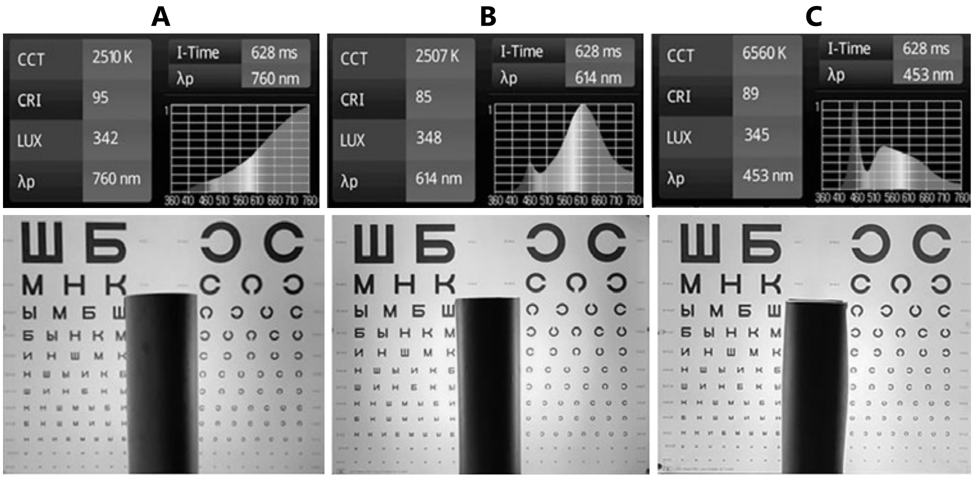


Fig. 1. Spectral characteristics of light reflected from the visual acuity table surface:
A is IL; B is WLEDL; C is CLEDL. Colour diagrams are spectral energy distribution, relative units. Along axes: *X* is wave length, nm, *Y* is energy spectral concentration, relative units. CCT is correlated colour temperature, K; CRI is general colour rendering index; LUX is illuminance of the optotypes Tables surface lx

cupies a central position on the wave length axis close to $V_\lambda$ maximum. A considerable CLEDL radiation part is displaced to a short-wave dark blue area relative to maximum $V_\lambda$.

### 2.2. Visual acuity measurements

Determination of the central vision acuity was made for each eye sequentially in monocular mode using a pair eye occluder. In each of twelve lines of the Table, beginning from the first, the number of unread optotypes (Landolt's rings) was recorded in absolute figures and as a percentage of the total optotype number presented in that line. The row with the least size signs, which the participant could recognise properly, was marked as a real visual acuity, which in some cases was above 1.0. The table with optotypes was fixed by means of a Rot device at the participant's eye height.

## 3. THE RESEARCH RESULTS

As a whole, a statistical average visual acuity of the schoolchildren was equal to 1.0, and not higher, while visual acuity of the students' group was not less than 2.0. Detailed information on the general ophthalmologic characteristics of the researched groups is given below.

### 3.1. Characteristic of the participant groups

The children's group (12–14 years old) consisted of 22 participants (44 eyes), eighteen boys (36 eyes) and four girls (8 eyes). There were 38 healthy eyes amongst them, two cases with high degree myopia without changes at the eye grounds and four cases of low degree myopia.

The group of young people (20–24 years old) consisted of 15 participants (29 eyes), including six men (11 eyes) and nine women (18 eyes).

There were 20 healthy eyes among them, four cases of farsightedness of low degree, one case of high degree myopia, one case of middle degree myopia and three cases of low degree myopia.

Refraction disturbances were completely compensated by glasses correction.

### 3.2. Assessment of light source efficiency by number of errors during optotype distinction

When researching visual acuity of schoolchildren of 12–14 years old, it was found that large-scale Landolt's rings of the first five lines are distinguished under all three light sources almost without errors, and the smallest rings in the 11$^{th}$ and 12$^{th}$ lines (visual acuity is 1.5–2.0) are completely indiscernible. Lines from the sixth to the tenth (visual acuity is 0.6–1.0) were recognised with errors, and the number of errors regularly increased with a reduction of the Landolt's ring size. Visual error relative number data of the school children group with the used light sources are presented in Table 1. As it can be seen from the Table 1, the highest number of errors when recognising optotypes was observed, when test tables were illuminated with the CLEDL lamp, and the lowest number was observed when using the

**Table 1. Number of erroneous answers (%) of the children's group (12–14 years old) when distinguishing Landolt's rings beginning from the sixth line of Golovin-Sivtsev's table (n = 44, M ± m, P < 0.05) ($V$ is visual acuity)**

| Table line | Lamp type | | |
|---|---|---|---|
| | IL | WLEDL | CLEDL |
| Line 6. $V = 0.6$ | 0.83 ± 0.047 | 1.25 ± 0.033 | 1.67 ± 0.041 |
| Line 7. $V = 0.7$ | 2.92 ± 0.068 | 2.08 ± 0.051 | 3.33 ± 0.061 |
| Line 8. $V = 0.8$ | 4.64 ± 0.093 | 3.57 ± 0.060 | 6.43 ± 0.077 |
| Line 9. $V = 0.9$ | 5.71 ± 0.130 | 4.29 ± 0.084 | 10.36 ± 0.243 |
| Line 10. $V = 1.0$ | 6.87 ± 0.179 | 7.19 ± 0.132 | 11.25 ± 0.163 |
| Line. $V = 1.5$ | 95.94 ± 0.882 | 96.25 ± 0.856 | 96.56 ± 0.855 |
| Line. $V = 2.0$ | 100.00 ± 0.983 | 100.00 ± 0.978 | 100.00 ± 0.977 |

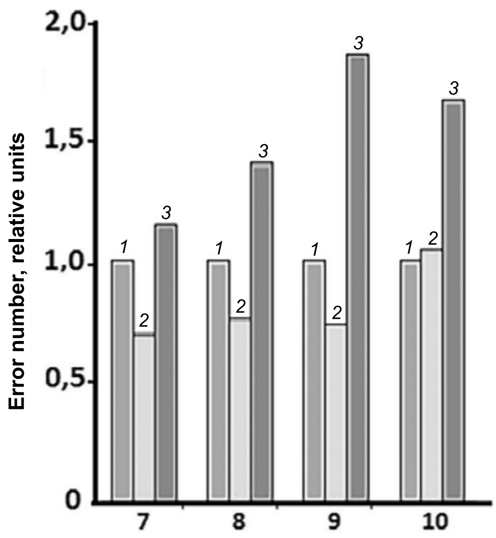


Fig. 2. Number of errors distribution diagrams when distinguishing optotypes for children (12–14 years old) depending on light source type normalised relative to the indications in the IL event.
First columns are IL, second columns are WLEDL, third columns are SDLH. Figures under the diagrams are line numbers of Golovin-Sivtsev's table

WLEDL lamp. In the IL case, the results were slightly lower than in the WLEDL case. These differences are shown more vividly in Fig. 2.

As a whole, the data presented in the Table and on the diagrams suggest that at the children's age, sources of warm white light allow solving visual tasks of recognizing black-and-white images on paper one and a half or even two times better.

The same experiments performed with the students' group (22–24 years old) did not reveal any noticeable dependence of visual distinction from spectral characteristics of the lamps used. Results of these measurements are presented in Table 2.

As it can be seen from Table 2, amongst younger adults (22–24 year old), irrespective of Landolt's ring size and of light source spectral composition, visual distinction errors are minimum and have a random nature.

## 4. DISCUSSION

The main result of the performed research is to reveal of a dependence of the black-and-white paper carrier image distinction and recognition by school age children from artificial illumination spectral composition. According to the obtained data, the highest number of errors in optotype distinction occurred when using the CLEDL. It was approximately 1.5–2 times greater than when using warm white light sources. And the IL showed almost the same ophthalmology – ergonomic indications, though slightly worse than the WLEDL. A probable reason for these differences is a different focusing of dark blue, yellow and red radiations on the eye grounds structures due to chromatic aberration of an eye. So according to the known dependences [4], dark blue peak of 450 nm wave length is defocused by 1–1.5 diopters relative to the yellow-orange radiation of 580 nm wave length. For the red spectrum, the same defocusing amounts to about 0.3 diopters. Therefore, it can be expected that of the used light sources, yellow-orange WLEDL radiation provides the best focusing of the image on eye grounds. The IL, with its radiation prevailing in the red spectrum interval, should be slightly behind when comparing with the WLEDL. And finally, CLEDLs with their superfluous dark blue radiation form the least focused dual blue-yellow image with indistinct gap designation in a Landolt's ring. One more reason for the low results regarding an eye resolution with CLEDL light can be the highest eye optical medium light scatter in the dark blue spectrum smearing image contours on the retina. Under real conditions of a classroom-based illumination with Illuminance of about 400 lx,

**Table 2. Number of erroneous answers (%) of the students' group (22–24 years old) when distinguishing Landolt's rings beginning from the sixth line of Golovin-Sivtsev's table (n = 29, M ± m, P < 0.05) (*V* is visual acuity)**

| Table line | Lamp type | | |
|---|---|---|---|
| | IL | WLEDL | CLEDL |
| Line10. $V = 1.0$ | 0.12 ± 0.03 | 0.12 ± 0.03 | 0.09 ± 0.03 |
| Line 11. $V = 1.5$ | 0.45 ± 0.09 | 0.33 ± 0.07 | 0.35 ± 0.07 |
| Line 12. $V = 2.0$ | 0.88 ± 0.15 | 0.85 ± 0.14 | 0.84 ± 0.14 |

i.e. with dilated pupils, chromatic aberration and light scattering effects can be of a measurable level. In case of children's sight, spurious optical effects of the dark blue spectrum appear to be more notable owing to a raised transparency of children's crystalline lenses in the dark blue spectrum, as well as due to a wider interval of pupil reactions of children's eyes. Quantitative dependences of an eye distinctive ability, which we have obtained, from light sources spectral composition can seem to be insignificant, however it must be noted that during long visual working tasks, they can affect the work accuracy and sight fatigue resistance. The differences between the data obtained with IL and WLEDL illumination of the same $T_{cc}$, but various radiation spectra, once again say that $T_{cc}$ of a light source cannot be an ophthalmology ergonomic characteristic of the light source. The experience of this study testifies that light source spectra analysis in conjunction with the known fundamental mechanisms of physiological optics allows making a preliminary estimation of the health impacts of different light sources. A methodical approach proposed by the study may be applicable to mass inspection of sight state in educational institutions. It should be noted that visual work without errors is a basis of educational material perception and of stability against fatigue development of the visual analyzer as a whole.

## 5. CONCLUSION

As a whole, the obtained data show that the most effective light source for visual distinction from the ones tested was the warm-white light emitting diode lamps. Further development and comparative research of other types of light sources and their effect on the resolution of children's eyes is needed.

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## REFERENCES

1. Zak P.P, Ostrovsky M.A. A potential danger of light emitting diode illumination for eyes of children and teenagers // Svetotekhnika. 2012,, #3, pp.4–6.

2. Zak P.P, Trofimova N.N. Dependences of visual functions from spectral composition illumination in comparison with characteristics of white light emitting diodes // Svetotekhnika, 2012, #5–6, pp. 31–34.

3. Zakgeim A.L. Light-emitting diode illumination system: energy efficiency, visual perception, safety for health (a review) // Svetotekhnika, 2012, #3, pp. 12–21.

4. Hartrige G. Modern successes of sight physiology. Moscow: IL, 1952, 328 p.

5. Behar-Cohen, F. et al. Light-emitting diodes (LED) for domestic lighting: Any risks for the eye? // Progress in Retinal and Eye Research. 2011, V. 30, pp. 239–257.

6. Foulds, W., Barathi, V., Luu, D. Progressive myopia or hyperopia can be induced in chicks and reversed by manipulation of the chromaticity of ambient light // Investigative Ophthalmology & Visual Science. December 2013, V.54, pp. 8004–8012. doi:10.1167/iovs.13–12476

7. Liu, R. et al. The Effects of Monochromatic Illumination on Early Eye Development in Rhesus Monkeys // Investigative Ophthalmology & Visual Science. March 2014, V.55, pp. 1901–1909. doi:10.1167/iovs.13–12276.

8. Qian, Y-F. et al. Transfer from blue light or green light to white light partially reverses changes in ocular refraction and anatomy of developing guinea pigs // Journal of Vision. September 2013, V.13, pp. 16. doi:10.1167/13.11.16.

9. International standard. ISO 8597. Optics and Optical Instruments – Visual acuity testing. Geneve, 1994.

***Alla A. Ryabtseva,***
Doctor of medical sciences, professor, Honoured Doctor of the Russian Federation. An ophthalmologist, the Head of the Ophthalmologic Department of the MONIKI of M.F. Vladimirsky, the Main ophthalmologist of Moscow Region and of the central federal district of Russia, a member of editorial councils of the Russian ophthalmologic journal, the Russian pediatric ophthalmology and of the Almanac of clinical medicine

***Anna S. Andryukhina,***
graduated from the Russian National Research University of N.I. Pirogov (2016). An ophthalmologist, doctor-intern of the MONIKI of M.F. Vladimirsky

***Alina A. Kovrizhkina,***
graduated from the medical department of the State Classical Academy of Majmonid (2014). An ophthalmologist, junior research worker of the MONIKI of M.F. Vladimirsky

***Victoria A. Lapina,***
Ph.D. A biophysicist, leading researcher of the Physics Institute of B.I. Stepanov of the National Academy of Sciences of Belarus, a winner of the State Prize of the RB of 2000 for a cycle of works "Mechanisms, of development, methods of treatment of glaucoma, cataract, photodamages of an eye retina"

***Natalia N. Trofimova,***
Ph.D., biophysicist, at present, she is the fellow of the Institute of Biochemical Physics of N.M. Emanuel of the Russian Academy of Sciences

***Pavel Zak,***
Prof., Doctor of biology Sciences, a biophysicist, conducting research of the Institute of Biochemical Physics of N.M. Emanuel of the Russian Academy of Sciences, a winner of the State Prize of the Russian Federation of 2006 for "The Scientific substantiation, development and introduction in the ophthalmologic practice of artificial crystalline lenses with a natural spectral characteristics", an associate editor of the Light and Engineering journal and of "The sensor systems"

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# DEVELOPING A DYNAMICALLY CONTROLLED LIGHT EMITTING DIODE ILLUMINATION SYSTEM WITH A WIDE INTERVAL OF CORRELATED COLOUR TEMPERATURES, $T_{cc}$ = (2800 ÷ 10000) K, AND A HIGH COLOUR RENDITION INDEX, $R_a$ > 90

Andrey V. Aladov[1], Sergey B. Biryuchinsky[2], Vladimir P. Valyukhov[3], Alexander L. Zakgeim[1], Nadezhda A. Talnishnikh[1], and Anton E. Chernykov[1]

*[1]The Scientific-Technological Centre of Microelectronics and Submicronic Heterostructures of the Russian Academy of Sciences Federal State Budgetary Science Enterprise*
*[2]LLC "Optical-mechanical systems"*
*[3]The St.-Petersburg State Polytechnic University of Peter the Great Federal State Budgetary Educational Enterprise*
*E-mail: zakgeim@mail.ioffe.ru*

## ABSTRACT

The article describes the theoretical basis, structure and technology, circuitry and programming aspects of creating a dynamically controlled light emitting diode system of a high-quality illumination in a wide interval of correlated colour temperatures $T_{cc}$ equal to (2800 ÷10000) K. To provide high colour rendition indices, the basis of the light emitting diode source should be a set of five-colour light-emitting diode matrices: red, dark blue, green, warm white and cold white. The last two components are phosphor light emitting diodes, which create the basic luminous flux. The first three are semiconductor monochromatic light emitting diodes, which provide a smooth adjustment of chromatic temperature in a wide interval and maintenance of high values of all special colour rendition indices $R_1 - R_{14}$. Power supply to the light emitting diode matrices is carried out in a pulse-width modulation mode, selecting the most efficient amplitude current for each type of light emitting diode, and assigning the required light intensity by modulating the supply current pulse duration. A standby (sleeping) mode is provided, with minimum power consumption. The optical system provides uniform colour mixing and spatial distribution of radiation, which is optimal for the illumination conditions. The software, remote control panel and radio channel remote control system allow controlling up to 30 illumination sources within a radius of 35 m setting any time intensity and illumination chromatic temperature algorithms.

The developed dynamically controlled light emitting diode illumination system is intended for various applications: general illumination of large-scale industrial objects (shops, depots, operational halls) and autonomous objects with creating an optimum light environment for work of personnel, as well as for special application, for example, medical illumination (surgery, diagnostics), museums, for architectural and decorative local illumination, etc.

**Keywords:** light emitting diode (LED), LED illumination system, colour mixing, colour rendition index, correlated colour temperature ($T_{cc}$), dynamically controlled light sources, remote control, wireless networks

## 1. INTRODUCTION

One of noticeable trends in light emitting diode (LED) illumination during the last years has been the shifting of interest from pure quantity indicators (luminance efficacy, luminous flux) to quality of the generated light. The success achieved in increasing LED efficiency based on quantum-size *AlInGaN* heterostructures is impressive: record efficiency values of dark blue LEDs, which are the basis of phosphor white LEDs, reached 84 %, crucially for real-life application, the efficiency remains high in a wide interval of current density and temperatures [1]. For white LEDs (laboratory specimens), Cree Inc. Company showed a luminance efficacy level (LE) of 303 lm/W [2], which is close to the theoretical limit, and serial device levels came near to 200 lm/W [3, 4]. The values are indicative of highly sophisticated structures and manufacturing technology of white LEDs based on dark blue *AlInGaN* radiating crystals with a radiation phosphor transformation. For context, ten years ago optimistic forecasts for LED luminous efficacy amounted to (80–100) lm/W. In this new environment, where world leading manufacturers like Nichia, Cree, Philips, Lumileds, Osram, and others have achieved a very high and similar luminance efficacy levels, competition has shifted to quality factors of the generated light. For the purposes of illumination, this involves primarily the ability to provide a wide interval of correlated colour temperatures $T_{cc}$ = (2800 ÷ 6500) K with high values of colour rendition [5]. According to modern requirements for a high quality illumination, general colour rendition index $R_a$ should be no less than 95, and special colour rendition indices for saturated colours $R_8 - R_{14}$, should be at least 85 [6].

Finally, a new quality factor, which might be the most important for LED illumination quality, is its controllability, i.e. the possibility to change spectral-colour parameters during operation. This feature, often designated as intelligent, adjusted, or personified light, is implemented in LED sources based on the polychrome matrices operation based on the colour mixing (RGB) principle. The spectral (or colour) controllability significantly expands functionality of light sources, providing solutions to many lighting problems, including the most widespread: artificial illumination. The degree of controllability can be different: from time variation within a certain chromatic temperature interval to reproduction of a natural wide colour range, including millions of chromatic shades [7, 8].

In order to stay competitive in the modern LED illumination market, a comprehensive perfection of LED illumination sources is necessary. Moreover, there is a need for transition from single sources to illumination systems as a whole, which allows combining high energy characteristics and high quality of light with a convenience and operational simplicity, illumination network remote control, reliability and a long life time. Creating effective, intelligent LED illumination systems involves at least the following aspects:

• Simulation and experimental research of colour mixing processes, substantiation of an optimal selection of initial LEDs according to radiation spectra to obtain white light with a set chromatic temperature, lumen-equivalent, colour rendition indices, or colour light determined by specific applications;

• Structural and technological aspect, which is the most large-scale and multifaceted: a development of LED technology and structure of polychrome multicrystal modules, secondary optics, electric interconnection, heat removal and so forth;

• Development of electronic units of standby and operation power supply, units of radiation mode designation by spectral-colour composition and intensity according to the set algorithms using pulse-width modulation, drivers directly providing LED matrix power supply, as well as wireless circuit elements: receive/transmit remote control modules using a radio channel from the remote-control panel or personal computer;

Fig. 1. General view of polychrome operated LS LEDDCIS with a control panel

• Development of software to carry out selection, setting and control of illumination modes, as well as of wireless network operation.

Approaches to solving these tasks are considered below as exemplified by the development of a LED dynamically controlled illumination system (LEDDCIS) fulfilled by the Scientific and Technological Centre of Microelectronics of the Russian Academy of Sciences according to State contracts together with the Ministry of Education and Science of the Russian Federation.

## 2. THE MAIN TECHNICAL DATA FOR THE LEDDCIS

The LEDDCIS should primarily provide a controllable light environment, optimal for the vital functions of a person in domestic and work rooms, including the following:

• To simulate illumination with a smooth change of chromatic temperature following the natural day cycle with its biological circadian rhythms in rooms without windows and consequently without natural light;

• To create special illumination conditions for personnel working under significant psychological and physical workload (air traffic controllers, control centre operators, crews of autonomous objects: submarines, spaceships, etc.) These conditions promote either an increase of working capacity and attention span, or fast relaxation and remediation of nervous stress during work breaks.

Other LEDDCIS applications are adjustable museum illumination for the best reproduction of all colour painting pallet and forming a comfortable light medium for perception of art object, as well as a special medical illumination for diagnostics and contrast revealing of healthy and damages tissue, etc.

For the specified purposes, the LEDDCIS including up to 30 separate light sources (LS), reproduces white light with the set spectral-colour and luminance characteristics, which can change in time according to a set program. In doing so, a wide interval of correlated colour temperatures (2800 ÷ 10000) K with discrete selection of no more than 200 K is provided. The main colour rendition index $R_a$ value is supported at no less, than 85, special colour rendition indices $R_{1}$–$_{14}$ are no less, than 70 within all chromatic temperature intervals. Maximum luminous flux radiated by the LS is no less than 3000 lm with possible weakening of 10 % from the maximum value, and a radiation angle by 0.5 level of not less, than $120^0$.

Radiation parameter control is carried out remotely using a radio channel from a remote control panel (RCP) or by means of a personal computer (PC). In this case, three operating modes are provided:

• Switched off: 220 V circuit is disconnected;

• Standby mode (sleeping): 220 V power supply is switched on, light is switched off;

• Operation mode: work in a mode, which supports the set requirements to the chromatic (colorimetric) and light (photometric) characteristics.

Power consumption of a separate LS from the power supply doesn't exceed 40 W in the operation mode, which allows avoiding a corrector of power factor. In the standby mode, power consumption doesn't exceed 0.5 W.

The LEDDCIS RCP provides the following features: keeping LEDDCIS operation modes in the inner memory; selecting programs and operation time by the user by means of RCP buttons; control of the LEDDCIS operation; synchronising operation of several LEDDCISs; connecting the operation mode to a real time (time of day); LEDDCIS control (a smooth change of the spectrum within a day with a possibility to repeat the cycle later) using a radio channel at a distance of to 35 meters. A brachigerous LEDDCIS circuit is a local radio network: the devices of a small operating range are used to replace physical cables in local networks of data transmission within a building or room.

The LS radiating LED module includes polychrome LED matrices, an optical system of forming luminous flux and electronic units: power supply, a microcontroller with control unit and LED matrix power supply drivers with adjustable luminous flux using pulse-width modulation (PWM) by the microcontroller program. The interval of PWM relative pulse duration adjustment is from 0 to 100 % with a step of 0.1 %. The microcontroller provides control command receiving from the RCP or from the PC, control of light characteristics and control of light emitting diode board temperature. A more detailed consideration of separate units will be given below. A general view of a separate LS LEDDCIS with the control panel is shown in Fig. 1.

## 3. POLYCHROME LIGHT EMITTING DIODE MATRICES: OPTIMISATION OF COLOUR MIXING TO OBTAIN HIGH QUALITY WHITE LIGHT

Colour mixing optimisation to obtain white light with a set chromatic temperature and an optimum compromise concerning the ratio; luminance efficacy – colour rendition index as applied to LEDs for the last 10–15 years were studied in detail both theoretically and experimentally [9–12]. The reviewed research results can be summarised as follows: with a typical halfwidth of monochromatic semiconductor radiator spectra of $\Delta\lambda_{0.5}$ ~ 15–40 nm, obtaining white light with a high general colour rendition index value $R_a$ ~ 90, requires radiation addition of 4–5 semiconductor radiators with peak wave length $\lambda_{peak}$, which are comparatively uniformly distributed in the visible interval. A further, more persistent absolutely black body (ABB) spectrum filling due to LED number increase, adds little to $R_a$ value but leads to substantial losses of luminance efficacy and to the system complication. At the same time, even a small deviation of the separate LED peak wave length $\lambda_{peak}$ from optimum values can lead to an abrupt decrease of separate colour rendition indices, especially $R_8 - R_{14}$, which are classified as saturated colours. Use of phosphor LEDs with a wider spectrum $\Delta\lambda_{0.5}$ ~70–100 nm for colour mixing, naturally facilitates the problem.

To solve the task of mixing semiconductor and phosphor LED spectra, we used a numerical model, developed by SOFT-IMPAKT Open Company. This model makes it possible to find an optimum according to a specially set objective function when varying a great number of mixing parameters [12]. As a result of the variation, a full combined light source spectrum can be found and its analysis can be done, that is, spectrum chromatic co-ordinates $x$, $y$, correlated colour temperature $T_{cc}$, general and special colour rendition indices $R_1 - R_{14}$, as well as radiation lumen-equivalent are determined. The model allows forming a multi-parameter objective function and optimising white light with a set correlated colour temperature either by full colour rendition index, or by lumen-equivalent value.

Using computer simulation results, we selected five LED matrix radiators for experimental research to synthesise high quality white light in the interval $T_{cc}$ = (2800 ÷ 10000) K. Here through slash, experimental values of $\lambda_{peak}$ and $\Delta\lambda_{0.5}$ are specified. Two phosphor LEDs of warm and cold light with $T_{cc}$ = 2800 K and $T_{cc}$ = 8000 K respectively were added. The selected initial LED spectral distribution view is given in Fig. 2. In the experiments on synthesis of the set chromatic temperatures, first LED optical powers obtained by the simulation results (optimisation by $R_a$ maximum) were set. And then, with a direct visual control of colorimetric characteristics using the OL 770-LED High-speed LED Test and Measurement System device, an individual adjustment of radiator powers by PWM was performed until the best coincidence with ABB locus for this chromatic temperature.

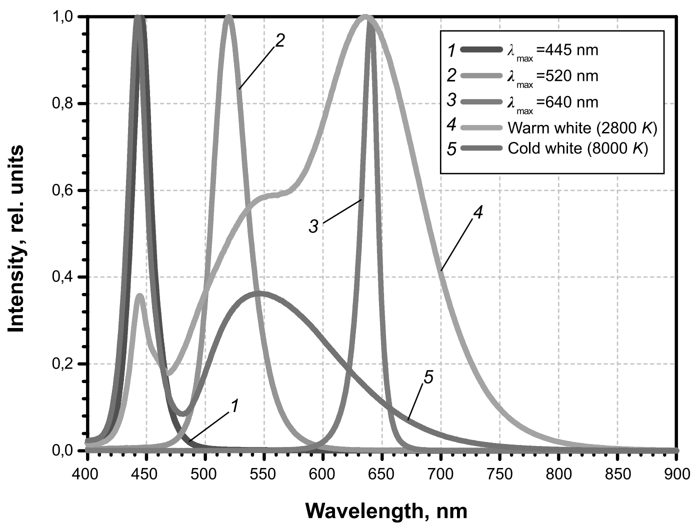


Fig. 2. Spectral distributions of three monochromatic and two phosphor LEDs used as bases for colour mixing

Experimental research together with the simulation show that the selected basic LEDs allow synthesizing high quality white light in a wide interval of $T_{cc}$ = (2800 ÷ 10000) K. Fig. 3 (a and b) shows the correspondent spectral distributions, values of the main $R_a$, and of special colour rendition indices $R_i$. It would be noted that for all chromatic temperatures, the main contribution to general luminous flux is brought by phosphor LEDs. Monochromatic LEDs of dark blue, green and red colour play a correcting role to "pull" special private colour rendition indices. As it can be seen from Fig. 3 b in the warm neu-

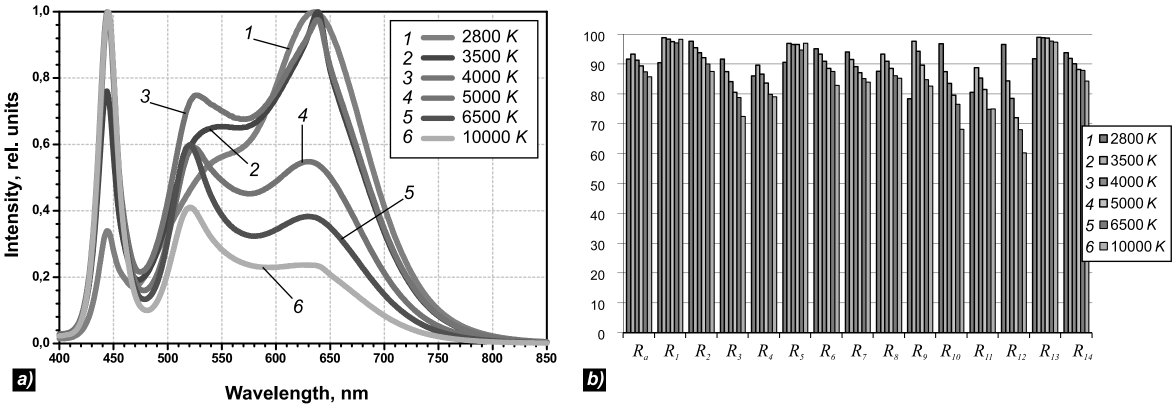


Fig. 3. Spectral distributions (a) and colour rendition indices values $R_a$, $R_i$ (b) for a set of white light sources with $T_{cc}$ = 2800 K, 3500 K, 4000 K, 5000 K, 6500 K and 10000 K

tral white light interval (2800 ÷ 5000) K, a situation takes place, when $R_a \geqslant 90$, and all special indices $R_i \geqslant 80$. Some special indices $R_1$, $R_5$, $R_{13}$ come near to 100. High values of special indices $R_9$, $R_{13}$, which reach 95–98, is especially important. They aren't taken into consideration when calculating $R_a$ but they play an important role for correct colour reproduction of biological tissues and skin. For very cold white shades of (6500 ÷ 10000) K only, which are rarely used for illumination, $R_a$ decrease to a level of 85–87 takes place, and separate special indexes $R_{10}$, $R_{12}$ decrease to 60–65.

## 4. STRUCTURAL AND TECHNOLOGICAL SOLUTIONS AND AN LS OPTICAL LAYOUT BASED ON POLYCHROME LED MODULES FOR LEDDCIS

The developed LEDDCIS can unite up to 30 LSs under one general control system. The primary goals of creating the separate LS are reduced to the following:

• Selection of the LED element basis, design of a multi-element module with a set radiator location with individual electric switching and effective heat removal;

• Development of an optical system providing a high transmission coefficient, set luminous intensity distribution in space, uniformity of chromatic parameters over the LS area and over distant areas;

• Development of a control circuit and electronic units including power supplies, a microprocessor, drivers, feedback detectors, a control data transmission radio channel, a control panel or personal computer and software.

The general structure of the LS is shown in Fig. 4. A key LS element is the polychrome module (a LED board with secondary optics, ***2***). Spectral characteristics of the LEDs forming the module were determined in the previous section. Further, it was necessary to select LEDs corresponding to them with a maximum luminous efficacy and maximum luminous flux. The modern LED industry (foreign) proposes a wide range of (3–4)-colours and white powerful LEDs as elements for polychrome sources.

By virtue of meeting multiple feature requirement (functional, structural, resource), we selected four-chip LEDs of Osram Opto Semiconductors Company: LE RTDUW S2W (R-G-B-$W_{(cold)}$) and **LECWUWS2W** ($W_{(cold)}$ –$W_{(warm)}$) [13]. The LS was made up of nine powerful four-chip LEDs, four of which were of R-G-B-$W_{(cold)}$ type and five were of $W_{(cold)}$ – $W_{(warm)}$ type. Such composition provides the best combination of limit luminous fluxes when varying spectral-colour characteristics. The LEDs were fastened on radiator Al supplied with fan ***3***. During the research, the LED active area temperature was measured using T3Ster and Ledmeter devices by temperature-dependent characteristics (for-

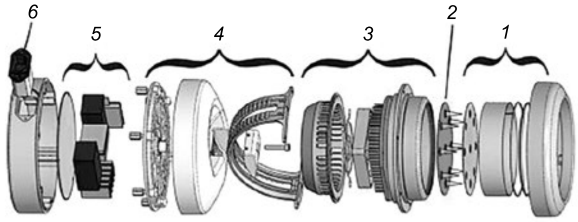


Fig. 4. A schematic view of LS main units. ***1*** – optical system, ***2*** – light-emitting diode module, ***3*** – radiator with a fan, ***4*** – case base with a rotary mechanism, ***5*** – electronic power supply and control unit, ***6*** – network filter

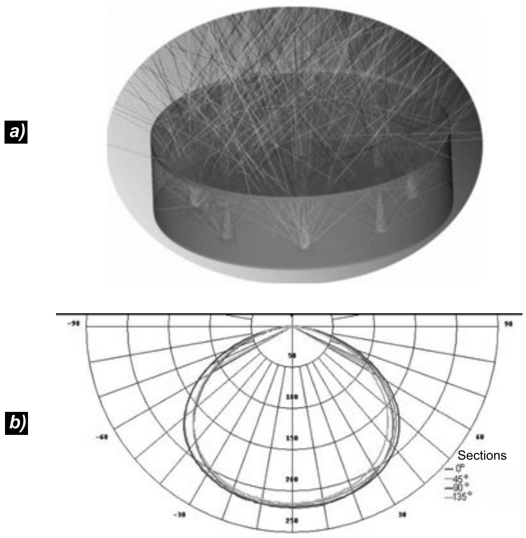


Fig.5. Simulation of optical system using the ray tracing method (a) and the graphic of spatial radiation distribution (b)

ward voltage), and the general temperature field over the LED module radiator board area was measured by means of the Svit IR thermal imaging device (Institute of semiconductor physics of the Siberian Branch of the Russian Academy of Science). As the thermal parameter analysis showed, in the most intense modes of operation, initial heating of the LED active area does not exceed $95^0$C (thermal resistance of separate LEDs $R_{th}$ is equal to about (4–5) K/W), and initial heating non-uniformity over the board is not more than 10 %. To maintain the thermal mode, the radiator board is supplied with a temperature detector switching fan ***3*** on.

LS optical system ***1*** should provide a high radiation transmission coefficient from the LEDs to the output window, a set spatial radiation distribution, as well as a colour uniformity within the distant and near fields that demonstrates good radiation mixing of separate LEDs. Calculations and optimisation of the optical circuit were made according to the optimum optical system architecture theory. Special optics to support reaching these requirements was supplied.

The first easily evident solution was to add a lateral reflector onto the inner surface of the LS case between the LED board and the output window. As the calculations show, this reflector increases output luminous flux by 20 %. The geometry of the secondary lens was further analysed in order to achieve an optimum ratio of the luminous flux and of the spatial-colour characteristics for the selected LEDs. Finally, a conic optical element, comparatively simple to manufacture, was selected. Ratios of the cone height to the diameter of its basis providing a compromise between the radiation output coefficient, colour mixing and uniform (without dips) directional pattern were computed.

The gain in light transmission efficiency was due to the conic optical element and lateral reflector, and made it possible to introduce an additional diffuser with insignificant optical losses and with a specific profile into the optical circuit, which significantly improves uniformity of light and chromatic distribution. The last optical element for increased light transmission was the introduction of a back diffuse reflector into the LED plane to fill the area between the radiators. The resulting optical system, in which all the listed elements were united in Fig. 4 by figure ***1,*** is optimal because it solves problems of a uniform and wide angular distribution, as well as of homogenization of chromatic characteristics over the radiating surface area and over the angle. Fig. 5 a illustrates the ray tracing method used in the calculation process, and Fig. 5 b shows a luminosity body in four sections: $0^0$, $45^0$, $90^0$ and 135 degrees. As it can be seen from Fig. 5 b, the spatial distribution is axisymmetric, with the halfwidth of the directional pattern $\Delta\theta_{0.5}$ at about 125°. The radiation module itself is located on a rotary device fastening to the LS case basis ***4,*** in which the electronic unit ***5*** is located. It includes sources of operation and standby power supply, receive/transmit modules of the RCP information interchange using a wireless communication channel, circuits of the microcontroller and drivers setting LED operation modes and accordingly, output characteristics. Input network filter ***6*** is placed directly at the converter input. Operation principles and electronic unit composition are considered in more detail in the next section.

## 5. FUNCTIONAL ELECTRIC CIRCUIT AND ITS FEATURES

The LS functional electric circuit is shown in Fig. 6. In case ***1***, input network filter (NF) ***2***, two converters connected in parallel with the NF (alternating current into direct current (AC-DC)) ***3*** are placed. They form the main power supply unit (PSU) as two components БП-1 and БП-2.

The LEDs form five chromatic groups (lines of radiators connected in series): ***4, 5, 6, 7, 8***, accordingly, **R, G, B, W $_{\mathbf{(cold)}}$** and **W $_{\mathbf{(warm)}}$** placed on the basis ***9*** and connected to five driver units (ДР1, ДР2, ДР3, ДР4, ДР5) ***10*** controlling light radiation power of each LED group. At the same place on the board, microcontroller (MC) ***11*** and power supply unit of the standby mode (SMPS) ***12*** are placed.

Output of the first БП-1***3*** is connected to the first inputs of two units ***10*** (ДР1, ДР2), and output of the second БП-2***3*** is connected to the first inputs of three other units ***10*** (ДР3, ДР4, ДР-5). The second inputs of units ***10*** (ДР1, ДР2, ДР3, ДР4, ДР5) are connected in order to the first, second, third, fourth and fifth outputs of control microcontroller ***11***. The LS radiation parameter control can be carried out by the signals sent to MC input ***11*** from PC1***3*** or via a radio channel from the RCP. The LS contains a temperature detector (TD) ***14*** placed on the basis ***9***, and fan (F) ***15*** installed under basis (***9***,). TD in this case is connected with MC input ***11,*** the output of which is connected with (F) ***15***.

An original solution is adding to the circuit two alternating current to direct current converters, each of which has rated power $P_{rp} = P_{inp}/2$. They form channels working independently from each other. A statistical independence of this alternating current to direct current converters causes uncorrelated electromagnetic inducings and noises, as well as inner noises, the total values of which appear to be less than the values of electromagnetic inducings, noises and inner noises of the $P_{inp}$ converter. Besides, application of two parallel half-power converters in the lighting device instead of one converter of alternating current to direct current, allows significantly reducing the occupied space. Following this reduction, there is a possibility to place an input network filter directly at the converter input, which also favourably influences the degree of industrial noises created by the lighting device because of a decrease of the connecting wire length between the input network filter and the converters.

Transformation of the power supply direct voltage into the LED current is made by drivers with adjustment of luminous flux by pulse-width modulation (PWM) according to the microcontroller program. The relative adjustment interval of the PWM pulse duration is from 0 to 100 % with a step

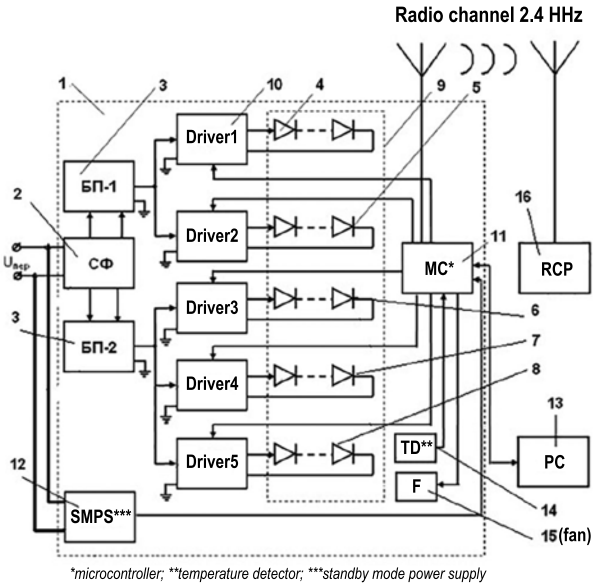


Fig. 6. A functional LS electric circuit

of 0.1 %. The microcontroller provides receiving control commands from the RCP or from PC, control of the light characteristics and temperature control of the LED board. The power consumption of one LS doesn't exceed 40 W in the operation mode. This allows operation without a power factor corrector. In the standby mode, power consumption doesn't exceed 0.5 W.

For LED control, raising pulse driver MAX16834 was selected, and luminous flux change was made using PWM with current up to 1500 mA.

RCP power supply is carried out from a power line with power consumption no more than 5 W in the programming mode, and power consumption in the operation mode is 0.5 W.

As LEDDCIS network control using RCP is carried out in the round-the-clock operating mode, power consumption reduction in the standby mode is important. The problem is solved by developing a power supply unit for the transmitter with a microcontroller both for RCP, and for LS. The latter consumes (60 ÷ 80) mW in the receiving mode and (1 ÷ 5) μW in the standby mode.

## 6. WIRELESS NETWORK AND ITS SOFTWARE

When creating the LEDDCIS network, which forms the LR-WPAN device (Low-Rate Wireless Personal Area Network), the main problem is transmission of comparatively small amounts of data across short distances with the network having minimal consumption when implementing monitoring and control for lighting tasks [14].

In the considered illumination system, the technology of network formation is based on IEEE802.15.4 standard and on its program superstructure ZigBee [15,16], which describe different levels of the open system interaction classical structure.

A low signal/noise relation allows the standard signals to successfully co-existing with alternative radiation sources at the same frequency (Wi-Fi, Bluetooth). The standard also provides for the channels, which aren't crossed by frequency with the competitors, and this makes it possible to form a network even in the immediate proximity of very powerful radiation sources. The data transmission model is determined by network topology; for our case it is the star [2] (Fig.7).

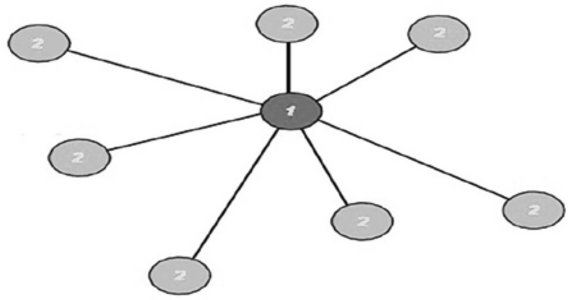

Fig.7. An optimum configuration of the LEDDCIS network – (the star):
***1*** – network coordinator, ***2*** – terminals

In any network, there should be only one network coordinator, which performs functions of its creation and arrangement exchange. In the LEDDCIS network, three versions of composition (arrangement) are implemented:

• Version 1 includes a computer as the network coordinator and the RCP as the terminal. This network is useful for adjustment, testing and loading control programs into the RCP.

• Version 2 includes a computer as the network coordinator (instead of the RCP) and the LS as terminals. Version 2 is intended to adjust and test the LEDDCIS, as well as to control illumination, when a long (round-the-clock) cycle is not required. An advantage of this approach is the simplicity with which the operating mode can be changed. Its disadvantages are: raised power consumption, complexity of standby mode creation, complexity of automatic computer reboot in emergencies (and additionally an increased time of reboot for the operating system and program).

• Version 3 includes the RCP as the network coordinator. It is intended to control illumination with a short and long (round-the-clock) cycle.

• A more complex input of the illumination control program is inherent to this version but its advantage is the possibility of the round-the-clock mode, minimum energy consumption by the whole system in the standby mode (when illumination is switched off) and a fast illumination recovery in emergency situations.

The RCP is made as a unit, which can be inserted into a power supply socket. It has a colour TFT indicator (diagonal size is 3.5") and a keyboard consisting of six buttons. The RCP provides a discrete assignment of the set chromatic temperatures, of light emitting diodes in each line of luminance, as well as mode and mode change for time of day. The microcontroller contains a quartz watch.

The RCP provides a variety of functions: storage of LS operating modes in the inner memory, choice of the programs and operation time by the user using RCP buttons, LEDDCIS operation control, synchronisation of several LEDDCIS, linking an operation mode with real time (time of a day), LEDDCIS control by a radio channel (a smooth spectrum change within a day with a possibility to repeat the cycle).

The RCP provides LS control at a distance up to 35 m. Wireless network data transmission range is determined by the receiver sensitivity, transmitter power and depends on noises (obstacles, including the walls and other sources of radio signals). The speed of data transmission is from 250 kb/s to 2.0 Mb/s, channel number is 16 with a pace of 5 MHz.

The network software is a set of programs, which allows the following operation modes:

• Control of a branched LEDDCIS network by means of RCP using a radio channel in a round-the-clock energy saving mode;

• Programming a unique factory address at RCP and LEDDCIS manufacture stages for each device to form a network while in service;

• LEDDCIS testing and network adjustment using a personal computer. In this case, the RCP is replaced with a PC USB adapter;

• Programming operation modes and program installation into RCP with PC connection through the adapter.

The software also provides for emergency switching-off in case the radiator temperature is exceeded because of the service conditions, and for adjusting fan rotation speed, if needed.

## 7. CONCLUSION

The article has presented the results of a comprehensive development of a dynamically controlled LED illumination system, which includes up to 30 sources controlled using a radio channel from the single panel or a personal computer. Structural and technological aspects of creating dynamically controlled semiconductor light sources, as well as circuit solutions for electronic control units and their software, have been described. It has been possible to achieve a high quality of illumination with main and special colour rendition indices of about 90 in a wide interval of correlated colour temperatures (2800 ÷ 10000) K and illuminance levels. The developed illumination system allows in accordance with the set algorithms, changing chromatic characteristics and illuminance level during a day either simulating natural light, or creating special illumination conditions suited for different functions. The system is mainly developed for industrial use: shops, depot, operational halls, autonomous objects without natural light. However, it can be also used in other premises, individually adjusting light favourable to the occupants.

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## REFERENCES:

1. Hurni Ch.A., David A., Krames M.R., et al. "Bulk GaN flip-chip violet light-emitting diodes with optimized efficiency for high-power operation". Applied Physics Letters, 2015, V.106, #3, ID1101.

2. Cree: First to Break 300 Lumens-Per-Watt Barrier, URLhttp://cree.com/News-and-Events/Cree-News/Press-Releases/2014/March/300LPW-LED-barrier (Addressing date: 06.2016).

3. Cree's MK-R LED Offers up to 200 Lumen-Per-Watt. LED professional Review 35, 2013, 6.

4. URL http://www.ledsmagazine.com/content/leds/en/articles/2014/05/cree-launches-200-lm-w-1226-lm-discrete-led-for-directional-ssl.html?cmpid=EnlLEDsMay282014 (Addressing date 06.2016)

5. Specifications for the Chromaticity of Solid State Lighting Products. ANSI/NEMA C78.377–2008.

6. LED Engin Achieves Highest Color Rendering in World's Smallest LED Emitters for High-End Directional Lighting. LED Professional Review LpR37 | May/June 2013, p.28. URL: www.led-professional.com/products/leds_led_modules/led-engin-achieves-highest-color-rendering-in-world2019s-smallest-led-emitters-for-high-end-directional-lighting]. (Addressing date: 06.2016).

7. Zakgeim A.L. "Light-emitting diode illumination systems: energy efficiency, visual perception, safety for health of a person". Svetotekhnika. 2012, #.6, pp.12–20.

8. Aladov A.V., Zakgeim A.L., Mizerov M.N. "Chernyakov A.E. Polychrome spectrally-reconstructed lighting devices with light emitting diodes: experience of development and application". Svetotekhnika, 2013, #5–6, pp.34–40.

9. Zukauskas A., Vaicekauskas R., Ivanauskas F., Gaska R., Shur M.S. "Optimization of white polychrome semiconductor lamps" // Appl. Phys. Lett. 2002, V.80, p.234.

S. Chhajed Y.Xi, Y. – L. Li, Th. Gessmann, E.F. Schubert. Influence of junction temperature on chromaticity and color-rendering properties of trichromatic white-light sources based on light-emitting diodes// J. Appl.Phys., 2005, V.97, #5, ID054506.

10. Ohno Y.. "Spectral design considerations for white LED colour rendering". Optical Engineering, 2005, V. 44, #11, ID111302.

11. Guttsait E.M., Zakgeim A.L., Kogan L.M., Maslov V.E., Soshchin N.P. "Concerning simulation of standard light sources by light-emitting diode modules". Svetotekhnika, 2013, #4, pp. 61–66.

12. Bulashevich K.A., Kulik A.V., Karpov S. Yu., Chernyakov A.E., Aladov A.V., Talnishnikh N.A., Zakgeim A.L. "Optimization of colour mixture for changeable solid-state light sources". Theses of a report of the 10th All-Russian conference, Gallium, indium and aluminium nitrides– structures and devices. S-Pb, 2015, p.12.

13. URLhttp://www.osram-os.com/osram_os/en/company/index.jsp (Addressing date 06.2016).

14. Aladov A.V., Valyukhov V. P, Zakgeim A.L., Chernyakov A.E., Tsatsulnikov A.F. Dynamically controlled light-emitting diode light sources for new illumination technologies // Scientific and technical sheets SPbPU. Physical and mathematical sciences, 2014, #4 (206), pp. 38–40.

15. Wireless networks ZigBee and IEEE802.15.4. Yu. Semenov (ITEP-IPT): http://book.itep.ru/4/41/zigbee.htm (Addressing date: 06.2016).

16. Aladov A.V., Valyukhov V.P., Demin S.V., Zakgeim A.L., Chernyakov A.E., Tsatsulnikov A.F. "Wireless networks of controlled energy-effective light-emitting diode illumination sources". Scientific and technical sheets SPbPU. Physical and mathematical sciences, 2015. #1 (213), pp. 50–60.

***Andrey V. Aladov***, graduated from the physics department of the Belarus State University in 1981. A senior fellow of the Scientific-Technological Centre of Microelectronics and Submicronic Heterostructures FSBUSE of the Russian Academy of Sciences

***Alexander L. Zakgeim***, Ph.D., graduated from the Leningrad Electrotechnical Institute of V.I. Ulyanov (Lenin) in 1972. At present, he is the Academic secretary and the laboratory chief of the Scientific-Technological Centre of Microelectronics and Submicronic Heterostructures FSBUSE of the Russian Academy of Sciences

***Sergey B. Biryuchinsky***, Ph.D., graduated from the St.-Petersburg State Institute of Fine Mechanics and Optics (technical university) in 1996. At present, he is the technical director of Optical-mechanical systems Open Company

***Nadezhda A. Talnishnikh***, graduated from the St.-Petersburg State Electrotechnical University (LETI) of V.I. Ulyanov (Lenin) in 2014. At present, she is a trainee researcher of the Scientific-Technological Centre of Microelectronics and Submicronic Heterostructures FSBUSE of the Russian Academy of Sciences

***Vladimir P. Valyukhov***, Prof., Doctor of Technical Science, graduated from the Leningrad Polytechnic Institute of M.I. Kalinin in 1963, lecturer of the St.-Petersburg State Polytechnic University of Peter the Great

***Anton E. Chernyakov***, Ph.D., graduated from the St.-Petersburg State Electrotechnical University (LETI) of V.I. Ulyanov (Lenin) in 2006. At present, he is the fellow of the Scientific-Technological Centre of Microelectronics and Submicronic Heterostructures FSBUSE of the Russian Academy of Sciences

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# ANALYSIS OF LIGHT POLLUTION FROM FLOODLIGHTING: IS THERE A DIFFERENT APPROACH TO FLOODLIGHTING?

Wojciech Żagan and Krzysztof Skarżyński

*Warsaw University of Technology, Institute of Electrical Power Technology, Lighting Technology Division*
*E-mails: wojciech.zagan@ien.pw.edu.pl, krzysztof.skarzynski@ien.pw.edu.pl*

## ABSTRACT

The research described in this article was inspired by a real floodlit object. The main distinctive feature is connected with the directionality of its lighting. The „Sezam" building was one of the first to be illuminated in the opposite way to the usual manner of floodlighting. The analysis, based on the measurement of horizontal illuminance on the pavement in front of the building and of the luminance on the facade, leads to some very unusual conclusions. It goes deeper than merely the assessment of the phenomenon of light pollution in the context of floodlighting. Additionally, a short survey about the preferences of lighting directionality in floodlighting and the general concept of light pollution was conducted on a group of over a dozen people. It turned out that people are quite aware of the phenomenon of light pollution and they rather prefer illumination from floodlighting to be from bottom to top.

**Keyword:** floodlighting, light pollution, obtrusive light, reversal of floodlighting

## 1. INTRODUCTION

Nowadays, light pollution has become more and more noticeable and is seen as a significant threat by many institutions and organizations. Its occurrence is connected with such adverse effects as sky glow, light trespass, light spill and the hindering of astronomical observations [1]. Different kinds of technical reports [2,3], standards and legal regulations, related to the control and reduction of this phenomenon, have recently been developed in all regions of the world. The protection of the environment from the negative effects of obtrusive light is described in relation to different approaches in different countries [4, 5]. A uniformity of action and response in this field has not yet been achieved. So far, the main reason for conducting various researches has been to find a proper calculation and measurement method to quantitatively characterise light pollution [6, 7, 8]. The literature describes this as one of the challenges of modern lighting technology, which researchers ought to manage in the near future [9, 10].

## 2. PROTECTION FROM OBTRUSIVE LIGHT EMITTED BY EXTERIOR LIGHTING INSTALLATION

The appearance of standard requirements, setting the limits of obtrusive light emitted by exterior lighting, were a long-awaited and much necessary legal act. In Poland, the contemporary applicable requirements can be summarised in the only table (Table 1) in the Polish Standard PN-EN12464–2 [11]. It is worth noting is that this is a direct translation from the European Standard EN12464–2 [12].

The environmental zones E1-E4 were defined in this Standard as areas that they refer to differ from each other by different levels of brightness of the luminous environment. The environmental zone E1 is characterising by the lowest level (e.g. national parks). At the same time, the environmental zone E4 is belonging to the highest level such as the centre of big cities. For each zone, maximum levels of average illuminance $E_v$ and luminance of the facades of buildings $L_b$ or luminance of signs $L_s$ are declared for the time of pre-curfew and post-curfew. Additionally, luminaire intensity *I* and the *ULR* parameter are taken into consideration. The comparison of these requirements to the practical approach of lighting design can be easily misunderstood. A lot of doubts and questions [13], as well as local interpretations [4, 5] of these seemingly universal lighting standards have been appeared. These differences arise from the attempt to apply such regulations to specific lighting situations, new projects and the evaluations of previously-made installations of exterior lighting. In addition, here are some of the most important questions, which need to be answered:

• Where penetrating light should be measured? It is obvious it should be measured on the surface of windows, but on which side? On the inner or on the outer side?

• Why have such big values of luminaire intensity been defined as the maximum in the case of potential intrusive directions? Though these values are referred to as the maximum, their luminous intensity is similar to the luminous intensity of a luminaire of quite large electrical power.

• What about the URL parameter? Does it relate to the case of the floodlighting of objects and does it take into account the fact that, in the majority of floodlit buildings, all of the luminaires are directed up to the sky (ULR=100 %)?

• Why is there no connection between the maximum average luminance of signs and the direction of observations?

• Why are such big values of luminance of signs defined as acceptable? These values are several times higher than the average luminance of most displays and screens, which, as we know, are effective advertisement carriers, even in photopic vision conditions.

Without any clarification of the details of the regulations, which are included in this standard, something remains unclear (or even confusing) for lighting designers. It consequently causes a lack of use of this standard in practice and what is more relevant it causes the situation to revert to situation, which existed before its publication.

## 3. OBTRUSIVE LIGHT DUE TO FLOODLIGHITNG

Exterior lighting equipment can cause the effect of obtrusive light and light pollution in many different ways [1, 14], especially in those devices, which are dedicated to floodlighting [15]. However, if the electrical power of these solutions is taken into consideration, it turns out that the scale of this phenomenon is rather small (e.g. in contrast to street lighting). Nevertheless, there is still niche for improvement in this area. If a light beam is not aimed properly (e.g. at a monument), it can reach the window of a residential house or hotel. In this situation, the emitted from the luminaire radiation penetrates the interior of the object and can interfere or cause some disturbance to residents or even hinder them from a restful sleep. If the light beam is also very narrow and is characterised by such a great value of luminous intensity that it is inconsistent with the applicable requirements of PN-EN12464–2, there is a high possibility of the occurrence of glare and, because of this, a resident could be blinded.

Luminaires, which are dedicated to floodlighting, are usually aimed directly up to the sky [17]. Based on this fact, all luminaires emit 100 % of the luminous flux to the upper hemisphere, regardless of their fixing point. The hypothesis that follows from this is that all pre-existing floodlighting projects lead to an increase in the effects of obtrusive light and an increase in the phenomenon of light pollution. Only those requirements connected with the average level of luminance of the building's facade appear to have been provided for in a proper way in the floodlighting standards. If the floodlighting project takes into account the requirements recommended by the CIE [17], the average levels of luminance achieved in practice are provided for, and do not exceed the levels described in Standard PN-EN-12464–2 [11].

In the context of floodlighting, the assurance that all is compatible with the requirements de-

**Table 1. Maximum obtrusive light permitted for exterior lighting installations [11]**

| Environmental zone | Light on properties | | Luminaire intensity | | Upward light | Luminance | |
|---|---|---|---|---|---|---|---|
| | $E_v$, lx | | $I$, cd | | $ULR$, % | $L_b$, cd·m$^{-2}$ | $L_s$, cd·m$^{-2}$ |
| | Pre-curfew | Post-curfew | Pre-curfew | Post-curfew | | Pre-curfew | Post-curfew |
| E1 | 2 | 0 | 2500 | 0 | 0 | 0 | 500 |
| E2 | 5 | 1 | 7500 | 500 | 5 | 5 | 400 |
| E3 | 10 | 2 | 10000 | 1000 | 15 | 10 | 800 |
| E4 | 25 | 5 | 25000 | 2500 | 25 | 25 | 1000 |
| a) In case no curfew regulations are available, the higher values shall not be exceeded and the lower values should be taken as preferable limits. | | | | | | | |

clared in the Standard is quite easy to achieve, especially if there are louvres and other special devices dedicated to reduce the glare and width of a beam. What is more, good practice in floodlighting design is that not only aesthetic effects should be taken into consideration, but also the possibility of using luminaires due to obtrusive light [15].

The biggest difficulty in customizing the installation of floodlights according to the regulations is limiting the luminous flux directed upwards (URL parameter) [1, 2]. The current requirements are impossible to be met, but can only be done in this way: the method of floodlighting and the angle of direction of luminous flux onto the illuminated object must be changed. Instead of illuminating in the traditional way – „from bottom to top", it has to be replaced by the idea of illuminating „from top to bottom". Is this even possible? Will the change and reversal of luminance distribution, the aesthetic effect and the typical places where shadows are created, be acceptable? Will it give the same impression? Will the current technical means of lighting equipment allow an object to be floodlit „from top to bottom"? These significant questions form the basis of these preliminarily prepared simulations, measurements and a short survey.

## 4. THE REVELSAL OF DIRECTION OF ILLUMINATION IN FLOODLIGHTING

Walking in the evening or through the night around the majority of cities in Europe, one will notice a lot of floodlit objects. By means of this, not only can the beauty of classical architecture be admired, but also that of modern architecture, such as shopping centres and malls. One of the most perfect examples of such architecture is an

Fig. 1. Shopping centre „Sezam" – a night view of elevation 1 (left side of the picture) and elevation 2 (right side of the picture)

Fig. 2. A method of obscuring luminaires on the elevation of „Sezam"

**Table 2. Results of illuminance measurements**

| | S [m$^2$] | $E_L$, lx | | | | $E_m$, lx | $E_{min}$, lx | $E_{max}$, lx | $U_0$,* rel.units |
|---|---|---|---|---|---|---|---|---|---|
| | | Distance of measurement line, m | | | | | | | |
| | | 0,5 | 2,5 | 3,5 | 5,5 | | | | |
| Elevation 1 | 325 | 566 | 259 | 59 | 38 | 202 | 23 | 690 | 0,11 |
| Elevation 2 | 175 | 645 | 217 | – | – | 431 | 78 | 1200 | 0,18 |

*which is defined as the following proportion: $E_{min}/E_m$

object called „Sezam" (Fig. 1), which is located in Warsaw.

The building stands out from its surroundings, not only due to its extraordinary and modern architecture, but also due to the surprising style of its floodlighting. Its illumination is done in a reverse way – „from top to bottom" in contrast to that of most floodlit buildings. It has to be said that the aesthetic effect of such an illumination is quite interesting. It can be assumed that during the course of its design there was close cooperation between those responsible for the appearance of the facade of the building and those responsible for the lighting. The luminaires responsible for the resulting lighting effect are hidden in niches (Fig. 2) over the entire surface of the facade of the object in a manner so precise that it is hard to believe that it was not previously intended.

Additionally, when the floodlighting of "Sezam" is observed for the first time, the observer has some troubles with the proper interpretation of the direction of lighting emission. It is not very obvious. It gets clearer when the very bright pavement (Fig. 3) in front of the elevation is noticed.

This effect results in the need to check the level of illuminance in that plane. Measurements were taken using an illuminance meter of class A (according to the CIE standards) and a valid calibration certificate. The results of these measurements are presented of the object at several different distances (Table 2, Fig. 5). For each of the lines, the average illuminance level $E_L$ was calculated. The average illuminance level $E_m$ and illuminance uniformity $U_0$ were also designated for the whole pavement in front of the elevation 1 and 2.

This kind of illumination has, of course, a few advantages. For instance, there is no need to use additional lighting equipment to light the exterior part of the restaurant located in this building (Fig. 4). However, it has to be taken into consideration that it also has an influence on the environment. The luminous flux indicated to the surface of the pavement is reflected and aimed towards the upper hemisphere. When the average illuminance $E_m$ and the size of this surface $S$ is known, the reflected luminous flux is possible to be calculated using the (1). The reflected luminous flux is scattered up into the atmosphere and is the main cause of sky glow and light tress pass.

Fig. 3. High luminance of the pavement as an undesired effect of floodlighting in a reverse way

Fig. 4. A night view of the restaurant located in the analysed object

**Table 3. Results of survey**

| No. | Content of question | Possible responses |
|---|---|---|
| 1. | Do you know of the phrase „light pollution phenomenon”? | YES – 13 (81 %)<br>NO – 3 (19 %) |
| 2. | Do you think that light pollution is important? | YES – 13 (81 %)<br>NO – 3 (19 %) |
| 3. | What is the main difference between these two visualisations?* | – The second case seems to be better illuminated.<br>– The arrangement of light sources.<br>– The first one is done from the top, the second from the bottom.<br>– Spots of luminaires.<br>– Emphasis of typical elements, the second case emphasizes the cornice. In the first one the cornice is only poorly visible.<br>– The surroundings in the first case are darker.<br>– There is a uniformity of colour in the first case and the second is illuminated irregularly.<br>– The floodlighting in the second case is more effective and spectacular.<br>– In the first one, there is higher brightness, in the second it is too low and the bottom of the building is badly visible. |
| 4. | Which visualisation presents floodlighting „from top to bottom”? | VISUALISATION1–16 (100 %)<br>VISUALISATION2–0 (0 %) |
| 5. | Which visualisation do you like the most? | VISUALISATION1–13 (81 %)<br>VISUALISATION2–3 (19 %) |

**only a selection of responses are given*

$$\Phi_\rho = E_m S \rho \ [lm]. \tag{1}$$

This calculation was made assuming that the surface of the pavement was characterised by a typical reflectance coefficient equal to 0.1. The calculations showed that the reflected luminous flux is approximately 14 000 lm in this particular case. This situation is the same as of the object being lit directly up towards the sky by a luminaire with a metal halide source of power 250W.

The level of luminance of the facade of „Sezam” was also measured by a luminance meter CS-200 (Konica Minolta). The values were measured at several dozen points along the whole surface of the elevation. The average level of luminance is about 11 cd/m$^2$. It is correlated with the requirements presented in the report of the CIE [18]. Interestingly, there is a variation in luminance values throughout the whole elevation. Higher values of this parameter are observed at lower heights. This effect is definitely caused by reflected luminous flux. Such high levels of luminance on the lower part of the building can cause some interference with the per-

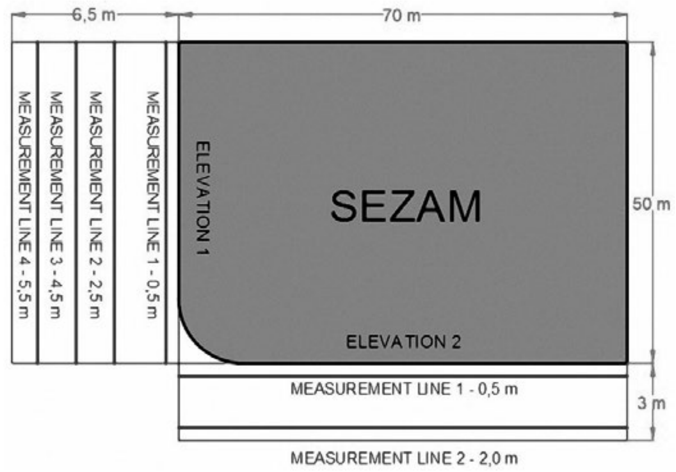


Fig. 5. Scheme of location of measurement lines located in front of the Sezam building

Fig. 6. Visualisation 1 – floodlighting "from top to bottom"

Fig. 7. Visualisation 2 – floodlighting "from bottom to top"

ception of the proper height of such an object. It can be perceived to be unnaturally flattened.

## 5. PREFERENCES OF LIGHITNG DIRECTIONALITY DUE TO FLOODLIGHTING

The analysis of a real example of floodlighting „from top to bottom" created the need to study the preferences of persons who observe this type of lighting. It seems that the aesthetic effect, which was achieved in the „from bottom to top" situation, is rather more natural, and, because of its widespread use, observers are more used to it. However, in order to check, it was decided to perform a short survey. Two variants of floodlighting of the chosen building were prepared by way of a computer visualisation of the lighting using 3dS Max. Visualisation 1 (Fig. 6) represents a typical method of floodlighting „from top to bottom" and visualisation 2 represents the reverse of this, „from bottom to top". These visualisations differ from each other only in the directionality of lighting. The same luminaires were used in both variants. The lighting equipment had the same photometrical web, the same luminous flux of the light source (3300 lm) and the same colour temperature (4000K). The only difference was in the setting and pointing of the luminaires (for the obvious reason of obtaining different lighting directions, Fig. 8). As a result, the average luminance level produced was similar in both directions of illumination. The difference was only in the direction of lighting and the consequent inverted luminance distribution.

Later, a laboratory scale survey was conducted. It consisted of five questions and 16 people participated in it. The participants would normal-


Fig. 8. Scheme of location, angle of direction and luminous intensity curves of the lighting equipment A1 – "from top to bottom", A2 – "from bottom to top"

ly have no connection with lighting technology in a professional manner. They only took part as potential observers of floodlit buildings. The age range of the survey participants was 22–28 years and they were alternately shown visualisations 1 and 2 (Fig. 6 and 7). The content of questions and the gathered results are presented in Table 3.

## 6. CONCLUSION

This paper is a serious attempt to look at the floodlighting of objects by means of the Standard EN12464–2, which specifies the requirements for exterior lighting installations, so as not to lead to increased light pollution. The research was inspired by one of the first project of floodlighting to be done in a reverse way „from top to bottom". This has led to the assessment of quantitative features (from a technical and engineering point of view) and to innovative solutions and issues connected with the aesthetic reception of floodlighting design. The conclusions, which resulted from the analysis conducted by the authors of the research, are as follows:

I. A comparison of the requirements included in the Standard EN12464–2 and the CIE Guide for Floodlighting shows a significant discrepancy between them. It seems that the main method to protect the night sky from light pollution is to reduce the average luminance level of the facades, but unfortunately the permissible value of this parameter was increased in the recent standard EN12464–2. This is a significant ambiguity and should be changed immediately.

II. Reversal of lighting direction in floodlighting is now possible. It requires only the right geometrical construction of the illuminated facade. It has to possess niches and special covers. This means that it is much easier in new buildings, where the project of floodlighting is foreseen at the initial stages of the architectural project, and is quite difficult for older ones (e.g. historical objects, monuments etc.).

III. Probably most people are familiar with the idea of light pollution and what is more important they think that it is significant.

IV. Reversal of direction of floodlighting is noticeable by viewers as a result of the perceived different localisation of lighting equipment, as amended by different luminance distribution and by the shape and localisation of the shadows.

V. Preliminary comparative studies of existing and new forms of floodlighting have shown that the majority of people who were surveyed can better assess the effects of traditional ways of directionality of lighting in the context of floodlighting „from bottom to top".

VI. The current prevalence of the idea of changing the direction of lighting in floodlighting requires the development and adjustment of lighting equipment to these changes. One of the change is in the thermal conditions of operating, where there is a greater possibility of noticing the luminaires, and where there is the need for extraordinary miniaturization.

VII. There is a strong need for the creation of regulatory requirements for light pollution due to floodlighting. The new standards should be clear and be possible to be implemented and verified, both at the project level and in reality, and after completion as well.

## REFERENCES


1. Garner, C. Tackling unwanted light: an international perspective. Light & Engineering, *2012*. V20, #1, pp. 24–39.
2. Commission Internationale de l'Eclairage. CIE126. Guidelines for minimizing sky glow. CIE, 1997. Vienna.
3. Commission Internationale de l'Eclairage. CIE150. Guide on the Limitation of the Effects of Obtrusive Light from Outdoor Lighting Installation. CIE, 2003. Vienna.
4. Cha JS, Lee JW, Lee WS et al. Policy and status of light pollution management in Korea. Lighting Research & Technology, 2014. V46, pp. 78–88.
5. CY Ho, HT Lin. Analysis of and control policies for light pollution from advertising signs in Taiwan. Lighting Research & Technology, 2015. V47, pp. 931–944.
6. Saraiji, R., Saju Oommen, M. Light Pollution Index (LPI): An integrated approach to study light pollution with street lighting and facade lighting. Leukos, 2012. V09, #2, pp.127–145.
7. Kollath, Z., Kranicz, B., Gyutai V. Measuring light pollution. Przegląd elektrotechniczny, 2008. V08, pp. 80–83.
8. Duriscoe DM, Luginbuhl CB, Elvidge CD. The relation of outdoor lighting characteristics to sky glow from distant cities. Lighting Research & Technology, 2014. V46, pp. 35–49.
9. Clanton N. Opinion: Light pollution...is it important?. Lighting Research & Technology, 2014. V46, pp. 4–10.
10. Habel J, Zak P. The present and future of lighting engineering. Light & Enginneering 2012; V20, #2, pp. 5–11.
11. Polish Standard: PN-EN12464–2. Light and Lighting – Lighting of work places – Part 2: Outdoor work places [Światło i oświetlenie. Oświetlenie miejsc pracy. Część 2: Miejsca pracy na zewnętrz]. PKN, 2008. Warsaw.
12. European Standard EN12464–2. Light and Lighting – Lighting of work places – Part 2: Outdoor work places. CEN, 2007. Brussels.
13. Żagan W. Opinion: Obtrusive light and floodlighting. Lighting Research & Technology, 2015. V47, p. 640.
14. Bierman A, Will switching to LED outdoor lighting increase sky glow? Lighting Research & Technology, 2012. V44, pp. 449–458.
15. Skarżyński K. Floodlighting of architectural objects and environmental light pollution [Iluminacja obiektów architektonicznych a zanieczyszczenie środowiska światłem]. Kosmos, 2015. V64, #4 (309), pp. 553–562.
16. www.meyer-lighting.com.
17. Żagan W. The floodlighting of objects [Iluminacja Obiektów]. ISBN83–7207–360–0 Oficyna Wydawnicza Politechniki Warszawskiej, 2003. Warsaw.
18. Commission Internationale de l'Eclairage. CIE094. Guide for Floodlighting. CIE, 1993. Vienna.



***Wojciech Żagan,***
Doctor of Science, professor. He graduated in Electrical Engineering from Warsaw University of Technology in 1976. He has 40 year of experience in Lighting Technology and he has guided 15 dissertations for Ph.D. Researchers. He has been the Chair of the Lighting Technology Division of Warsaw University of Technology since 1997. He has designed over 100 floodlighting arrangements in Poland, Ukraine, Germany and the Netherlands

***Krzysztof Skarżyński,***
Master of Science. He graduated in Electrical Engineering at Warsaw University of Technology in 2014 and since then he has been a Ph.D. student at the Lighting Technology Division. He also works as a lighting designer at his own company called DKS Światło

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# VISIBILITY RANGE OF SIGNAL LIGHT EMITTING DIODE LIGHTS

Gennady A. Kaloshin[1], Cergei A. Shishkin[1], Vladimir P. Budak[2],
Vyacheslav I. Anisimov[3], and Vladimir V. Zhukov[3]

*[1]The Institute of Atmosphere Optics of V.E. Zuev of the Siberian Branch of the Russian Academy of Sciences, Tomsk;*
*[2]The Moscow Power Institute National Research University, Moscow;*
*[3]EKRAN Scientific Research Institute Joint-stock Company, Samara*
*E-mail: gkaloshin@iao.ru*

**ABSTRACT**

Calculation results of signal light emitting diode lights (LEDL) luminous intensity are presented, which are minimum requirements for the reliable visual detection of flight landing strip (runways) operating in practice. The following applications of runway LEDLs are considered: input; runway landing last 600 m stretch; and, restrictive. Threshold detection levels are selected, an analysis of runway LEDL effectiveness is given under various weather conditions at night-time, in twilight and in the day-time. Questions of 1 %, 3 %, 10 %, 30 % and 100 % step adjustment of the LEDL luminous intensity according to the ICAO standards are also considered (the results of the calculation and of the analysis).

**Keywords**: visibility range, signal light emitting diode lights, runway, pupil illuminance, observer, luminous intensity, meteorological visibility range

## 1. INTRODUCTION

Application of light emitting diodes (LED) in signal lights is currently the most advanced technology in visual facilities of orientation and signal systems for transport. It allows creating a new light-signal system using light emitting diode lights (further – LEDL) capable of replacing “high intensity lights” (HIL), the disadvantages of which include their high energy consumption and labour intensity during operation. The LEDLs can provide for the landing of airplanes under ICAO first category conditions.

When you understand the potential scope of LEDL sources development, the airport industry becomes an important field where their wider introduction as light-signal equipment could be seen in the future. At present, as part of the perfection of airfield lighting equipment, a significant modernisation of runway lighting facilities takes place. Its main objective is to increase the efficiency and reliability of light-signal devices, improve their lighting parameters – visibility range and discernibility of signal indications.

This leads to increased flight safety, decreased ergonomic and psychophysiological pressure on crews during the most crucial stages of the flight: take-off and landing.

Below the calculation results of LEDL efficiency are given during night-time, twilight and day-time under dense atmospheric smoke and fog conditions. Special attention was given to evaluations of minimum luminous intensity necessary for LEDL visual detection under actual operational practice conditions.

## 2. LUMINOUS INTENSITY CALCULATION

Approaches to visual perception of group lights and calculation of direct and diffused ra-

**Table. LEDL radiation parameters**

| Parameter | LEDL group | | | |
|---|---|---|---|---|
| | ***ALG*** | ***ALY*** | ***ALR*** | ***ALB*** |
| Light intensity, cd | 10000 | 10000 | 2500 | 3 |
| Vertical radiation angle $\theta_v$, grade | 0 – 10 | 0 – 7 | 0 – 5 | 2 – 6 |
| Horizontal radiation angle $\theta_h$, grade | ± 5.5 | ± 6.5 | ± 6.0 | ± 180.0 |
| Peak wave length, mcm | 0.53 | 0.58 | 0.62 | 0.47 |
| Spectrum halfwidth, mcm | 0.04 | 0.02 | 0.02 | 0.03 |
| Radiation type | Uninterruptable | | | |

diation fluxes are provided in reasonable detail in a variety of publications, with the example of laser signal system [1 – 4]. For this study, a calculation of the required LEDL luminous intensity was carried out following a method similar to that used in [4] for laser radiators[1].

### 2.1. Location layout and LEDL parameters

The basic layout for calculation of LEDL radiation parameters is given in Fig. 1. The LEDL system consists of three light groups: input green (*ALG*) located along the runway threshold perpendicularly to the axis; landing yellow (*ALY*) located on both sides of the runway; restrictive red (*ALR*) located along the runway boundary perpendicularly to the axis from the runway side opposite to the threshold.

The LEDL parameters are given in the Table.

### 2.2. Calculation procedure

A minimum luminous intensity necessary for reliable visual detection of $I$ is determined by the following values: meteorological visibility range $S_{\mathrm{m}}$, luminance of an observer's eye adaptation background $L_{\mathrm{b}}$, azimuth $\alpha$ and place angle $\beta$ of the radiation direction response pattern; radiation angles $\theta_h$ and $\theta_v$, horizontal and vertical respectively; $\lambda_{peak}$ radiation wavelength; threshold brilliance $E_{\mathrm{th}}$; group light number $N$ and distance

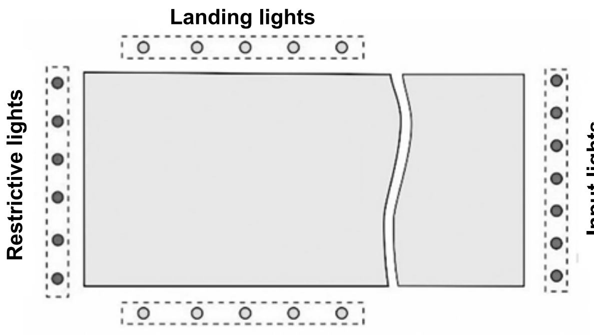


Fig.1. LEDL placing layout

of detection $D_{\mathrm{lim}}$. Thus, a functional dependence is found:

$$I = f(S_{\mathrm{m}}, L_b, \alpha, \beta, \theta_h, \theta_v, \lambda, E_{th}(\lambda, L_b), N, D_{\mathrm{lim}}). \quad (1)$$

Necessary values of $D_{\mathrm{lim}}$ are considered to be equal to (1.0 – 1.6) km from the runway threshold with $S_{\mathrm{m}}$ = (0.8 – 10) km. The observation conditions are: twilight is at $L_{\mathrm{b}} = (10^{-2} - 10)$ cd/m$^2$; night-time is at $L_{\mathrm{b}} = (10^{-4} - 10^{-2})$ cd/m$^2$; daytime is at $L_{\mathrm{b}} = (10 - 10^3)$ cd/m$^2$.

In general, calculation of $I$ necessary for a reliable LEDL detection is as follows:

- Values of the LEDL energy characteristics, $S_{\mathrm{m}}$ value, threshold characteristics of sight, as well as geometry of the LEDLs and the observer places layout were set.
- For every LEDL, $I$ value was calculated for various energy, spectral characteristics and visibility conditions. The registered $I$ was determined as $I$ sum of separate LEDLs.

The diffusing environment consisted of the following components: continental atmosphere

[1] For signal LEDLs as well as for laser sources some values are kept, by means of which light radiation field is quantitatively described, namely: luminous flux and light energy, luminous intensity, illuminance and exposition, luminance and luminosity [5]. Thereby it is considered that non-white LEDs are classical non-coherent quasi-monochromatic radiators.

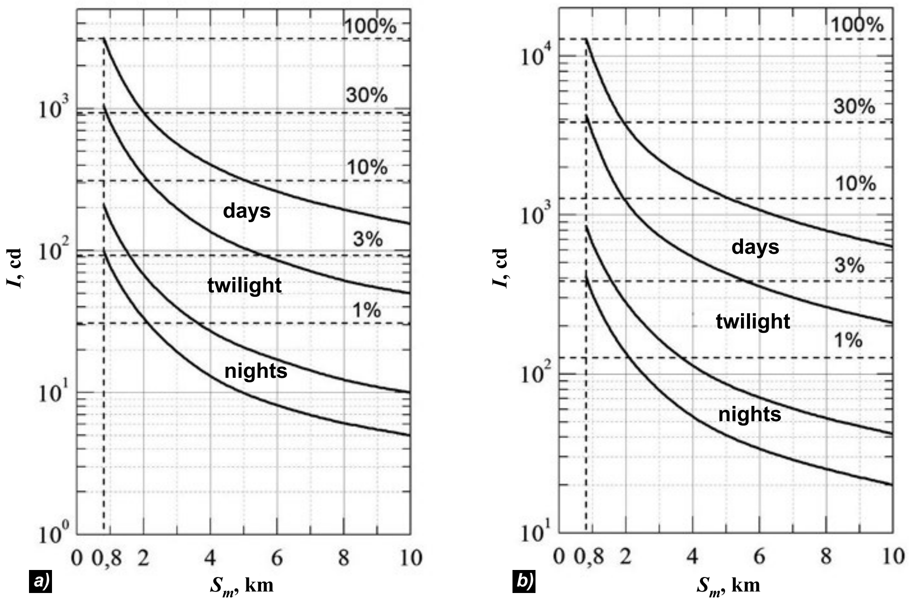


Fig. 2. Determination of input (green) LEDL luminous intensity *I* at distances from the runway threshold of 1 km (a) and 1.6 (b) km

characterised by meteorological visibility range $S_m$ value, sea and coastal atmosphere characterised by speed and direction of the wind, by wave fetch, by relative humidity, height, radiation spectral interval and by spectrum of the particle size, which were input parameters for the *MaexPro* sub-program [6–11]. The results of the calculations were spectral coefficient of aerosol extinction $\sigma(\lambda)$ equal to $3.92/S_m$ and diffusion indicatrix. It should be noted that the main energy losses of optical signal in the visible interval during its propagation within the atmospheric surface layer, are mainly caused by aerosol extinction [11]. Differences between coefficients of aerosol extinction and of diffusion are within instrumental errors. In this case, the aerosol absorption coefficient in the *MaexPro* model is determined by an imaginary part of the complex refraction index.

Further calculation was carried out using the *Range* program [12, 13], which allows calculating energy extinction of laser, light emitting diode and «traditional» light source radiation, taking into account aerosol extinction on lines within the surface layer of continental, sea and coastal atmosphere.

As threshold sight characteristics for night and twilight observation conditions, standard ICAO data were used in the study, alongside Russian domestic standards, both accepted in the State Optical Institute, and used when designing visual facilities of navigation equipment, based on recommendations of the Department of Navigation and Oceanography of the Ministry of Defence of the Russian Federation and of the International Association of Lighthouse Authorities [14 – 17].

Calculation of a minimum luminous intensity *I* of the light emitting diode group necessary for reliable visual detection depending on meteorological visibility range $S_m$ was carried out in the approach of first-order diffusion using the expression:

$$I = k_{as} E_{th} K_m V(\lambda) D^2 \exp\left(\frac{3.92D}{10^3 S_m}\right) \left(1 + \frac{3.92}{4\pi S_m} \int_0^{\Omega}\int_0^{\Psi} x(\lambda, \omega + \phi) d\omega d\phi\right)^{-1}, \tag{2}$$

where $k_{as}$ is the assurance coefficient equal to 50 [1]; $E_{th}$ is the threshold illuminance when observing uninterruptible sources, W/m$^2$; $K_m$ is maximum spectral luminous efficiency of sight equal to 683 lm/W; $V(\lambda)$ is relative spectral luminous efficiency of sight; $D$ is distance between the LEDL and the observer, m; $S_m$ is meteorological visibility range, km; $x(\lambda,\omega+\varphi)$ is diffusion indicatrix; $\Omega$, $\psi$, are LEDL angular aperture and eye visual angle accordingly.

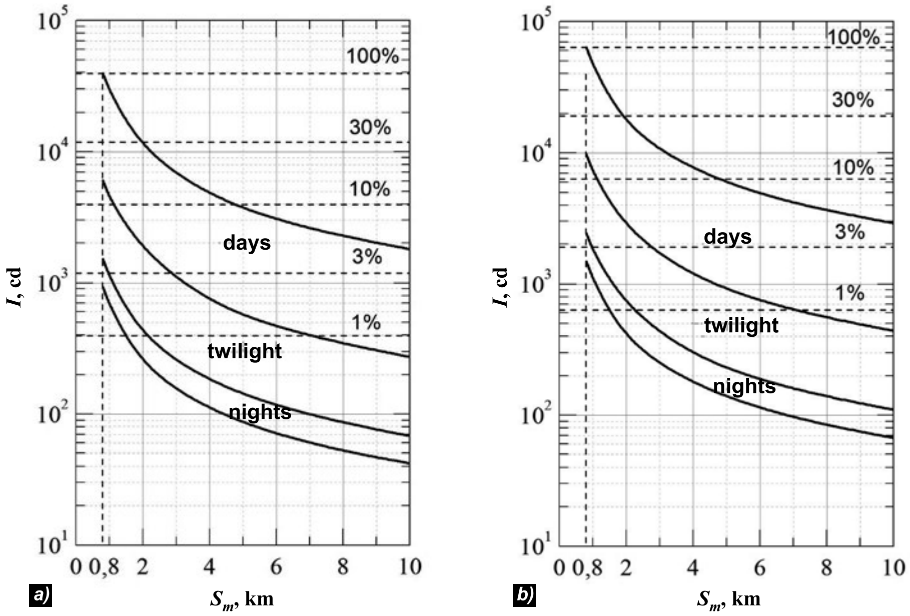


Fig. 3. Determination of landing (yellow) LEDL luminous intensity $I$ at distances from the runway threshold of 1 km (a) and 1.6 (b) km

A direct calculation of $I$ using (2) is possible by means of the iterative method based on $D$.

## 3. CALCULATION RESULTS

### 3.1. Input LEDLs

Fig. 2 shows calculation results of luminous intensity of input (green) LEDLs at distances from the runway threshold $D_{\text{lim}}$ = 1 and 1.6 km for different $S_{\text{m}}$ and different background observation conditions. The presented results allow taking into consideration big differences of $L_{\text{b}}$ and thus determining required values of the LEDL minimum luminous intensity including three wide categories of daytime, twilight and night-time observation conditions.

An analysis of these results shows that luminous intensity of the input LEDLs equal to 10000 cd is sufficient for the set $D_{\text{lim}}$ under all observation conditions except daytime for $S_{\text{m}}$ = 0.8 km and $D_{\text{lim}}$ = 1600 m. And for night-time and twilight observation conditions, the set luminous intensity is superfluous.

### 3.2. Landing LEDLs

Fig. 3 shows calculation results of luminous intensity of landing (yellow) LEDLs for distances from the runway threshold $D_{\text{lim}}$ = 1 and 1.6 km for different $S_{\text{m}}$ and different background observation conditions.

An analysis of these results also shows that luminous intensity of the landing LEDLs equal to 10000 cd, is sufficient for the set $D_{\text{lim}}$ under all observation conditions except daytime at $S_{\text{m}}$ = 0.8 km and $D_{\text{lim}}$ = 1600 m. And for night-time and twilight observation conditions, the set luminous intensity is also superfluous.

### 3.3. Restrictive LEDLs

Fig. 4 shows calculation results of luminous intensity of the restrictive (red) LEDLs for distances from the runway threshold $D_{\text{lim}}$ = 1 and 1.6 km for different $S_{\text{m}}$ and different background observation conditions.

An analysis of these results shows that luminous intensity of the restrictive LEDLs equal to 2500 cd is superfluous under night-time and twilight observation conditions for the set $D_{\text{lim}}$. As to the daytime conditions, for $S_{\text{m}} \leqslant 2$ km, axial luminous intensity of the restrictive LEDLs is insufficient.

## 4. DISCUSSION

The performed calculations allow formulating the following main conclusions and recommendations concerning LEDL luminous inten-

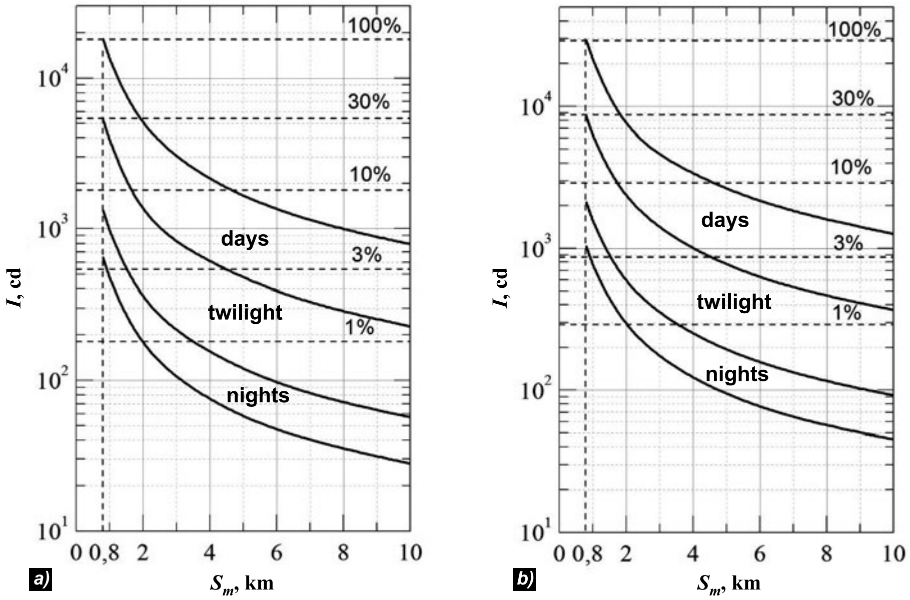


Fig. 4. Determination of restrictive (red) LEDL luminous intensity $I$ at distances from the runway threshold of 1 km (a) and 1.6 (b) km

sity and their step adjustment according to ICAO standards. The calculation data given in Figs. 2 – 4 make it possible to consider big differences of background luminance values and thus to determine the required values of LEDL luminous intensity, including three wide categories of daytime, twilight and night-time observation conditions. Four curves in these figures differentiate three intervals determining day, twilight and night conditions. The uppermost curve (day) belongs to luminance background of 10000 cd/m$^2$ and to the correspondent threshold illuminance. The following curve (a boundary between day-time and twilight periods of day) corresponds to the background luminance of 1000 cd/m$^2$. The third curve (a boundary between twilight and night-time) corresponds to the background luminance of 1 cd/m$^2$. And the lowermost curve corresponds to $10^{-2}$ cd/m$^2$ (dark night).

It follows from Figs. 2 – 4 that two main dependencies are characteristic for them:

• All of the curves have approximately the same conventional slopes meaning that a minimum required luminous intensity for $S_m$ = 10 km, amounts to 1/30 of the luminous intensity needed for $S_M$ = 0 km. Hence, for any LEDL under any known conditions, one can draw three curves, if a correspondent required luminous intensity is known for $S_m$ = 0 km. Thus in practice, the curve of extreme condition boundary in the daytime comes to an end not at the zero visibility point but at the point, where visibility range is equal to 1.5 km and inclination of the curves corresponds to the general case;

• The vertical interval between the curves (width of the intervals for daytime, twilight and night-time in the figures) is a value constant for all LEDL types within this interval. Therefore, the daytime interval is 1.5 times wider than the night-time interval, and the twilight interval is 2 times wider than the daytime interval.

As a whole, it should be stated that for input, landing and restrictive LEDLs under night and twilight observation conditions, there is a necessity of their step adjustment according to the ICAO standards. Under daytime conditions, such an adjustment is not required.

## 5. CONCLUSIONS

1. Luminous intensity of the input (green) and of the landing (yellow) LEDLs equal to 10000 cd, is sufficient for the set $D_{lim}$ (from the runway threshold) under all observation conditions except daytime for $S_m$ = 0.8 km and $D_{lim}$ = 1.6 km. And for night-time and twilight observation conditions the set luminous intensity is superfluous.

2. Luminous intensity of the restrictive (red) LEDLs equal to 2500 cd is superfluous under night-time and twilight observation conditions for

the set $D_{lim}$ (from the runway threshold). For the day-time conditions, at $S_m \leqslant 2$ km, axial luminous intensity of the restrictive LEDLs is insufficient.

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## REFERENCES

1. Zabelina I.A. Calculation of visibility of stars and far lights. Leningrad: Mashinostroyeniye, 1973.184 p.

2. Kaloshin G. A., Shishkin S.A. Concerning visibility of runway group signal lights in diffusing atmosphere //Materials of the XVIIIth International symposium "Optics of atmosphere and ocean. Physics of atmosphere", 2–6nd July, 2012, Tomsk. – Publishing house of the Institute of atmosphere optics of the Siberian Branch of the Russian Academy of Science, pp. B-187–B-192.

3. Kaloshin G.A., Matvienko G.G, Shishkin S.A., Anisimov V.I, Butuzov V.V., Zhukov V.V. Operational efficiency of the laser subsystem of plane landing on runways under actual practice operation // Defence facilities. 2014, # 1–2, pp. 81–87.

4. Shubert E.F. Light-emitting diodes. – New York: Cambridge University Press, 2003, 313 p.

5. Kaloshin G.A., Matvienko G.G. Aerosol Microphysical Model of the Marine and Coastal Atmosphere Surface Layer for Calculation of Extinction in Visible and IR Radiation Wave Band // Proc. 5th Asian Aerosol Conf., Aug. 26–29, 2007. Kaohsiung, Taiwan, 2007, pp.1121–1123.

6. Kaloshin G.A., Matvienko G.G. Aerosol Model Development for Environmental Monitoring in the Coastal Atmosphere Surface Layer // Proc. International Conference on Lasers, Applications, and Technologies (ICONO/LAT 2007), Minsk, Belarus, May 28-June 1, 2007, p. 51.

7. Piazzola J., Kaloshin G. Performance evaluation of the coastal aerosol extinction code "MEDEX" with data from the Black Sea // Journal of Aerosol Science. 2005, V. 36, № 3, pp. 341–359.

8. Kaloshin G.A., Grishin I.A. An Aerosol Model of the Marine and Coastal Atmospheric Surface Layer // Atmosphere-Ocean. – 2011. – Vol. 49, № 2. – P. 112–120.

9. Kaloshin G.A., Shishkin S.A. A programme to calculate comprehensive refractive indices of sea and coastal aerosol particle substance MieCalc / Certificate on the state registration of computer programme #2012616943. Registered in the Register of computer programmes 3.08.2012, 26 p.

10. Kaloshin G.A., Shishkin C.A. A programme to calculate of spectral coefficients of aerosol extinction in the surface layer of sea and coastal atmosphere MaehR-go / Certificate on the state registration of computer programme #2012616945. Registered in the Register of computer programmes 3.08.2012, 68 p.

11. Kaloshin G.A, Shishkin S.A. Detectable distance calculations for a visual navigation system using a scanning semiconductor laser with electronic pumping // Appl. Optics. 2011, V. 50, № 20, pp. 3442–3448.

12. Kaloshin G.A, Shishkin S.A. A programme-technological package Range to calculate propagation of optical radiation with due regard for aerosol extinction in the surface layer of continental, sea and coastal atmosphere / Certificate on the state registration of computer programme #2012616944. Registered in the Register of computer programmes 3.08.2012, 83 p.

13. Manual on designing airfields. Part 4. Visual facilities. Doc9157 AN/901. The fourth edition, July, 2004.

14. Luizov A.V. Eye and light. – Leningrad: Energoatomizdat, LO, 1983, 144 p.

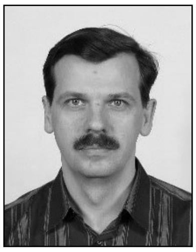
15. Klimuk P.I, Zabelina I.A., Gogolev V.A. Visual observations and optics pollution in space. Leningrad: Mashinostroyeniye, LO, 1983, 224 p.

16. The IALA Navguide. 5th ed. 2006.

17. Instruction on navigation equipment (NEI-2000). – SPb: Chief Directorate for Navigation & Oceanography of the Ministry of Defence of the Russian Federation, 2001, 328 p.

***Vyacheslav I. Anisimov,***
Ph.D., a senior lecture, graduated from the Kuibyshevsky Aircraft Institute of S.P. Korolyov with a specialisation in «Aircraft construction» in 1973. Chief of a laboratory of EKRAN Scientific Research Institute joint-stock company, Samara

***Vladimir P. Budak,***
Prof., Doctor of Technical Science, graduated from the Moscow Power Institute in 1981 with a first-class honours degree, Lecture at the Chair «Light and Engineering» of the Moscow Power Institute National Research University. An Associate editor of the Svetotekhnika (Light and Engineering) Journal



***Vladimir V. Zhukov,***
radio- engineer, graduated from the Kuibyshevsky Aircraft Institute of S.P. Korolyov in 1988 with a specialisation in the radio engineering, chief of a laboratory of EKRAN scientific research institute joint-stock company, Samara

***Gennady A. Kaloshin,***
Ph.D., graduated from the Tomsk State University in 1972 with a specialisation in Radio physics and quantum electronics, a leading research scientist of the Institute of Optics of Atmosphere of V.E. Zuev of the Siberian Branch of the Russian Academy of Sciences, Tomsk

***Sergei A. Shishkin,***
a design engineer, graduated from the Tomsk University of Control Systems and Radio Electronics in 2000, a research associate of the Institute of Optics of Atmosphere of V.E. Zuev of the Siberian Branch of the Russian Academy of Sciences, Tomsk

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# DEFINITION OF THE FUNCTIONAL UNIT FOR LIFE CYCLE ASSESSMENT OF A LIGHT POINT OF THE STREET LIGHTING

Luz García Ceballos and Jose Ramón de Andrés Díaz.

*University of Málaga, Escuela Politécnica Superior. Departamento de Expresión Gráfica, Diseño y Proyectos. Málaga, Spain.*
*E- mails: mlgarcia@uma.es.; deandres@ctima.uma.es*

## ABSTRACT

Life Cycle Assessment (LCA) is an evaluation tool of increasing importance for deciding a planning of a product or service. So, an appropriate definition of the Functional Unit (parameter of reference) is needed in order to be consistent with the goal and scope of a LCA. Street lighting systems provide illumination during operation, but they can be designed with different technologies depending on the type of light sources, luminaries or auxiliary equipments (ballasts, condensers, etc.). This paper presents a Functional Unit (FU), which allows LCA of a light point for street lighting. With the FU proposed, environmental impact of different light points can be compared regardless their technology or their features. In order to define such a FU, characteristics of the light point components, as well as the technical terms describing characteristics of its operation, will be considered. An example is presented to demonstrate that we can compare different technology light points with this FU.

**Keywords:** LCA, energy efficiency, functional unit (FU), street lighting, envivonmental impact, luminaire, light point

## 1. STREET LIGHTING

Street lighting includes every light system whose luminous flux is projected on any public outdoor space (road, street, park, ornamental lights, etc.)

In some countries street lighting requires a significant energy consumption, which, as is the case of Spain, is generated mostly from solid fuels, therefore contributing to global warming. 61 % of total greenhouse gases and nearly 75 % of the total $CO_2$ produced result from activities related to energy (electricity and heat generation, transport, etc.) [1]. In Spain in 2010, public street lighting systems represented an electrical consumption of 3,630 GW·h, which meant 657 $GgCO_2$ emissions per year [2].

Due to the urban growth during the last ten years in our country, the number of street lighting systems and electricity consumption have increased very quickly (energy consumption registered a 60 % increase between 1990 and 2003 [3]. Nowadays, street lighting systems are undergoing technological and legislative advances, which will bring as a consequence change in consumption trends. Thus, the Spanish regulations on energy efficiency in street lighting systems [4], the appearance of LED technology and the public administrations hiring of Energy Service Companies, can make a milestone in the near future in order to reduce such energy consumption.

On the other hand, some legislative improvements have been made related to product design. The Spanish Royal Decree 1369/2007 creates the bases for establishing requirements of applying ecological design to energy consuming products, in order to achieve a high level of environmental protection. This Royal Decree seeks to improve energy efficiency of industrial products while keeping their functional qualities. To achieve this goal, it is mandatory to act from the design phase of the product, as the pollution of the products along their life time is determined at this stage.

## 2. CHARACTERISTICS OF A PUBLIC STREET LIGHTING SYSTEM

A public street lighting system is defined as a lighting system used for security purposes, especially night security, in public streets, cycle paths, pavements and pedestrian areas, and within public parks and gardens [5].

In order to design street lighting systems, several luminotechnical and energy efficiency criteria must be taken into account. In Spain, these criteria must comply with the rules established by the Spanish Royal Decree 1890/2008 [4].

In our paper, Light Point will be defined as an optic, mechanical and electrical set consisting of light sources, luminaries and auxiliary equipments (ballast, starter, capacitor, power supply, etc.). Supporting elements, such as columns or different bases, and electrical installation are not considered to be parts of the Light Point.

The Light Points of a street lighting system provide illumination to different spaces.

**Luminous Flux** is defined as the energy emitted by a light source as a visible radiation, valued according to its capacity to produce luminous sensation, and considering the variation of eye sensitivity with the wavelength. Its symbol is $\Phi_v$, its unit is lm [5].

According to the Spanish Royal Decree 1890/2008 [4], **energy efficiency**(ε) of an outdoor system is defined as the product of the illuminated surface multiplied by the average illumination and divided by the total installed power. It can be calculated taking into account the efficiency of lamps and auxiliary equipments (lm/W), the factor of maintenance and the factor of use of the system. Energy efficiency of a system formula is as follows:

$$\varepsilon = \varepsilon_L \cdot f_m \cdot f_u \left( \frac{m^2 \cdot lx}{W} \right), \tag{1}$$

where $\varepsilon_L$ is a luminous efficiency of a light source and auxiliary equipments, $f_m$ is a factor of the maintenance, $f_u$ is a factor of the use.

Although light source is the determining element of the quantity of light emitted, the concept light point will determine the final use of the light generated: because of the performance of the luminaire or its auxiliary equipment, because of the possibility of dirt getting inside the luminaire, and because of the spatial distribution of the light emitted.

The **performance** ($\eta$) of the luminaries of the light points described as the ratio between total luminous flux, measured under determined experimental conditions with its light source/s, and the sum of the individual luminous fluxes of the same light source/s when these are outside the luminaire, with the same equipment and under the same conditions [5].

$$\eta = \frac{FlowLuminary}{FlowLightsource}\%, \tag{2}$$

Another important element to be considered is that 1,000 lm is a common reference parameter to check the characteristics of the manufacturers of the luminaires and of the light points in general. Diverse measurements and tests of light points or light sources (theoretical luminous flux, distribution of the luminous intensity, etc.) are normalized using this standard parameter [6].

## 3. FUNCTIONAL UNIT IN A LCA

UNE EN ISO 14040 ON Life Cycle Assessment (LCA) defines Functional Unit (FU) as *the quantified performance of a product system for use as a reference unit in life cycle assessment study* [7]. Therefore, the main purpose of the FU is to provide a reference for calculation (a parameter) so that environmental impact (i.e. energy use, emissions, etc.) can be compared across different systems. FU is the measure of the studied system function and provides a reference of the related system outputs and inputs.

This paper proposes a FU for light points of street lighting, which allows the calculation of its LCA regardless of the kind of luminaire or the technology of the light sources.

Therefore, considering the previous aspects, in order to define our FU, the following parameters of the light points must be taken into account:

– Type of light source, by means of luminous performance and flux emitted;

– Type of luminaire, according to its performance and IP;

– Lifetime of the light source, to take into account the number of times it has to be replaced;

– Time of use and lifetime of the public lighting facility.

## 4. FU FOR A LIGHT POINT OF A STREET LIGHTING SYSTEM

Before starting this study, several publications related to the purpose of this research have been consulted, including:

– Papers on LCA comparing only the light source. They base the FU on the difference between the luminous flux and the lifetime of the sources. The FU chosen was $10^6$ hours of useful lighting [8,9,10,11,12].

– Papers on LCA comparing different light sources and using as FU the longer lifetime of the light sources [13](Osram., 2009).

– Papers on LCA to assess a public lighting facility with different parameters of comparisons such as, replacement of the light source (20 millions of lumen/hour) [14] (Scholand, M.J.; Dillon, H.E., 2012), one kilometer of street to be illuminated [15], one hour of lighting [16], or lifetime of the facility [17].

From our point of view, none of these proposed FU considers all the parameters defined in the above section, which can affect a light point of the street lighting. Therefore, they cannot be used as a reference for the calculation of system outputs and inputs for a street lighting system as they reduce the evaluation of the performance to partial criteria of ifs design. Furthermore, as we have already mentioned, these criteria must be the result of the addition of the parameters of the different elements composing the light point (useful luminous flux, total power of the whole set, lifetime of the light source, etc.).

A criteria we must take into account to define the FU is the useful luminous flux. This we can express as **useful Lumen** (uL). This can be defined as the total luminous flux, which comes out from the light point and is projected towards the element to be illuminated. It is calculated multiplying the luminous flux of the light source ($\Phi_v$) by the performance of the luminaire (η) and by the percentage of luminous flux, which does not emit to the upper hemisphere ($ULOR_{inst}$):

$$uL = \Phi \upsilon \cdot \eta \cdot (1 - ULOR_{inst}). \tag{3}$$

$uL$ takes into account several characteristics of the light point, including flux of light source (and therefore the kind of source and its power), and the performance of the whole set (and therefore the kind of luminaire and the $ULOR_{inst}$).

To apply this parameter ($uL$), we are going to use the standard of 1,000 lumens, here in after referred to as 1,000 $uL$ or 1 $kuL$.

In order to consider another parameter for our FU, a 20 year lifetime has been estimated for our street lighting system [17,18]. Therefore, if we consider an average time of 4.000 h per year, the street lighting system will have worked 80,000 hours. During this time, replacements of the light source will be carried out, as well as several maintenance operations depending on the kind of luminaire and light source. This 20 year length of time of the facility has also been proposed because this period of study means that light sources of any technology would be replaced at least once, and because it is the period usually fixed for the maintenance of street lighting systems in many of the Communities of our country (for example, Madrid city council, 2010) [18]. A shorter study would ignore future savings related to the used technologies, and a longer study would not be realistic since new more efficient technologies will no doubt provide better parameters in the future.

Consequently, we propose 1 *kuL* as FU throughout the working lifespan of the street lighting system, that is, 1 *kuL* 80,000 *h*.

Finally, we would like to highlight the similarity of the final unit obtained between 1 *kuL/h* and I *kW/h*, which is used to measure the energy consumption.

## 5. EXAMPLE OF APPLICATION

As an example, we will apply the FU proposed on a series of real Light Points (whose features are detailed in Table 1), and will point out how this unit takes into account the parameters mentioned for the design of street lighting systems.

**Table 1. Main features of example light points**

| Light Points | Light Source | $\Phi_v$, lm | $P_T$, W | Efficiency, lm/W | Life time Light Source, h | $\eta$ | ULOR, % | $uL^*$, lm | IP |
|---|---|---|---|---|---|---|---|---|---|
| ***Light Point 1*** | LEDs | 5,280 | 51.2 | 120 | 70,000 | 0.87 | 1 | 4558.1 | 2X |
| ***Light Point 2*** | HPS | 5,900 | 81 | 82 | 28,000 | 0.76 | 1 | 4439.2 | 6X |
| ***Light Point 3*** | MH | 7,230 | 81 | 101 | 14,000 | 0.73 | 1 | 5225.1 | 6X |
| ***Light Point 4*** | LEDs | 3,850 | 53 | 73 | 50,000 | 0.73 | 1 | 278.,4 | 6X |

**uL* calculated by Equation 3.

**Table 2. Number of light points of each illumination device with regard to the FU**

| Light Points | *Lm* | *Lu* | Number of Light Points |
|---|---|---|---|
| ***Light Point 1*** | 1,000 | 4558.1 | 0.22 |
| ***Light Point 2*** | 1,000 | 4439.2 | 0.23 |
| ***Light Point 3*** | 1,000 | 5225.1 | 0.19 |
| ***Light Point 4*** | 1,000 | 2782.4 | 0.36 |

**Table 3. Ratio of working years of the light source with regard to the facility lifetime**

| Light Source | Working years | Number of Replacements |
|---|---|---|
| ***LEDs Light Point 1*** | 17.5 | 1.14 |
| ***HPS Light Point 2*** | 7 | 2.86 |
| ***HM Light Point 3*** | 3.5 | 5.7 |
| ***LEDs Light Point 1*** | 12.5 | 1.6 |

We will calculate the number of light points needed from each set in order to satisfy the first part of the FU of 1 kuL. To do so, we have to consider uL of each set of illumination to be able to produce the 1,000 lm of reference, that is, we will divide the 1,000 lm between the uL of each point and we will calculate the number of light points (Table 2.)

Another feature to be calculated will be the number of replacements of light sources. This refers to the number of replacements required by each technology in order to provide the luminous flux throughout the lifetime of the systems. At this stage, lifetime of the light source of the different technologies and the time the system has been working will be considered. To do so, the number of working years of the light source will be calculated, dividing the lifetime of each source by the 4,000 h average working time per year of a light point. Then, the number of replacements needed for the 20 working years of the street lighting system will be calculated, dividing the 20 years h by the number of years of working of each light source.

Table 3 shows the number of replacements of the light sources required by each technology of the example to provide the luminous flux for the lifetime of the facilities.

The flux emitted by an outdoor light point can be gradually reduced during its lifetime due to dirt and dust. This term is represented by the code of protection of the luminaire (IP). This gradual deterioration is mainly caused by the accumulation of dirt and dust suffered by the light sources and luminaires. As the facility must work for 20 years, the number of maintenance operations of each light point must also be calculated based on its IP.

## 6. CONCLUSIONS

In order to evaluate the environmental profile of a light point of public lighting, to consider all the elements involved in its life cycle (provision of resources, production/manufacture, consumption, transport, end of life) and to be able to calculate and reduce environmental impacts, a measurement parameter (FU) adequate to the function of the system and to the own features of a public lighting facility is required.

The election of the FU of 1 $kuL$·80,000 has a unit to compare different illumination devices is adequate, as it considers relevant aspects of the different features of the light points. With this FU, the function of street lighting system is correctly defined as it considers the following:

– Light source: power, flux, lifetime;
– Luminaire: type and performance;
– Time of working of the facility;
– Energetic efficiency as it considers uL.

This FU will provide a common base to analyze Light Points, as 1 kuL/80,000 h represents a quantified measure of actuation, which can be used as a base to compare the environmental evaluation of the different street public systems. As pointed out throughout the paper, and with the example shown, the main features of a light point are considered in order to design the system, although lighting systems are not equivalent.

## 6. REFERENCES

1. BAUMERT, K.A.; HERZOG, T.; PERSHING, J., 2005. *Navigating the Numbers: Greenhouse Gas Data and International Climate Policy*. [np]. Copyright © 2005 World Resources Institute. All rights reserved. ISBN: 1–56973–599–9. Library of Congress Control Number: 2005936305.

2. OFICINA CATALANA DEL CANVI CLIMÁTIC, 2011. *Guía práctica para el cálculo de emisiones de gases de efecto invernadero (*GEI). Generalitat de Catalunya Comisión Interdepartamental del Cambio Climático, march 2011.

3. CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas), 2006. *Situación de la energía en el Mundo, en Europa y España*. http://www.energiasrenovables.ciemat.es/especiales/energia/espana.htm.

4. MINISTERIO DE INDUSTRIA, TURISMO Y COMERCIO, 2008.*R. D. 1890/2008*, de 14 de noviembre, por el que se aprueba el Reglamento de eficiencia energética en instalaciones de alumbrado exterior y sus Instrucciones técnicas complementarias EA-01 a EA-07.

5. CIE (International Commission on Illumination), 2011. *Vocabulario Internacional de Iluminación*. CIE Central Bureau Viena, Austria. CIE S017/E:2011.

6. CIE (International Commission on Illumination), 1996.*Informe Técnico. Fotometría y Goniofotometría de Luminarias*. CIE Central Bureau Viena, Austria. CIE121:1996. ISBN3–900–734–74–7.

7. AENOR, 2006. UNE-EN–ISO 14040: 2006. Gestión ambiental. Análisis del ciclo de vida. Principios y marco de referencia. Madrid, España.

8. GYDESEN, A; MAIMANN, D., 1991. *Life cycle analyses of integral compact fluorescent lamps versus incandescent lamps. Energy and Emissions*. University of Denmark. Denmark.

9. HARTLEY, D.; JURGENS, C.; ZATCOFF, E., 2009. *Life Cycle Assessment of Streetlight Technologies*. Mascaro Center forSustainableInnovation. University of Pittsburgh.; USA.

10. PFEIFER, P. R. (1996). Comparison between Filament Lamps and Compact Fluorescent Lamps. INT J LIFE CYCLE ASS, 8–14. (Cited by Solid-State Lighting Program).

11. NAVIGANT CONSULTING, 2009. *Life Cycle Assessment of Ultra- Efficient Lamps*. Defra, department for Environment, food and Rural Affairs.

12. DALE T., A.; BILEC, M.M.; MARRIOTT, J.; HARTLEY, D.; JURGENS, C.; Y ZATCOFF, E., 2011. *Preliminary Comparative Life-Cycle Impacts of Streetlight Technology*. J INFRASTRUCT SYST, vol. 17, No. 4 © ASCE, ISSN1076–0342/2011/4–193–19.

13. OSRAM, 2009. *Life Cycle assessment of Illuminants. A Comparison of Light Bulbs, Compact Fluorescent lamps and LED Lamps*. OSRAM Opto Semiconductors GmbH and Siemens Corporate Tecnology- Germany.

14. SCHOLAND, M.J.; DILLON, H.E., 2012. *Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products. Part 1*: Review of the Life-Cycle Energy Consumption of Incandescent, Compact Fluorescent, and LED Lamps. Solid-State Lighting program.Building technologies program,

U.S. Department of Energy. Prepared by: Pacific National Laboratory and N14 Energy Limited.

15. TÄHKÄMÖ, L.; YLINEN, A.; PUOLAKKA, M.; HALONEN, L., 2011. *Life cycle cost analysis of three renewed street lighting installations in Finland*.INT J LIFE CYCLE ASS.

16. WELZ, T.; HISCHIER, R., HILTY, L.M., 2010. *Environmental impacts of lighting technologies – Life cycle assessment and sensitivity analysis*. ENVIRON IMPACT ASSES.

17. COLON, C. J. 2010. *Assessing the economic and environmental impacts associated with currently available street lighting technologies*. Department of the air force air university. Air force institute of technology. March 2010.

18. URRACA PIÑEIRO, J.I. Y URRACA ETAYO, I., 2005. *Instalaciones de alumbrado exterior. Guía técnica de aplicación ampliada y comentada*. AENOR ediciones.Spain. ISBN: 84–8143–444–2.

19. AYUNTAMIENTO DE MADRID,2010.*Pliego de Condiciones Técnicas Generales. Alumbrado Exterior, capítulo 18*. Área de gobierno de obras y espacio públicos. Madrid, España.

20. IDAE, 2012. Alumbrado exterior. El alumbrado exterior y la eficacia energética. http://www.idae.es/index.php/id.644/relmenu.355/mod.pags/mem.detalle [On line, august, 2012].

21. MINISTERIO DE CIENCIA Y TECNOLOGÍA, 2002. *ITC-BT-09*, *Instalaciones de alumbrado exterior.*

22. MINISTERIO DE INDUSTRIA, TURISMO Y COMERCIO, 2007. *R. D. 1369/2007*, de 19 de octubre, relativo al establecimiento de requisitos de diseño ecológico aplicables a los productos que utilizan energía.

***Luz García Ceballos***
Ph.D. degree with the thesis entitled «Life Cycle Analysis of Public Light Points». Associate Professor and Researcher at University of Malaga. She has the degree of Industrial Technical Engineering by the Polytechnic School and Engineering in Industrial Organization, from the Higher Technical School of Industrial Engineering, both belonging to the University of Malaga. She works at the Department of Graphical Expression, Design and Projects at the University of Malaga. Her teaching and research interests are in the field of Graphic Expression and the Eco design. She is part of the research group: Efficient design Projects TEP935

***Jose Ramon de Andres Diaz***
received the Ingeniero Industrial degree from de University of Comillas (ICAI), and Ph.D. degree from de University of Malaga Spain, in 1989 and 1998 respectively. Currently he is an Associate Professor of the Department of Graphical Expression, Design and Projects at the University of Malaga. His research interests include Product Design, LCA, Project Management and Lighting

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# SPECTRAL RECONSTRUCTION FROM TRISTIMULUS VALUES WITH THE USE OF PRINCIPAL COMPONENT ANALYSIS AND GENETIC OPTIMIZATION

András Horváth[1], Zsolt Sávoli[1], and Balázs Kránicz[2],

[1] *Department of Physics and Chemistry, Széchenyi István University, Hungary*
[2] *Veszprém, Hungary*
*E-mails: horvatha@sze.hu, savolizs@revai.hu, balazskranicz@gmail.com*

## ABSTRACT

Reconstruction of spectrum or spectral reflectance using only tristimulus values is impossible because of the infinite number of metamers. However, with additional information about the type of light source or surface, approximate reconstruction is possible. Several studies were written on this topic using Principal Component Analysis (PCA): using a sample set of spectra (or spectral reflectance) the search space for appropriate metamer can be narrowed. In this paper a new PCA-based optimization method is presented, which is more accurate than that of published before and gives non-negative, smooth results. Using precalculated lookup tables, the time and memory consumption will be very small. This method can produce a good reconstructed, realistic spectrum of an illuminant or spectral reflectance function for a surface based on tristimulus values of a digital image.

**Keywords:** spectral reconstruction, tristimulus values, principal component analysis, smooth metamers, illuminants, look-up table

## INTRODUCTION

One of the most important fact of colorimetry is that any colour stimulus can unequivocally be given with three numbers, e.g. with CIE *XYZ* tristimulus values or the coordinates of any other suitable colour space (*RGB, Yxy, L*a*b*, L*u*v** etc). These tristimulus values can be calculated from spectral data (spectrum of an illuminant or spectral reflectance of a surface and the spectrum of light source). The opposite direction is not univocal: for given *XYZ*-triplet there is infinite number of metamers.

However, in a lot of lighting engineering problems it would be very useful if we could reconstruct approximate spectrum from tristimulus values, because a lot of devices measures tristimulus values only. For example, if we have a digital image of a surface and knowledge about the light source, then reconstructing the spectral reflectance makes it possible to calculate the tristimulus values of the surface with an another light source. This way we could calculate the colour change of solid bodies under different lighting conditions.

One of the hottest topics in lighting engineering is connected with changing the light sources in our environment to modern, more efficient ones. The problem is that changing the light source has complex impact on perception of indoor and outdoor environment [1]. Using the proposed reconstruction method it is possible to give a good approximation on colour changes of a realistic environment based on calibrated three-colour digital images, some knowledge about the type of materials and the light sources. This type of spectral reconstruction can be applied to calculate the scotopic luminance based on digital images. Similar, but simpler, calculations were applied in [2].

To find good reconstruction of spectral data, researchers in colorimetry have started to examine how they can determine or give approximately the reflection spectra of surfaces with only few numbers. Principal Component Analysis (PCA), which is based on elements of mathematical statistics and linear algebra, has appeared to be an especially strong and interesting tool.

Several studies have dealt with the usage of Principal Component Analysis in colorimetry; therefore the mathematical presentation of it is not the subject of the present article. Publication [3] provides a general view how it works. In order to apply this method effectively, it is necessary to have a set with large number of known spectra. PCA produces the eigenvectors and finds principal components belonging to the sample set. The most important eigenvectors will appear in the order of importance at the beginning of their list. The details are given in references [4–9].

Up to now, some researchers have used Principal Component Analysis to represent the spectral distribution of every element belonging to a large sample set by the help of some base vectors and their weights. In this way, it is possible to reproduce all of the thousands of elements of a sample set with the linear combination of a few most relevant eigenvectors with expected accuracy. According to former studies, the use of the first three eigenvectors provides quite accurate results; however, further vectors can be used for reconstruction if we want to be more accurate. Fig.1. displays the results when we apply the first three or the first five eigenvectors for one of our samples. There is more information about the role of the eigenvectors, which are produced by the analysis in articles [10–12] and about the mean vector in article [13].

The above mentioned studies present reconstruction of samples that have known and measured spectra. The question is whether it is possible to say anything about the spectrum of colour samples that have unknown reflectance functions if we only know the tristimulus values *X, Y, Z*. In some of the researches focusing on this problem [14, 15], the spectral reconstruction has been done with an algorithm using pseudoinvers matrix operations. However, Principal Component Analysis has been used in other studies. Corresponding to the tristimulus values, the three eigenvectors, whose eigenvalues are the greatest ones, are enough to get the same *X, Y, Z* values as the result of reconstruction [16, 17]. More spectral accuracy can be reached with more components, but they lead to undetermined equation systems, as the tristimulus values can be given in several ways from more than three components. Because of this critical statement, three vectors have been considered to be satisfactory in most cases.

The accuracy of the reconstruction has been improved with the division of the Munsell colour system, with reconstruction on subsets [18], with the application of adaptive PCA algorithm [19], moreover, with the use of weighted PCA (wPCA) [16]. It is true for any variation of PCA that we can produce a metamer, which resembles a depicted element of the sample set with the use of three principal components, however, we have experienced that the qualitative features of the reconstructed spectrum are bad as there are lobes and spikes. Moreover, the final result is sometimes negative, which is physically not realistic.

In this article we prove that if we use more than three eigenvectors in the reconstruction, we can choose one metamer from that high number of possible metamers so that the reconstructed spectrum will own the qualitative features of the real cases, i.e. they will be non-negative and free of strong oscillations. Applying more eigenvectors will also lead to a more accurate reconstruction of the elements of the sample set.

The main point of our method is that non-linear optimization has to be done with the use of a little more than the minimal three components for each chromaticity coordinate-pair in order to get a metamer, which has the best

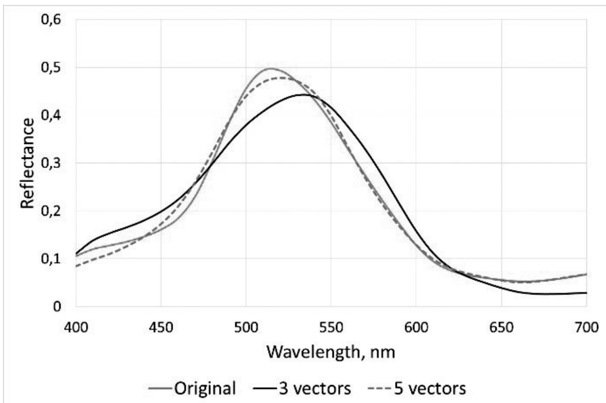


Fig.1. The colour line depicts the original spectrum, the black line depicts the reconstruction with 3 vectors, the dashed line depicts the reconstruction with 5 vectors

qualitative features. Fortunately, this complicated calculation can be done in advance. The first few eigenvectors given by PCA for the sample set have to be fixed, then we have to determine the coefficients of the eigenvectors for each chromaticity value of a quite dense interpolation table and we have to store them. After that, if we take a sample whose spectrum is unknown, the values of the coefficients of the eigenvectors have to be read from the table on the basis of the chromaticity of the sample. So we can get the right metamer that complies with the elements of the sample set and has good qualitative features in a very short time.

Contrary to former works, this method does not directly use the measured spectra of the original training set for reconstruction, it uses only the tristimulus values of the observable samples, the most significant eigenvectors and the above mentioned coefficients. The samples of the original training set are only used to determine the eigenvectors.

Finally, we observe the reflectance functions of surfaces instead of spectra for the sake of simplicity. Therefore, we examine the spectra of surfaces as if we lit them with different illuminants with familiar spectral power distributions. Moreover, we would like to know what happens if we do not know the spectral components of the illuminant. The illuminants are as it follows. CIE E, CIE D65, CIE D50, CIE A, CIE F11, white LEDs with phosphor and three-band white LEDs with 5000 K and 6504 K correlated colour temperature are also applied. Because of size in this article we can show only the reconstruction with the CIE E illuminant.

### The formalism of optimization

During calculation, we work with spectra (reflectance functions) whose resolution is given, therefore, we use finite-dimensional vectors instead of continuous functions. Let $N$ denote the dimension number of these vectors. For example, if we think of a spectrum with a range of 400 nm – 700 nm and with an equidistant wavelength step of at 10 nm, then $N$=31.

Let us denote the eigenvalues of the PCA method arranged in decreasing order by $\tau_1 \geq \tau_2 \ldots \geq \tau_N \geq 0$, the eigenvectors relating to the eigenvalues by $v_1, v_2, \ldots, v_N$, and the mean vector by $m$. The linear combination of $M$ eigenvectors and the principal components $c_1, c_2, \ldots, c_M$ provides the following spectrum.

$$f(c_1, c_2, \ldots, c_M) = \sum_{i=1}^{M} c_i \cdot v_i + m. \tag{1}$$

$f(c_1, c_2, \ldots, c_M)$ is also an $N$ – dimensional vector.

Having $M$ fixed, variables $c_1, c_2, \ldots, c_M$ determine the spectrum of the reconstructed $f$ according to equation (1). As a next step, we create a function that measures the difference between this type of spectrum and the ideal spectrum. The difference is small for smooth and non-negative metamers, and it is greater and greater if the tristimulus values deviate from the stipulated ones, or if the function oscillates strongly, or it takes up negative values. It is easy to calculate the tristimulus values of the spectrum with the application of colour-matching functions.

$$\begin{gathered} X_0 = \sum_{i=1}^{N} f_i \cdot S_i \cdot \overline{x}_i, Y_0 = \\ = \sum_{i=1}^{N} f_i \cdot S_i \cdot \overline{y}_i, Z_0 = \sum_{i=1}^{N} f_i \cdot S_i \cdot \overline{z}_i . \end{gathered} \tag{2}$$

In Eq. 2 $\overline{x}_i, \overline{y}_i, \overline{z}_i$ denote the discrete versions of the colour-matching functions, which have the same resolutions as that of the spectra. $S_i$ is the discrete spectral power distribution of the illuminant. Obviously, the values of $X_0, Y_0, Z_0$ depend on the coefficients $c_i$, but we do not emphasize this dependence for the sake of brevity.

We can calculate with the squared sum of the differences to show how much values $X_0, Y_0, Z_0$ deviate from the predefined values $X, Y, Z$.

$$\begin{gathered} d_0(c_1, c_2, \ldots, c_M) = \\ = (X - X_0)^2 + (Y - Y_0)^2 + (Z - Z_0)^2 . \end{gathered} \tag{3}$$

This $d_0$ value is equal to 0 when a metamer complies with the definition. If $M = 3$, the equation system of the metamer has a single solution. A lot of earlier studies which used PCA ended with giving this solution. If $M > 3$, it has an infinite number of solutions, and we can choose the most realistic one with the use of constraints on negativity and strong oscillation. Further details can be found in article [20].

The cost function whose minimum is assumed to determine the metamer with the best qualitative features is the following.

$$d\left(c_1, c_2, \ldots, c_M\right) = d_0 + P_n + P_v. \quad (4)$$

We can get $d_0$ from (3), $P_n$ responsible for negativity and $P_v$ responsible for oscillation [20]. All in all, $d$ is a non-linear function with $M$ variables, whose minimum corresponds to the best function for us, in other words, vector $\left(c_1, c_2, \ldots, c_M\right)$, which gives the location of the extremal values, contains the optimal weight of the eigenvectors used in the reconstruction.

**The method of optimization**

In order to find the minimum point of the function $d$, which has been given in equation (4) above, we use our own genetic optimization program. The genetic algorithm has been depicted because $d$ has a lot of local minima (mainly because of the oscillation term) and the gradient-based methods generally cannot find the global minimum in these cases.

Our genetic algorithm uses the standard genetic operators, e.g. mutation and crossing, and in order to accelerate the search for local maxima, it uses hill-climbing steps. We have already applied this code to solve more industrial optimization problems [21].

The optimization program is able to start calculating right from the beginning, not knowing where the optimum can be in the searchable space, but it is possible to assign that a certain element must be in the starting population that is observed. This latter feature is very useful, because when we want to produce the final tables, we have to run the program that is searching for optimal coefficients $c_i$ for several similar colour coordinates $x, y)$. In several cases, when the value pairs $(x, y)$ are close to each other, the optimal sets of coefficients are close to each other.

Some free parameters of the optimization program such as the probability of mutation, the size of the population etc. were determined in the preparation phase when a lot of trial calculations were done.

**The examination of textile samples**

First, we used 2,832 textile samples. The reflectance functions of the samples were given between 400 nm and 700 nm at 10 nm step $N = 31)$. This meant a 31-dimensional vector space, so the eigenvectors were 31-dimensional. These spectra were used to produce the ($v_i$) of PCA. The Principal Component Analysis of the samples was done by *Matlab* software. Fig. 2 shows the distribution the textile samples and the first five eigenvectors and the mean vector ($m$) which plays a very important role.

The next step was to reconstruct some randomly chosen textile samples with the formerly mentioned process of reconstruction in order to find the ideal coefficients $c_i$. When $M = 3$, we got the only metamer with a good approximation. This metamer was a bit distorted by the penalty terms, but the deviation of the resulted valu-

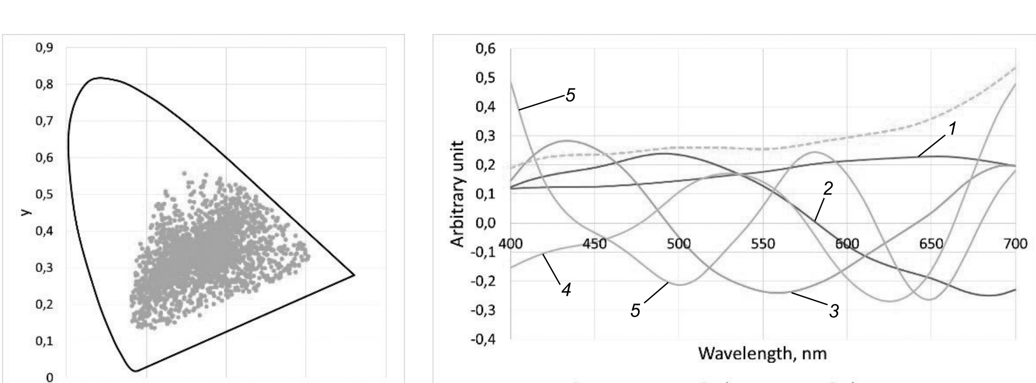


Fig. 2. The distribution of the textile samples in the chromaticity diagram CIE-*xy*. Mean vector (dashed line) and the first 5 eigenvectors for these samples

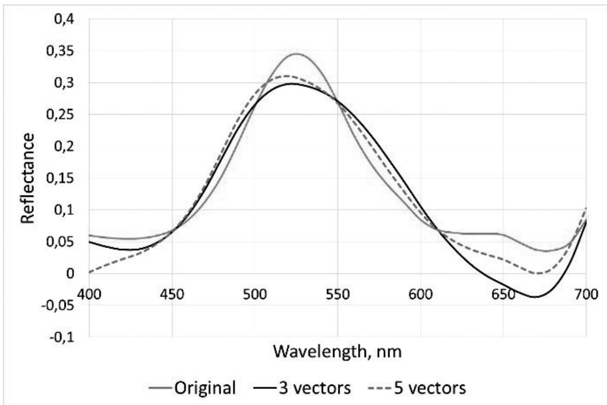


Fig. 3. The black line represents the reconstruction with $M = 3$ and function $d_0$. The dashed line represents the reconstruction with $M = 5$ and function $d$

es $X_0, Y_0, Z_0$ from the stipulated ones was under 1 per mille. On the other hand, the advantage of the method appeared with the increase of *M*: we got nearly accurate metamers, but smoother functions were produced and this qualitative error disappeared where our function was negative. Fig. 3 shows such an example.

We cannot expect a perfect reconstruction even when $M = 5$, as the problem is 31-dimensional, on the other hand, it can be seen that the use of 5 eigenvectors improves the qualitative and quantitative features. According to the pre-calculations, raising $M$ above five improves the accuracy and the qualitative features very slowly, but it lengthens the time of optimization significantly. Therefore, we are to use this value. The following Fig. 4 shows the reconstruction of 4 randomly chosen colour samples among the dozens of reconstruction with the combination of the most important eigenvectors given by PCA and the coefficients determined by the genetic optimization algorithm. It can be seen that there is a deviation mainly at the edges of the visible spectral range. Since the colour-matching functions of CIE have very small values here, this deviation is much smaller than inside the visible range.

The mean value of GFC (goodness of fit coefficient) by new algorithm is 0.9926, the maximum value is 0.9996. The data show that our method, i.e. applying five eigenvectors and constraints on the reflectance functions the real samples provides more accurate reconstruction.

It appears when approaching saturated colours, which are close to the boundary of the *CIE-xy* chromaticity diagram, even optimization cannot find a totally non-negative solution. The rea-

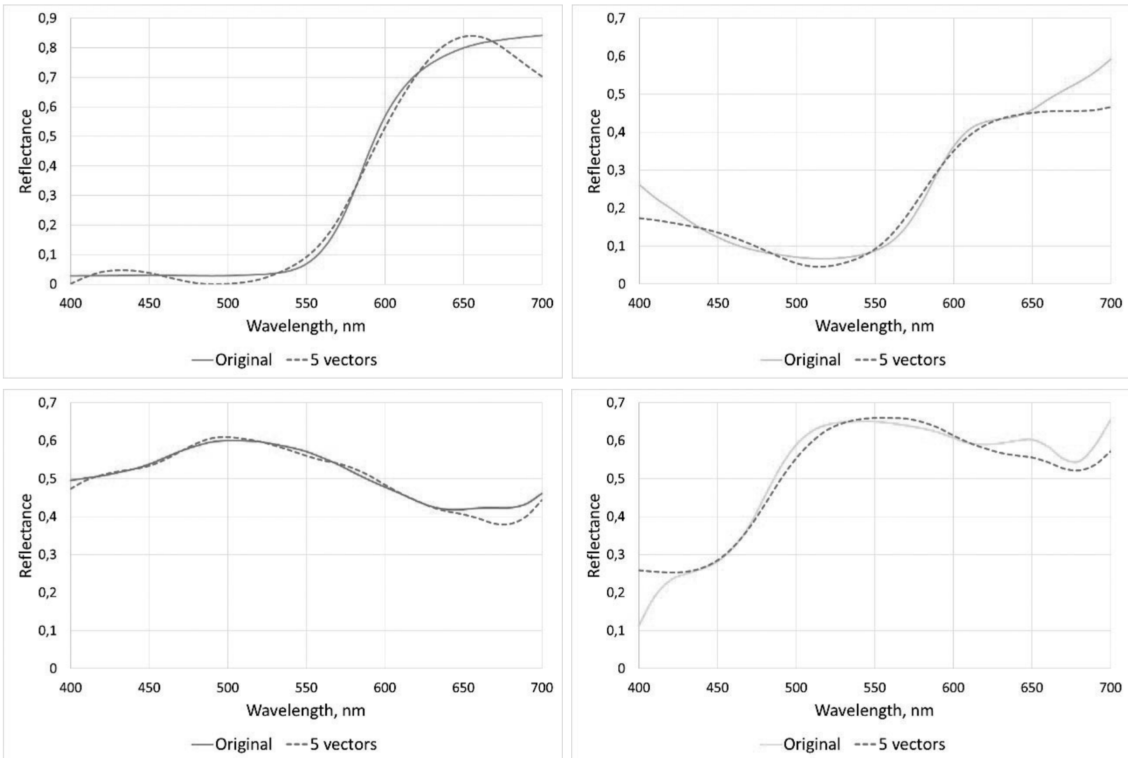


Fig. 4. The reconstruction of 4 samples randomly chosen from the training set when $M = 5$. The original spectrum is represented with line, the reconstructed one is represented with dashed line

son that a very saturated surface colour does not have a real metameric pair except itself or simply does not exist in reality at all, therefore the optimization is able to generate only non-real metamers.

### A quick search for coefficients by the help of look-up tables

When we know the tristimulus values of a sample, it is possible to reconstruct the spectrum of one of its metamers, which approaches well the unknown original spectrum and has good qualitative features by the use of the previously described method. It has only one problem: it takes a long time to run the necessary optimization. When $M=5$, it takes 5–10 minutes to optimize only for one triplet of tristimulus value on a strong, modern personal computer. It is a considerable obstacle in practice, e.g. when we want to do reconstruction on the pixels of a digital photograph.

Fortunately, PCA has to be done only once for a given sample set. If we do the optimization on a lot of samples only once and we store the coefficients $c_i$, later we can reconstruct the spectrum from these in a very short time.

Thinking of digital photographs, we have chosen the chromaticity coordinates $x, y$ and the brightness value $Y$, however, optimization can also be done with other equivalent coordinates. Now, we postulate a hypothetical camera whose colour channels have spectral responses that are the same as the CIE colour-matching functions. We can suppose the same accuracy when we have a real camera, but we have to know the spectral sensitivity of the camera.

To reach our goal, we divide the *CIE-xy* diagram with a mesh of 0.01 along both axes and we determine the coefficients for each grid point. The process is the following. First, we have to determine the chromaticity coordinates $x, y$ from the tristimulus values of the observed sample.

$$x=\frac{X}{(X+Y+Z)},\quad y=\frac{Y}{(X+Y+Z)}. \tag{5}$$

Since the information $Y$ about the brightness disappears in the space given by the coordinates $x, y$, we use the value $Y'=18.42$ on the basis of the gamut of the real colour samples depict able in the colour space *xyY*. This *Y'* is the same as the brightness factor $L^*=50$ in the CIELAB as well as the CIELUV colour space. This is the value where the diameter of the gamut representing real colour samples (colour solid) seems to be the greatest in these colour spaces. As a next step, we determine the values $X'$, $Z'$ related to $Y'=18.42$ for the function (4) using equations (6).

$$X'=\frac{Y'}{y}\cdot x,\ Z'=\frac{Y'}{y}\cdot(1-x-y). \tag{6}$$

Although it is true that we will not get the coefficients $c_i$ belonging to the original values $X,Y,Z$, we will get the spectrum belonging to the original tristimulus values $X,Y,Z$ with good approximation when we multiply the reflectance function derived from the linear combination with these coefficients $c_i$ and the values $\frac{Y'}{Y}$. Fig. 5 shows such an example. We can see the unscaled spectrum belonging to the values $X',Y',Z'$ and the scaled spectrum belonging to the original values $X,Y,Z$.

We have produced the spectra of a dozen samples with this method and we have used only the chromaticity coordinates $x, y$ of the samples and the predefined $Y'$. Table 2 shows the mean values $\Delta E^*_{ab}, RMS, GFC$ of the reconstruction.

The values gained with scaling are good and similar to the earlier results and are much better than the results given by the classical PCA and by the wPCA with regard to all parameters. (See Table 1.)

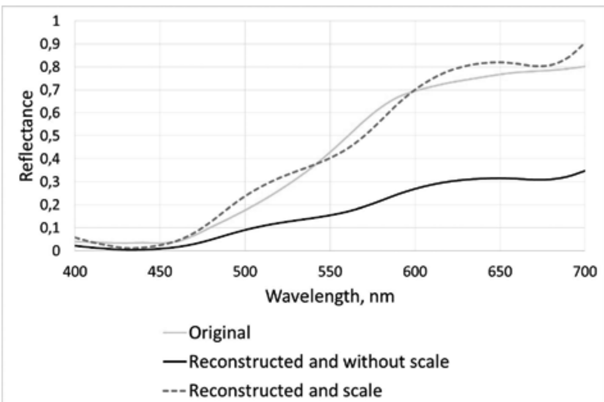


Fig. 5. Displaying scaled and unscaled spectra. The original spectrum is depicted with grey line, the unscaled one with black line and the scaled one with dashed line

**Table 1. The values describing the accuracy of the reconstruction for other textile samples under CIE D65 illuminant on the basis of the data in article [16]**

| | new algorithm | | PCA [16] | | wPCA[16] | |
|---|---|---|---|---|---|---|
| | mean | max | mean | max | mean | max |
| $\Delta E^*_{ab}$ under CIE A | 1.3674 | 3.0269 | 3.200 | 9.740 | 1.820 | 5.040 |
| $\Delta E^*_{ab}$ under CIE E | 0.0100 | 0.0230 | n/a | n/a | n/a | n/a |
| $\Delta E^*_{ab}$ under CIE D65 | 0.3926 | 0.8852 | n/a | n/a | n/a | n/a |
| RMS (root mean square) | 0.0300 | 0.0412 | 0.073 | n/a | 0.059 | n/a |

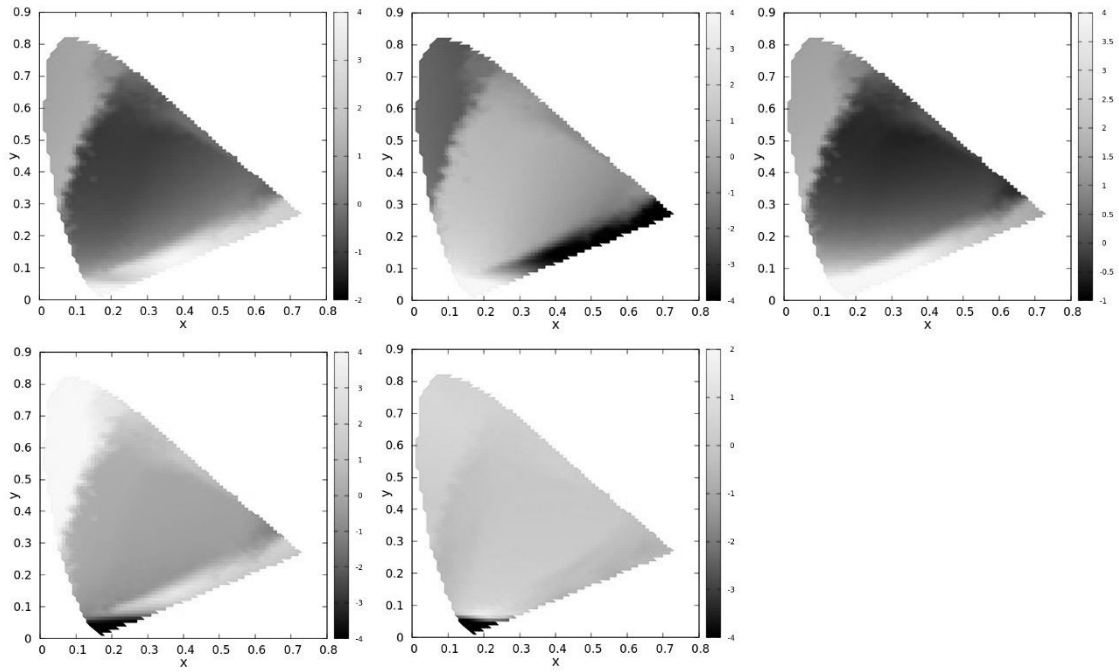

Fig. 6. The coefficients $c_1$, $c_2$, $c_3$, $c_4$, $c_5$, of textile samples in the *CIE-xy* plane

The coefficients belonging to the given points $x, y$ are stored in look-up tables, in this way five blocks with the size of $85 \times 75$ (because of the CIE *x, y* chromaticity diagram) are needed for storage all together. The reconstruction can be done by the use of these tables, the first five eigenvectors of PCA, the mean vector and the values $X, Y, Z$ of a colour sample or pixel which spectrum is unknown.

**Table 2. The mean values $\Delta E^*_{ab}, RMS, GFC$ of the spectra derived from values *x, y* with scaling**

| | |
|---|---|
| $\Delta E^*_{ab}$ under CIE E | 0.0110 |
| $\Delta E^*_{ab}$ under CIE A | 2.1072 |
| $\Delta E^*_{ab}$ under CIE D65 | 0.5059 |
| RMS | 0.0414 |
| GFC | 0.9922 |

Then the coefficients $c_i$ belonging to the pairs $x, y$ can be read from the generated tables. These coefficients have to be used in the linear combination given by equation (1) and the spectrum resulted from this combination has to be scaled as it is described above.

If the requested pair $x, y$ is not on the grid of the look-up table, the desired coefficients can be given with the linear interpolation of the points that are in the neighbourhood of the requested point.

The generation of look-up tables are done in two steps. First of all, optimization is run after

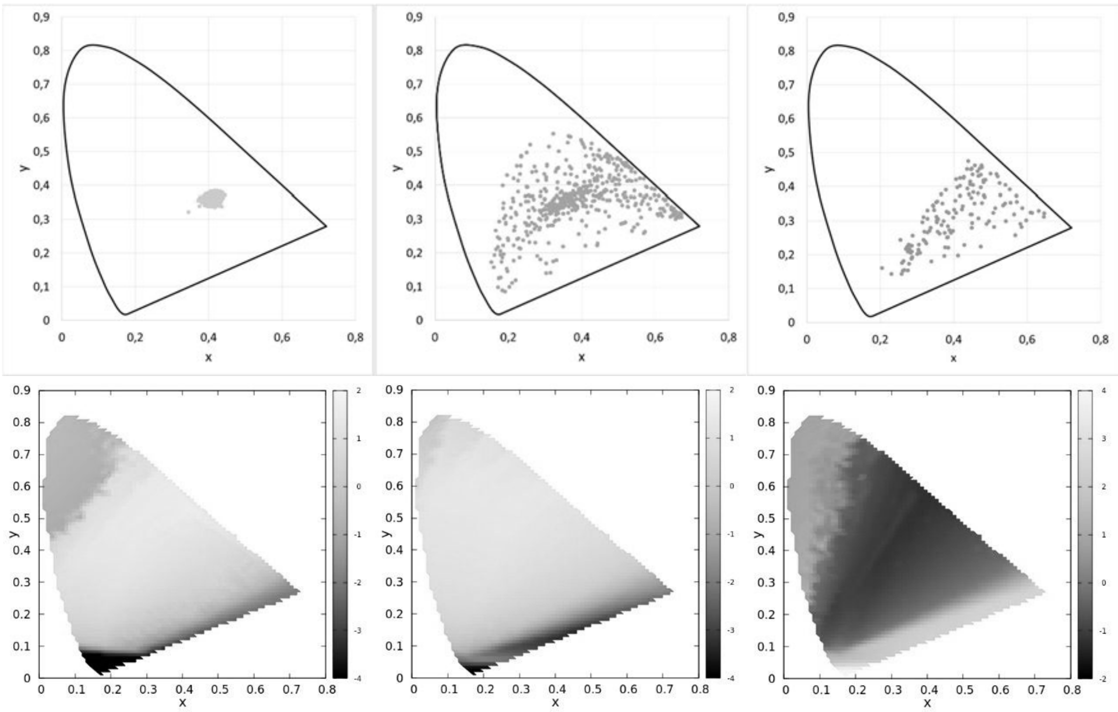

Fig. 7. The distribution of skin, paint and flower samples in the CIE-*xy* plane, and the coefficients $c_1$ belonging to them

all the calculations are done in the whole searching space with a random starting population. The resultant look-up tables are used in the second round of optimization. Here, the starting population contains the coefficients of the neighbouring elements to the tables generated in the first round. This step reduces the chance to keep a result that is in a local minimum, because it is supposed that the optimal coefficients of the points laying close to each other are very similar.

Fig. 6 shows the coefficients $c_i$ for textile samples with colour tones. A certain size of oscillation can be seen in the position of the coefficients in the *CIE-xy* plane. The oscillation is approximately 1 %-2 % and its influence on the reconstructed spectra is negligible.

**The resource needs of the method**

We need to store the following data in order to use the final results of the calculations quickly.

- The mean vector determined with PCA and the first $M$ vector. It means $(M+1)\cdot N = 6\cdot 31 = 186$ floating point values.
- $M$ $75\cdot 85$ -sized tables with 0.01 resolution. It means $M\cdot 75\cdot 85 = 5\cdot 75\cdot 85 = 31{,}875$ floating point values.

Even if we use double point storing, it means 256 kB of data, which is very little compared to the memory size of a modern computer, even if we talk about mobile devices.

The calculation needs are small as well. We can derive $x$ and $y$ from the values $X,Y,Z$ with less than 10 basic operations. We can obtain the corresponding values $c_i$ with linear interpolations in the tables, which means less than 100 operations when $M=5$. Knowing values $c_i$, we can solve equation (1) with $M\cdot N\cdot 2 + N = 341$ operations, so the reconstruction from tristimulus values can be done with less than 1,000 operations.

So it is an important feature of the method that after PCA and calculating the look-up tables, only little memory and short time is needed to do spectral reconstruction. The resource need would remain manageable if the values $M$ and $N$ were greater for the sake of greater accuracy.

**The observation of further colour sample sets**

The first question is what the coefficients and the reconstructed spectra are if we use other samples than textile samples. It is supposed that different spectra will belong to the same values $X,Y,Z$ if we use other training sets. We have completed the analysis for 148 flower samples, 565 paint samples and 8,533 human skin samples (See Fig. 7) and have generated the look-up tables. Fig. 7 also shows only the distribution of the co-

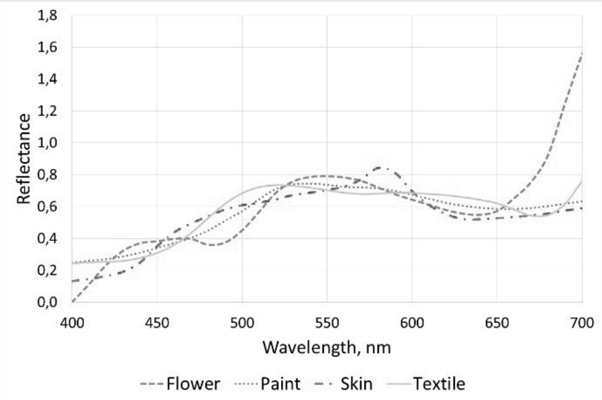


Fig. 8. The reconstructed spectra for given tristimulus values in case of different training sets

efficients $c_1$ for keeping the size of the paper manageable. Seemingly, they are different for the different sample sets.

The second question is how the reconstructed spectrum deviates when the eigenvectors of PCA and the coefficients $c_i$ are different for different sample sets. In other words, if the chromaticity coordinates $x, y$ are given and the spectrum belonging to the chromaticity coordinates is determined on the basis of the four sample sets and it is scaled, in what measure are the reconstructed spectra different? Fig. 8 shows such an example, it shows the reconstructed spectrum belonging to the point $x = 0.37, y = 0.41$.

Fig. 8 shows that different spectra belong to the give tristimulus values and that it depends on the training set. The reconstructed spectra of the textile samples show less oscillation than the spectra of paint and flower samples, which corresponds to their features. Further details can be found in article [22].

All in all, we can reconstruct spectrum for the chromaticity coordinates of a colour sample with unknown spectrum, and we can determine the features of the spectrum when the unknown sample was of skin, of paints or of flowers. Certainly, the method can be made more accurate by the use of further sample sets or with the increase of the number of elements in the existing sample sets.

## SUMMARY

The main goal of our study was to observe whether we could determine the spectrum of a metamer of a colour sample with unknown spectrum in a way that the result should be as similar to the original spectrum as possible and it should have good qualitative features. Therefore, we used five instead of three eigenvectors of PCA under a given illuminant, and we applied a genetic algorithm to derive the coefficients of the less oscillating and possibly non-negative metamers from these vectors. Our method helps us to generate the coefficients, which relate to the grid of the CIE-*xy* plane and are necessary to produce the spectrum for different colour sample sets in advance. The results can be stored in computer memory of a small size and only few calculations are needed to use them. It is apparent that our method makes it possible to find the spectrum in such cases when we do not have enough data to do other type of optimization. This method is even applicable on mobile devices to do approximate spectral reconstruction if we have some information about the content of the picture. Calculations show that this type of spectral reconstruction works well with different illuminants [20].

## REFERENCES

1. Habel J and Žák P.: The present and future of lighting engineering, Light & Engineering, 2012, Vol. 20, No. 2, pp 5–11.

2. Horváth A and Dömötör G.: Computational Simulation of Mesopic Vision Based on Camera Recordings, Light & Engineering, 2014, Vol. 22, No 1, pp. 61–67.

3. Tzeng DY, Berns RS. A Review of Principal Component Analysis and Its Application to Color Technology. Color Research and Application, 2005 April, Volume 30, Number 2, pp.84–98.

4. Maloney LT. Evaluation of linear models of surface spectral reflectance with small numbers of parameters. Journal of Optical Society of America, 1986, 3, pp. 1673–1683.

5. Jaaskelainen T, Parkkinen J, Toyooka S. Vector-subspace model for color representation. Journal of Optical Society of America, 1990, 7, pp. 725–730.

6. Vrhel MJ, Gershon R, Iwan LS. Measurement and analysis of object reflectance spectra. Color Research and Application, 1994, 19, pp.4–9.

7. García-Beltrán A, Nieves JL, Hernández-Andrés J, Romero J. Linear bases for spectral reflectance functions of acrylic paints. Color Research and Application, 1998, 23, pp.39–45.

8. Tajima J. A huge spectral characteristics database and its application to color imaging device design. Proceedings of the 6th IS&T/SID Color Imaging Conference, IS&T, Springfield, VA; 1998. pp. 86–89.

9. Hardeberg JY, Schmitt F, Brettel H. Multispectral color image capture using a liquid crystal tunable filter. Opt Engineering 2002, 41, pp. 2533–2548.

10. Maloney LT, Wandell BA. Color constancy: a method for recovering surface spectral reflectance. Journal of Optical Society of America, 1986, 3, pp. 29–33.

11. D'Zmura M. Color constancy: surface color from changing illumination. Journal of Optical Society of America, 1992, 9, pp. 490–493.

12. Dannemiller JL. Spectral reflectance of natural objects: how many basis functions are necessary? Journal of Optical Society of America, 1992, Vol. 9, No. 4, pp.507–515.

13. Worthey JA, Brill MH. Principal Components Applied to Modeling: Dealing with the Mean Vector. Color Research and Application, 2004, Vol. 29, No. 4, pp.261–266.

14. Zhao Y, Berns RS. Image based spectral reflectance reconstruction using Matrix R method. Color Research and Application, 2007, Vol. 32, pp. 343–351.

15. Babaei V, Amirshahi SH, Agahian F. Using weighted pseudo-inverse method for reconstruction of reflectance spectra and analyzing the dataset in terms of normality. Color Research and Application, 2011, Vol. 36. pp. 295–305.

16. Farnaz A, Seyed AA, Seyed HA. Reconstruction of reflectance spectra using weighted principal component analysis. Color Research and Application, 2008, Vol. 33, No. 5, pp.360–371.

17. Simone B. Reflectance spectra recovery from tristimulus values by adaptive estimation with metametric shape correction. Journal of Optical Society of America, 2010, Vol. 27, No. 8, pp.1868–1877.

18. Zhang X, Xu H. Reconstructing spectral reflectance by dividing spectral space and extending the principal components in principal component analysis. Journal of Optical Society of America, 2008, No. 25, pp.371–378.

19. Mansouri A, Sliwa T, Hardeberg JY, Voisin Y. An adaptive-pca algorithm for reflectance estimination from color images. Proceedings of the 19th IEEE International Conference on Pattern Recognition, 2008, pp. 1–4.

20. Sávoli Zs, Dr. Kránicz B, Dr. Horváth A: Spectral reconstruction in case of different illuminants, Annals of Faculty Engineering Hunedoara – International Journal of Engineering, University Politehnica Timisoara, 2016, Vol 14.1, pp. 45–54.

21. Horváth A, Horváth Z. Optimal shape design of Diesel intake ports with evolutionary algorithm. M Feistauer (szerk.) Numerical Mathematics and Advanced Applications, ENUMATH 2003.

22. Zs. Sávoli, A. Horváth, B. Kránicz: Spectral reconstruction with genetic optimization in case of different sample sets, Acta Technica Jaurinensis, Széchenyi István University, Győr, 2016, Vol 9, No 1, pp. 54–64.

***András Horváth,*** graduated as physicist at Eötvös Lóránd University (Budapest, Hungary) in 1992. He received Ph.D. in 1999. At present time, he is an associated professor of Széchenyi István University (Győr, Hungary), Dept. of Physics and Chemistry

***Zsolt Sávoli,*** graduated in physics and chemistry from the Attila József University of Szeged (Hungary). He studied in Information Technology at Pannon University of Veszprém (Hungary). At present, he researches in colorimetry as a Ph.D. student at István Széchenyi University of Győr (Hungary)

***Balázs Kránicz,*** graduated in Information Technology at Pannon University of Veszprém (Hungary). He obtained a Ph.D. degree in Information Technology at Pannon University of Veszprém. He co-authored numerous scientific publications and invented patents in colorimetry. He taught at Pannon University of Veszprém and gained some awards

# LUMINANCE PARAMETERS OF THE STANDARD CIE SKY WITHIN NATURAL ROOM ILLUMINATION CALCULATIONS AND THEIR APPLICATION UNDER VARIOUS LIGHT CLIMATE CONDITIONS IN RUSSIA

Victor A. Zemtsov [1], Aleksei K. Solovyov [2], and Igor A. Shmarov [1]

*[1]The Scientific Research Institute of Construction Physics RAACS, Moscow*
*[2]The MSCU Federal State Budgetary Educational Institution of the Higher Vocational Training, Moscow*
*E-mail: ins-es@yandex.ru*

**ABSTRACT**

The main aims of the national standard project "Construction Climatology" are described. Calculation parameters of natural illumination are presented, considering firmament luminance distribution, and their application under various light-climate conditions in Russia are discussed. It is noted that this standard is a modification of the corresponding international *ISO* standard.

Fifteen types of firmament designated by the international standard are considered, and a technique is offered to select a firmament type matching specific conditions of a local light climate in Russia. Approaches to light climate accounting in calculation of building natural illumination are analysed.

**Keywords:** light climate, natural illumination, firmament types, cloud amount, clear sky, overcast sky, equiluminous sky, luminance distribution, homogeneous firmament, scattering indicatrix, diffuse illuminance, total illuminance

## INTRODUCTION

Natural illumination parameters are major indicators of indoor environmental quality and safety, in rooms regulated by the Building regulations (SNiP) [1]. Calculations of these parameters take into account many factors, which are heavily researched in the fields of building and light engineering. A collection of the rules and regulations is intended for their account [2]. It is created based on updating the Building regulations SNiP 23–05–2003* and 23–102–2003.

These rules and regulations should be adapted relative to the international ISO standard 15469:2004 / CIE S011/E: 2003 and to the other correspondent international standard documents.

### Modern methods of analysing the firmament luminance distribution when calculating daylight factor

Natural illumination calculations are based on the main assumption of an overcast sky with ten-point cloudiness. This was accepted as standard by the CIE based on P. Moon and D. Spencer's law and it is applicable to comparative natural illumination calculations for buildings constructed under various light-climate conditions across Russia. According to this key assumption, the relation of the sky luminance $L_\theta$ at horizon angle $\theta$ to the sky luminance at zenith $L_z$ can be expressed as:

$$\beta = \frac{L_\theta}{L_z} = \frac{1+2\sin\theta}{3}. \qquad (1)$$

Therefore, according to this assumption, luminance only changes with height (by meridian). As latitude changes, at the same $\theta$, luminance remains constant.

As the basis of the room daylight factor calculation is the calculation of the geometrical daylight factor only dependent on a solid angle, which is passing from a reference point through the light opening in case of an equiluminous sky, overcast sky luminance is accounted for using coefficient $q$ connecting luminance of a firmament site with its average luminance:

$$q = \frac{(1+2\sin\theta)\cdot 3}{7}. \qquad (2)$$

In reality, a ten-point overcast sky is not a very frequent condition in various regions of Russia, and its probability is extremely seasonally variable. In some regions, clear sky (Transbaikal, North Caucasus, Crimea) prevails. In northwest regions, according to general opinion, an overcast sky is prevalent. Sky luminance distribution depends on the weather and climate, and changes during a day depending on the sun's position. A firmament luminance distribution standard for Russia is needed to simulate the sky in a wide range of weather conditions: from cloudy to clear sky.

The most complete presentation of different states of the firmament can be found in the 15 models developed by Slovak scientists S. Darula and R. Kittler [3]. The scientists determined the application field of these typically homogeneous models to calculate natural illumination in different cases: for example, when designing light openings, when calculating blindness levels, annual natural light profiles, or annual usage time of natural illumination. The correspondent standard luminance distributions over the sky for different cloudiness conditions should be determined by a standard.

The 15 models mentioned above are symmetric relative to a solar meridian and are the functions of angular distance $Z_s$ between the sun's position and zenith. They are determined by smooth continuous functions. These properties are typical for clear sky and for separate types of sky condition with uniform cloud cover and raised luminance near the solar disk, or in case of ten-point cloudiness. Intermediate luminance distributions provide an approximate luminance expression of a variably cloudy sky, which is exact enough and only possible in terms of statistics to calculate natural illumination.

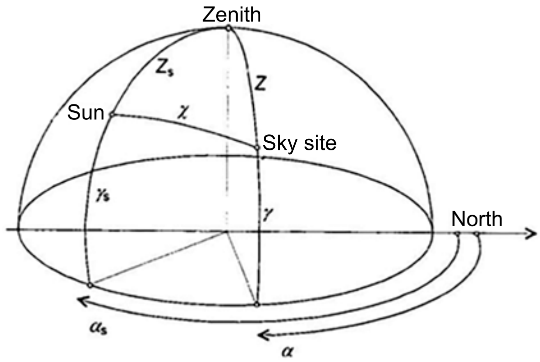


Fig. 1. Angles determining the sun's position and luminance of a sky site

Fig. 1 shows the angles designating the sun and the sky site, the luminance of which is to be determined.

Relation $\beta$ of a sky site luminance $L_\alpha$ to zenith sky luminance $L_z$ (a relative luminance) is expressed as follows:

$$\beta = \frac{L_\alpha}{L_z} = \frac{f(\chi)\cdot\varphi(Z)}{f(Z_s)\cdot\varphi(0)}, \qquad (3)$$

where $\varphi(Z)$ is sky site luminance gradation function correlating the sky site luminance with its zenith angle $Z$:

$$\varphi(Z) = 1 + a\cdot\exp\left(\frac{b}{\cos Z}\right), \quad \text{where } 0 \le Z < \frac{\pi}{2}; \qquad (4)$$

$f(\chi)$ is relative scattering indicatrix representing relation of the sky relative luminance at a point to its angular distance $\chi$ from the sun:

$$f(\chi) = 1 + c\left[\exp(d\chi) - \exp\left(d\frac{\pi}{2}\right)\right] + e\cdot\cos^2\chi\ , \qquad (5)$$

$$f(Z_s) = f(\chi) \text{ for } \chi = Z_s;$$

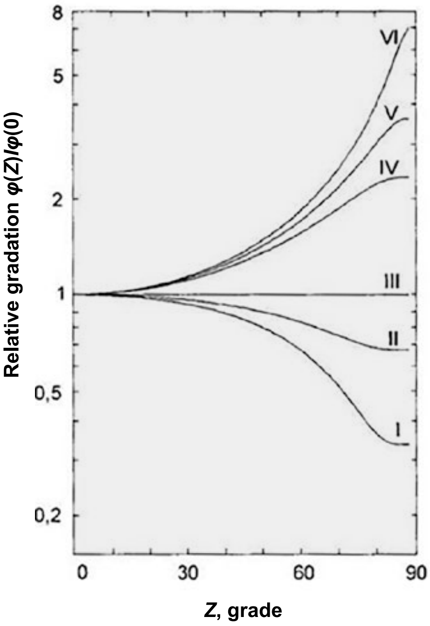


Fig. 2. Function groups of typical luminance changes when changing zenith distance $Z$

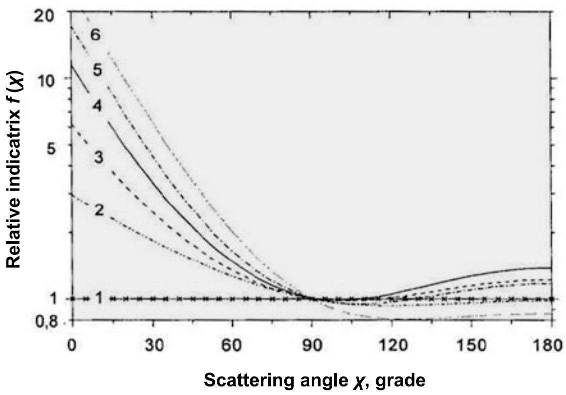


Fig. 3. Function groups of typical sky luminance indicatrix when changing scatter angle $\chi$

$a$, $b$, $c$, $d$, $e$ are parameters selected according to Table 1, where 15 typical models of the sky relative luminance distribution proposed by Darula and Kittler and modified by *ISO* are listed. They are divided into six groups (six by gradation and six by scattering indicatrices groups).

Thus according to formulas (3) – (5) and Table 1, it is possible to find $\beta$ values for any point position at the firmament and for any of the 15 firmament models. And in order to better understand the $\varphi(Z)/\varphi(0)$ relation influence on the sky luminance depending on $Z$, our calculation diagram in Fig. 2 can be used. Furthermore, to determine $f(\chi)$ indicatrix, Fig. 3 can be used. All of this facilitates the calculations.

## Selection of the sky state and of the sun position for the calculations

Unfortunately, the question of the model selection remains, as does that of the sun's position selection for the calculations.

Calculations of natural illumination are mainly intended to compare natural illumination conditions with the standard. It is not possible to use the 15 standard firmament models unless we first determine which of them is applicable to a specific region's light and climate. Without determining this applicability, the daylight factor concept loses its meaning as a comparison value.

At present, comparative calculations of daylight factor are performed according to the CIE overcast sky approach. Sky relative luminance $\beta$ calculations according to Moon and Spencer's law (1) and for the CIE standard sky (type 1 sky) by formula (3), the results of which are given in Fig. 4, show that at horizon with $Z = 83 – 90^{o}$

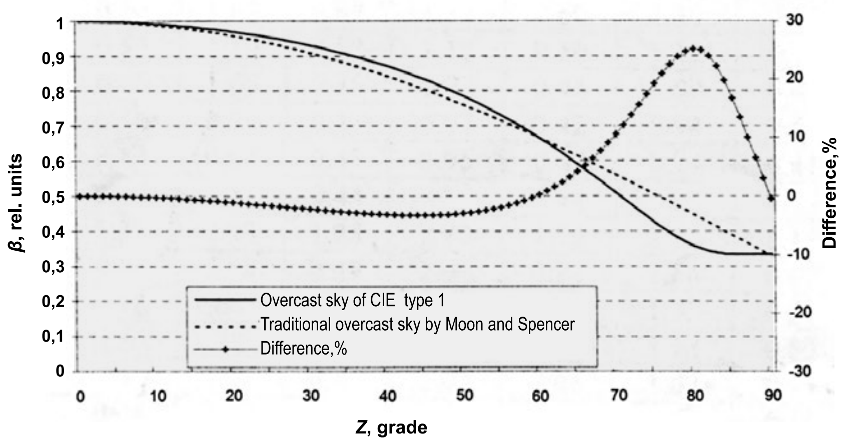


Fig. 4. Difference between type 1 sky and the sky by Moon and Spencer's law

**Table 1. Standard luminance sky parameters**

| Sky type | *Gradation group* | *Indicatrix group* | *a* | *b* | c | *d* | *e* | *Description of light distribution* |
|---|---|---|---|---|---|---|---|---|
| 1 | I | 1 | 4.0 | -0.70 | 0 | -1.0 | 0 | **CIE standard sky «CIE overcast sky»,** gradation of light luminance increase towards zenith, azimuth uniformity |
| 2 | I | 2 | 4.0 | -0.70 | 2 | -1.5 | 0.15 | Overcast sky with high clouds and a small luminance increase towards the sun |
| 3 | II | 1 | 1.1 | -0.8 | 0 | -1.0 | 0 | Cloudiness with an average change and azimuth uniformity |
| 4 | II | 2 | 1.1 | -0.8 | 2 | -1.5 | 0.15 | Cloudiness with an average change and a small luminance increase towards the sun |
| 5 | III | 1 | 0 | -1.0 | 0 | -1.0 | 0 | **Uniform sky luminance** |
| 6 | **III** | 2 | 0 | -1.0 | 2 | -1.5 | 0.15 | An alternating cloudiness without luminance change towards zenith and easy light gap towards the sun. |
| 7 | III | 3 | 0 | -1.0 | 5 | -2.5 | 0.30 | An alternating cloudiness without luminance change towards zenith, a light gap towards an area near the sun |
| 8 | III | 4 | 0 | -1.0 | 10 | -3.0 | 0.45 | An alternating cloudiness without luminance change towards zenith and with a clear halo round the sun |
| 9 | IV | 2 | -1.0 | -0.55 | 2 | -1.5 | 0.15 | An alternating cloudiness with the sun closed by clouds |
| 10 | IV | 3 | -1.0 | -0.55 | 5 | -2.5 | 0.30 | An alternating cloudiness with luminance increase near the sun |
| 11 | IV | 4 | -1.0 | -0.55 | 10 | -3.0 | 0.45 | White-blue sky with a clear solar halo |
| 12 | V | 4 | -1.0 | -0.32 | 10 | -3.0 | 0.45 | **The Clear Sky CIE standard with a high transparency of atmosphere** |
| 13 | V | 5 | -1.0 | -0.32 | 16 | -3.0 | 0.30 | **The Clear Sky CIE standard with contaminated atmosphere** |
| 14 | VI | 5 | -1.0 | -0.15 | 16 | -3.0 | 0.30 | Cloudless sky with a low transparency of atmosphere with a wide halo round the sun |
| 15 | VI | 6 | -1.0 | -0.15 | 24 | -2.8 | 0.15 | White-blue sky with a high transparency of atmosphere with a wide halo round the sun |

and with sky type 1, $L_{\theta}/L_Z = 0.333$, and according to Moon and Spencer's law, this value is constant at $Z = 90^o$ only. It also can be seen from Fig. 4 that the correspondent relative difference at $Z = 80^o$ reaches 25 %. This suggests that traditional daylight factor calculations (by Moon and Spencer's law) overestimate the results in comparison with those accepted in Europe. So for example, in a room 6m in length, on a floor point which is at a distance of 1m from the wall opposite the windows, the overstatement of coefficient $q$ would amount to about 10 %. At the centre of the room with the same dimensions and with a standard window height, this difference is negligible.

Under city building conditions, when the lower part of the horizon is blocked by an adjacent building, and firmament sites with $Z = 15 - 60^0$ get through the window to the reference point, *q* calculation values for the CIE standard sky (type 1 sky) are higher, which increasingly influences the calculation of the daylight factor in the studied room.

$$\frac{L_\alpha}{L_z}=\frac{\left\{1+c\left[\exp(d\chi)-\exp\left(d\frac{\pi}{2}\right)\right]+e\cdot\cos^2\chi\right\}\cdot\left[1+a\cdot\exp\left(\frac{b}{\cos Z}\right)\right]}{\left\{1+c\left[\exp(dZ_s)-\exp\left(d\frac{\pi}{2}\right)\right]+e\cdot\cos^2 Z_s\right\}\cdot\left[1+a\cdot\exp b\right]}. \quad (6)$$

Comparative calculations are possible, when sky luminance does not depend on the orientation of the light opening, i.e. when luminance azimuth uniformity takes place. It happens in cases of sky types 1, 3 and 5 (Table 1). And in these cases, the daylight factor does not depend on the sun's position. In regions with frequent sunny days sky luminance distribution depends on many factors (sun's position in the sky at the moment of calculation, window orientation, etc.). The CIE Clear Sky standard at a high atmosphere transparency is firmament of type 12, and at a polluted atmosphere of big cities it is of type 13.

According to formulas (3) – (5), (see eqn. 06)

Substituting *a*, *b*, *c*, *d*, *e* values for type 12 sky into formula (6), we obtain R. Kittler's formula previously standardised by CIE. This formula can be suitable for practical calculations if $\chi$ and $Z_s$ values are used. For this it is necessary to know the orientation of the light opening and the sun azimuth at the moment of calculation.

One of the methods for room natural illumination in the case of a clear sky is given in article [4]. Within this method, calculating the sun's position is such that clear sky daylight factor is minimal at a given light opening orientation, and external illuminance tends to critical ($E_{cr}$)[1]. To determine the calculation for the sun's position, $E_{cr}$ values were selected according to the expression

$$E_{cr}=E_{ar}^{norm}\cdot 100/e, \quad (7)$$

where $E_{ar}^{norm}$ is normalised artificial illuminance, *e* is normalised daylight factor value.

They amounted to 10000, 7500, 5000 and 2500 *lx* [5], which covers practically all $E_{cr}$ value interval.

[1] It should be noted that the daylight factor concept with reference to clear sky conditions is convenient. For an overcast sky and with azimuthal sky uniformity of type 1, 3 and 5, the daylight factor in a given point of the room is a constant value. For a clear sky, in case of luminance distribution as per R. Kittler, it depends on the sun's position relative to the light opening.

Article [4] also shows that the most unfavourable orientation area of a light opening in relation to the solar meridian is between 105 ° and 225° angles.

Open air levels of total and diffuse illuminance can be determined using analytically obtained formulas [3] or by means of approximating natural measurements performed within the CIE research program. Using the results of these research projects, P. Tregenza proposed empirical formulas [6], the application of which allowed us to ob-

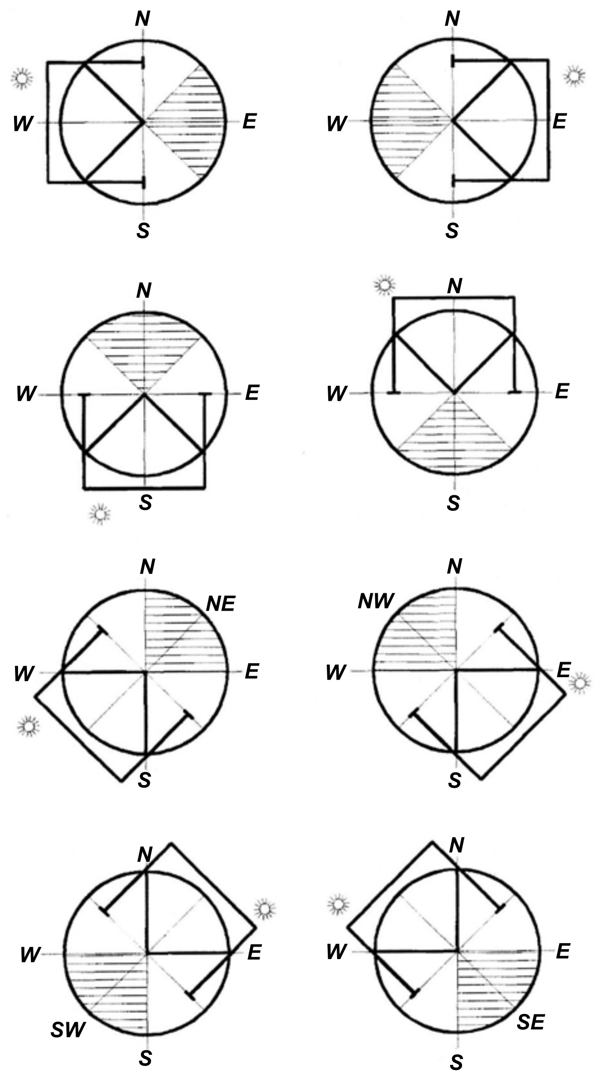


Fig. 5. A diagram for calculating sun positions at different orientations of the vertical light opening. Unfavourable firmament sectors are dashed

tain solar heights $h_s$ for the selected $E_{cr}$ (Table 2) [4].

$E_{cr}$ time in different latitudes for each day of the year and sun azimuth for this time can be determined using $h_s$ for this latitude by means of formulas known from astronomy [7]. In Fig. 5 firmament sectors are shown, in which most unfavourable luminance distribution over the firmament is observed when the sun is there.

For these unfavourable conditions, some parameter values for northern latitudes 70°, 55° and 40° are computed, for which the daylight factor values should be calculated in case of clear skies (Table 3). Standard $\beta$ distribution diagrams of clear sky are proposed for atmosphere transparency $P = 0.7$ and 0.6. Coefficient $q$ distribution diagrams are also proposed (Fig. 6).

**Selection of the firmament calculation type**

The diagrams above mentioned are applicable to comparative calculations. But it is necessary to determine, when to use the overcast sky assumption, and when the clear sky assumption.

An account of the light climate resources according to document [2] is based on an updated model of room light mode, which allows assessing the influence on natural illumination of such factors, as cloudiness mode in the considered construction location annual cycle, orientation of light openings relative to the horizon sides and real luminance distribution over firmament corresponding to the cloudiness mode in the considered interval.

**Table 2. Calculation height ($h_s$) and zenith distance ($Z_s$) of the sun**

| $E_{cr}$, lx | $h_s$, grade | $Z_s$, grade |
|---|---|---|
| 2500 | 4 | 86 |
| 5000 | 7.5 | 82.5 |
| 7500 | 10.6 | 79.4 |
| 10000 | 13.8 | 76.2 |

Average annual illumination quantity indoors is accepted to be an assessment criterion of a room's light mode. This criterion is based in physiology and addresses the need to keep the same level of visual working comfort in regions with different light and climate conditions. When the document [2] was being developed, three models of luminance distribution over firmament were known: the cloudy sky, the clear sky and the average sky. When calculating average annual illumination quantity indoors, firmament state of the cloudy sky was assessed by 10 points, of the average sky by 3–7 points and of the clear sky by 0 points.

The developed standard, which basis is international standard ISO 15469:2004/CIE S011 /E:2003 "Spatial distribution of daylight – CIE standard overcast sky and clear sky" [8], makes it possible to analyse more details of the local light climate, which will considerably raise the accuracy of assessment of natural illumination for different room and building functions.

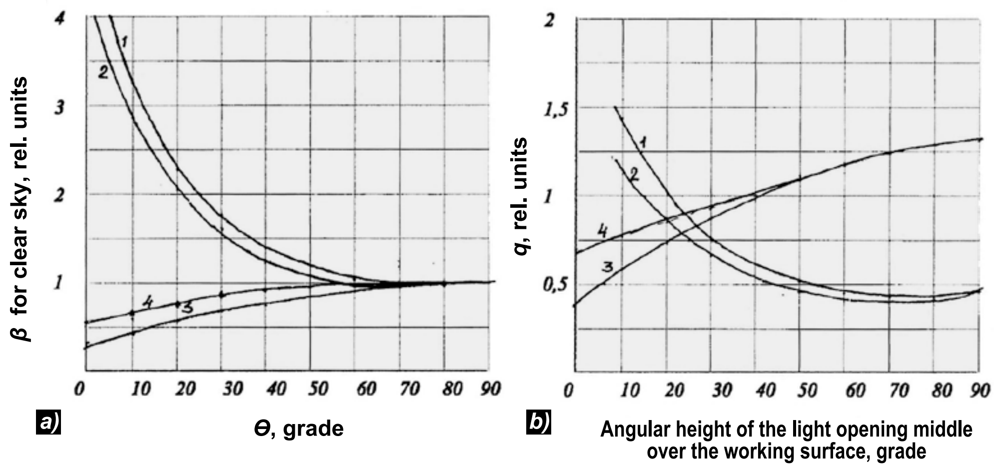


Fig. 6. Standard diagrams of relative luminance distribution $\beta$ of clear sky at $P = 0.7$ (1) and 0.6 (2), as well as distribution diagrams of $q$ coefficients at the same $P$ values. To be compared, $\beta$ and $q$ values are given for overcast sky (curves 3) and $q$ values – for overcast sky and steady snow cover (4)

**Table 3. Relative luminance values of sky sites $\beta$ ($\theta$) and of the correspondent coefficients $q$ at sun calculation height $h_s$ and atmosphere transparency $P$ = 0,7 and 0,6 ($\theta$ and $h_s$ are in grades., $E_{cr}$ is in lx)**

| $P$ | $\theta$ | $h_s$ = 3.95; $E_{cr}$ = 2500 | | $h_s$ = 7.5; $E_{cr}$ = 5000 | | $h_s$ = 10.6; $E_{cr}$ = 7500 | | $h_s$ = 13.8; $E_{cr}$ =10000 | |
|---|---|---|---|---|---|---|---|---|---|
| | | $\beta$ | $q$ | $\beta$ | $q$ | $\beta$ | $q$ | $B$ | $q$ |
| 0,7 | 10 | 3.47 | 1.54 | 3.35 | 1.47 | 3.23 | 1.41 | 3.08 | 1.35 |
| | 20 | 2.43 | 1.08 | 2.34 | 1.03 | 2.26 | 0.98 | 2.15 | 0.94 |
| | 30 | 1.84 | 0.82 | 1.77 | 0.78 | 1.70 | 0.74 | 1.62 | 0.67 |
| | 40 | 1.48 | 0.66 | 1.42 | 0.62 | 1.37 | 0.60 | 1.30 | 0.57 |
| | 50 | 1.24 | 0.55 | 1.19 | 0.52 | 1.15 | 0.50 | 1.11 | 0.48 |
| | 60 | 1.10 | 0.49 | 1.06 | 0.46 | 1.02 | 0.44 | 0.99 | 0.43 |
| | 70 | 1.03 | 0.46 | 0.99 | 0.43 | 0.97 | 0.42 | 0.94 | 0.41 |
| | 80 | 0.98 | 0.44 | 0.97 | 0.43 | 0.96 | 0.42 | 0.94 | 0.41 |
| | 90 | 1 | 0.44 | 1 | 0.44 | 1 | 0.44 | 1 | 0.44 |
| 0.6 | 10 | 3.05 | 1.33 | 2.93 | 1.25 | 2.82 | 1.19 | 2.66 | 1.13 |
| | 20 | 2.16 | 0.94 | 2.08 | 0.89 | 2.00 | 0.84 | 1.88 | 0.80 |
| | 30 | 1.66 | 0.72 | 1.60 | 0. 68 | 1. 53 | 0. 65 | 1.45 | 0. 62 |
| | 40 | 1.35 | 0.60 | 1.30 | 0.56 | 1.25 | 0.53 | 1.18 | 0.50 |
| | 50 | 1.15 | 0.50 | 1.11 | 0.47 | 1.07 | 0.45 | 1.02 | 0.43 |
| | 60 | 1.01 | 0.44 | 0.98 | 0.42 | 0.95 | 0.40 | 0.91 | 0.39 |
| | 70 | 0.97 | 0. 42 | 0. 95 | 0. 41 | 0. 92 | 0. 39 | 0.90 | 0.38 |
| | 80 | 0. 96 | 0. 42 | 0.95 | 0.41 | 0.94 | 0. 40 | 0. 92 | 0. 39 |
| | 90 | 1 | 0. 44 | 1 | 0. 43 | 1 | 0. 42 | 1 | 0.43 |

To assess the light climate for a particular location based on the cloudiness calculation, a technique for sky type selection is needed (Table 1), as a basis for natural illumination calculations.

If we assume that statistically cloudiness ranges from overcast to clear sky continuously under homogeneous firmament conditions, as it is shown in Table 1, a simple technique can be used, which was proposed by G. Gillette and S. Trido [7] to account for local cloudiness. For this technique, they used a relation of diffuse and total solar radiation levels, which they named the cloudiness coefficient $K_o$. If $K_o$ is close to 1, then at this period in this place, an overcast sky prevails. If $K_o$ = 0.1–0.2, clear sky prevails. S. Darula and R. Kittler's article [3] also describes a method of the sky classification with the criterion: zenith fraction. However, this method is rather complex and difficult to apply in practice. One more parameter is the relation of sunlight diffuse illuminance $D_v$ to diffuse illuminance $E_v$ without sunlight, which is also proposed by these authors, and is simpler to apply. Hwever, it is also based on theoretical calculations.

Diffuse and total solar radiation level ratio $K_o$, data for which are available at numerous actino-

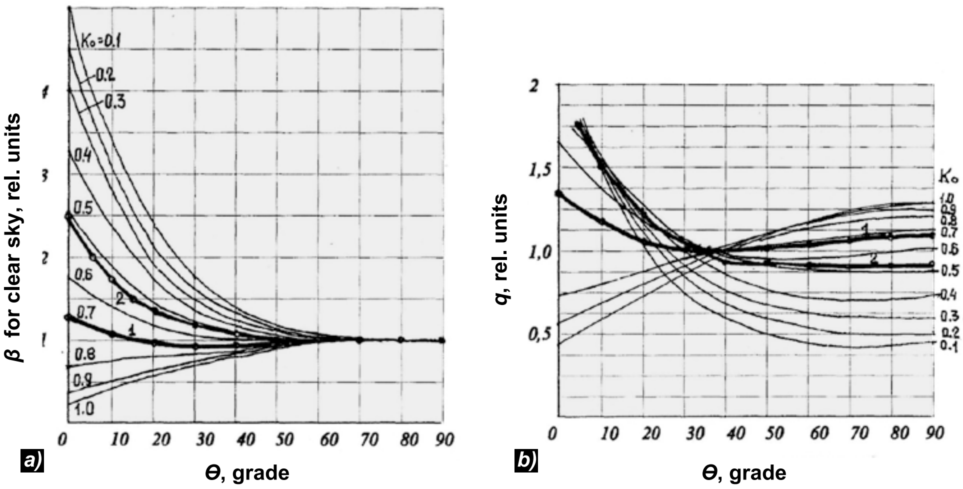


Fig. 7. Distribution of relative luminance $\beta$ and of coefficient $q$ with different cloudiness probabilities.
—○— – Calculation diagrams for N, S, E, NE, SE orientations (1) and W, NW, SW (2)

metric stations in Russia, as well as data on diffuse ($E_D$) and total ($E_Q$) illuminances connected with the first ones using light equivalents ($K_o = E_D/E_Q$), are available in СП 23–102–2003. Luminance of any point of the sky determined by zenith ($Z$) and azimuth ($\alpha$) angles $L$ ($Z$, $\alpha$) can be presented at a time as the weighted average of its two extreme values:

$$L(z,\alpha)=\xi \cdot L(z,\alpha)_{\text{clear}}+ \\ +(1-\xi)\cdot L(z)_{\text{overcast}}, \tag{9}$$

where $L(z, \alpha)_{\text{clear}}$ is luminance of clear sky by R. Kittler's formula; $L(z)_{\text{overcast.}}$ is luminance of overcast sky by Moon and Spencer's law; $\xi$ is a phase function corresponding to the normal distribution law confirmed by natural researches in work [7]:

$$\xi=\frac{1+\cos(K_o\cdot\pi)}{2}. \tag{10}$$

Statistical probability of such a luminance distribution is determined by probability and by processing natural measurements at actinometric stations.

## Conclusions and recommendations for further research

As an example, the СП 23–102–2003 data on $E_D$ and $E_Q$ in Moscow (55° N) and Khabarovsk (48° N) were used. We have computed $K_o$ average annual values for these cities for light opening orientation to NW, W and SW, as well as to N, S, E, NE and SE. For Moscow they appeared to be equal to 0.58 and 0.70 accordingly, and for Khabarovsk they were 0.50 and 0.53. These values are obtained as an average before 12:00 and after 12:00, because the first are typical for light opening orientation to NW, W and SW, and the second – for E, N, NE and SE orientations.

Dependence of relative luminance average values of $\beta$ ($\theta$, $\alpha$) point and of the sky non-uniform luminance account coefficient $q$ ($\theta$, $\alpha$) on the angular height $\theta$ of this point within the most unfavourable orientation of the sky sectors relative to the solar meridian (105° ⩽ $\alpha$ ⩽ 225°) at different cloudiness coefficients $K_o$ is shown in Fig. 7 [4].

For Moscow these values are presented by curves 1 (for light opening orientation to N, S, E, NE and SE) and by curves 2 (for their orientation to NW, W, SW). It can be seen from diagrams 1 and 2 that at $\theta$ =35 – 90°, $\beta$ = 1 and $q$ = 1, in the first case for Moscow $K_o$ = 0.70, and in the second case $K_o$ = 0.58, which corresponds to the equiluminous sky. In Khabarovsk, the number of clear and semi-clear days a year is higher, which is characterised by $K_o$ values: 0.53 and 0.50 accordingly. However, in spite of this, at θ = 35 – 90°, $\beta$ and $q$ also come close to 1. This means that with an upper natural illumination in regions with $K_o$ = 0.5 – 0.7, for all sky points, $q$ value can be considered to be equal to 1.

The Northwest of the European part of Russia, including St Petersburg, is traditionally considered an overcast region. Average $K_o$ value calculations show that both with window orientation to S, E, NE and SE, and to W, NW and SW, $K_o = 0.53$, i.e. the same as for Khabarovsk. That is with the upper natural illumination, here again $q = 1$.

For lateral light openings, $\theta = 15 - 30^o$ values (reference points are in the centre of the room and at a distance of 1m from the room's back wall) are characteristic. For orientations 1, $q = 1.1 - 1.0$ and for orientations 2, $q = 1.4–1.0$. A goal for future research is an analysis of light climate cloudiness and $K_o$ calculation for sunnier regions (North Caucasus, Crimea, Transbaikal, etc.). After these results are obtained, it will be possible to pursue a local light zoning of the territory of Russia and to correct light climate coefficients using the natural illumination standards.

## REFERENCES

1. Sanitary rules and standards SanPiN2.2.1/2.1.1. 1278–03 "Hygienic requirements to natural, artificial and combined illumination of inhabited and public buildings". It is registered in the Ministry of Justice of the Russian Federation on April, 23rd, 2003.

2. Rules and regulations СП 52.13330.2011 "Natural and artificial illumination". – Moscow: DPC State Unitary Enterprise, 2011, 69 p.

3. Darula S., Kittler R. A Metod of natural illumination calculation and modern trends of natural light assessment // Svetotekhnika. 2006. # 1, pp. 28–34.

4. Solovyov A.K. Luminance distribution over firmament and its account when designing natural building illumination // Svetotekhnika. 2008. # 6, pp.18–22.

5. Gusev N.M., Kireev N.N. Illumination of industrial buildings. – Moscow: Stroyizdat, 1968, 160 p.

6. Tregenza P.R. Measured and Calculated frequency distributions of daylight illuminance // Lighting Research & Technology. 1986. V.18, No. 2, pp. 71–74.

7. Gillette G. at al. The issue of sky conditions // Lighting Design & Application. 1985. March, pp. 22–27.

8. ISO 15469:2004 / CIE S011/E:2003 "Spatial distribution of natural illumination".

***Victor Zemtsov,***
Ph.D. Chief of the natural illumination and insolation laboratory of the Scientific Research Institute of Construction Physics (RAACS)

***Alexei K. Solovyov,***
Prof., Doctor of Engineering, graduated from the MISI of V.V. Kuibyshev in 1965. At present, he is the Professor of the Chair "Architecture of civil and industrial buildings" of the Moscow State Building University, National Research University. A member of the European Academy of Sciences and Arts, a member of editorial board of "Light and Engineering" journal

***Igor A. Shmarov,***
Ph.D. Graduated from the MEPhI in 1979. Chief of the artificial illumination laboratory of the Scientific Research Institute of Construction Physics (RAACS)

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# METHODS OF DESIGNING IMMOVABLE SUN PROTECTION DEVICES

Alexander T. Dvoretsky[1], Mariya A. Morgunova[1], Oleg V. Sergeichuk[2], and Alexander B. Spiridonov[3]

*[1]The Crimean Federal University of V.I. Vernadsky, Simferopol, Russia*
*[2]The Kiev National University of Construction and Architecture, Kiev, Ukraine*
*[3]The Scientific Research Institute of Construction Physics of the RAACS, Moscow, Russia*
*E-mail: dvoretskyat@ukr.net, riya@ukr.net, ovsergeich@mail.ru, spiridonova@aprok.org*

An architect can perfectly control natural illumination, if he/she knows the trajectory of the sun.
*Frank Lloyd Wright, an American architect*

**ABSTRACT**

Mathematical models for a building insolation process are presented. These models are based on solar geometry described by the daily cone of solar rays; knowing this is necessary for any professional and high-quality design of energy-efficient buildings and cities. To form shaping immovable sun protection devices as spatial configurations, a method based on the use of the daily cone of solar rays is appropriate. The method is easily implemented using special computer software.

This informative and universal method of designing immovable sun protection installations is based on using solar maps.

**Keywords**: sun-protective devices, daily cone of solar rays, solar map, insolation, microclimate of rooms

## INTRODUCTION

One of the major factors of influencing the microclimate of rooms is insolation, which can be adjusted using sun protection devices (SPD). One of the challenges in increasing the energy efficiency of buildings, is determining SPD its configurations in such a way that during the period of overheating, when cooling of a building is require, solar radiation does not penetrate into the room; whilst during the cold (heating) period, the room is being maximum insolated, obtaining additional heat inputs from the sun [1–3].

Creating a system of Russian standards for sun protection absolutely necessary in the near future; it will promote an increase of thermal and visual comfort in rooms, as well as decrease in energy spending by building operators [4].

There are two important tasks connected with the adjustment of room insolation mode: 1. A calculation of insolation duration and its correspondence to health and safety rules [5]. They normalise duration of a continuous insolation, for example in the central regions (48–58° N) since March, 22$^{nd}$ to September, 22$^{nd}$ – not less than 2.0 hours a day; 2. SPD form shaping with the set properties.

This article analyzes the existing form shaping methods of various SPDs with due regard for climate conditions and facade orientation.

### Methodical basis. Geometrical model of a point insolation process on the earth surface within a day

All methods of an optimum form and shape for an immovable sun protection device are based on the geometry of the visual movement of the

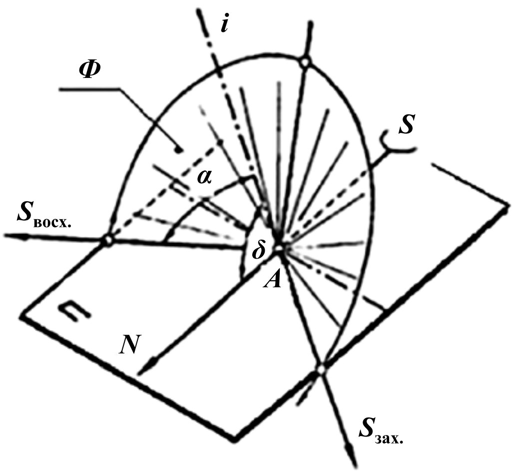


Fig. 1. Geometrical model of a solar ray daily cone: *A* – insolated point; *Φ* – daily cone of solar rays (DCSR); *α* – angle between cone generatrix and its axis; Π – horizontal plane (earth surface in insolated point); *δ* – geographical latitude of the place; *i* – earth rotation axis; *S, N* – south and north directions; $S_{восх.}$ – sunrise direction; $S_{зах.}$ – sunset direction

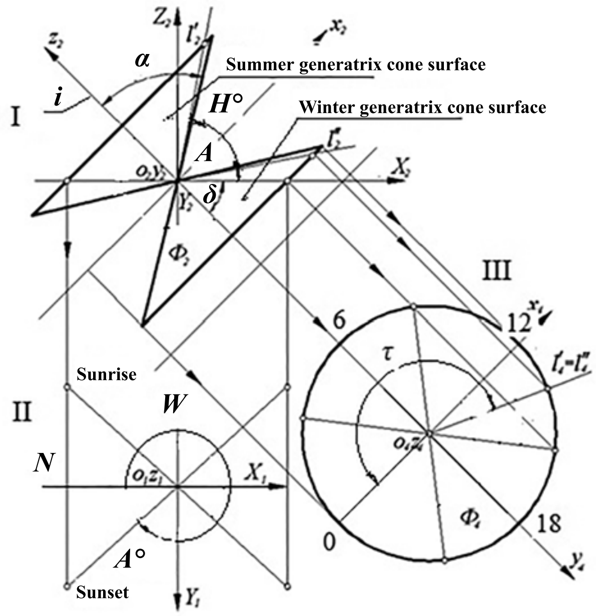


Fig. 2. Rectangular projections of solar ray daily cone: *H*° – angular solar altitude; Π – horizontal plane; $A°_{зах.}$ – sunset azimuth; *τ* – hour angle; $l^i$ – cone generatrix. Other letter designations are the same as in Fig. 1

sun over the firmament, namely it is a geometrical model of a point insolation process on the earth surface within a day. This model represents a one-parametric set of the solar rays coming to this point within a day. According to Prof. A.L. Podgorny's findings, this is a daily cone of solar rays (DCSR) [2]. The DCSR is a basis of all methods of SPD form shaping and of most methods to determine insolation duration.

Out of a broad variety of insolation calculation methods [6, 7], methods based on the DCSR mathematical model are most exact.

Fig. 1 shows an image of the DCSR daytime section, and Fig. 2 shows a DCSR in rectangular projection. On the front projection *I,* two DCSRs are represented[1]: summer and winter. Height *H*° in Fig. 2 corresponds to 12:00 time. Plane Π dissects cone halves along two generatrices, which on horizontal projection *II* specify directions towards sunrise and sunset. On an additional projection *III* along the cone axis direction, an hour diagram is plotted. For any position of the sun, the correspondent cone generatrix can be found, for example $l^i$ time, and day time *τ* can be determined. With the aid of the DCSR, it is possible to do the following: 1. Determine the direction and time of sunrise and sunset in any day of a year; 2. Determine the azimuth and solar altitude at any moment; 3. Construct a sundial and any graphic tools for solving insolation tasks.

For a set geographical latitude *d*, DCSR for an arbitrary day is determined as follows:

- Within the vertical plane parallel to the north-south direction, cone axis inclination relative to *X* axis is determined: the axis is inclined at an angle *d* downwards in the northern hemisphere, and upwards in the southern hemisphere;
- Angle a between cone generatrix and its axis is determined as follows:

$$\alpha = \arccos\left[\begin{array}{c} \cos 66{,}55° \cdot \\ \cdot \cos\left(\dfrac{360°}{365} \cdot N\right) \end{array}\right], \qquad (1)$$

where 66.55° is the Earth's rotation axis inclination to its orbit plane; 360° is an angle, which the Earth traces for a year moving round the sun; 365 is the number of days in a year; *N* is the day number counted from the 22nd June to a certain day of the year.

The required SPD geometry can be determined graphically, analytically, or using graphic

[1] A conic surface formed by rotation of the straight line (generatrix) round an axis crossed with it and consists of two parts or halves joined at the point of intersecting generatrix and cone axis being the cone vertex.

programs (for example, *INTEAR* (Kiev), Solaris (Ekaterinburg), *Lara* (Nizhny Novgorod), as well as using *AutoCAD*, *ArchiCAD*, *3ds Max*, etc.). The solutions used in the past for many generations have been graphic and quite labour intensive.

## Main methods for determining an optimal configuration for the immovable SPDs

All methods of shaping the form of an SPD are based on the DCSR. The main methods are as follows: by means of solar maps [2, 6, 8]; using horizontal and vertical shadow angles [1]; and based on the DCSR [3].

### *Using solar maps*

A solar map is a graphic tool for insolation calculations and SPD design. It can be formed by projecting onto a horizontal plane of the visible sky dome. A solar map displays solar trajectories, hour lines and coordinate gird consisting of azimuthal lines and almucantarats (concentric circles, by means of which solar altitude is determined). Depending on the type of projection, a solar map can be orthogonal, stereographic, etc. Solar maps are constructed for a specific geographical latitude. A stereographic projection (Fig. 3) is most convenient for manual construction and in cases, when the above mentioned computer programs are used. Stereographic solar maps display the followings:

1. Radial lines, using which the sun azimuth is determined;
2. Almucantarats, which are concentric circles, by means of which solar altitude is determined;
3. Circle arcs, which are a stereographic projection of the sky dome crossing with day cones for the 22 day of each month;
4. Circle arcs, which are solar hour lines.

To construct a protection screen shadow mask on the solar map with a subsequent determination of insolation duration, one should know angular height of the rays passing through the protection screen points and the reference point (*RP*). *RP* is a point of median surface intersection with a ray, which touches the SPD and the light opening lower inner contour within vertical secant plane perpendicular to the light opening median surface.

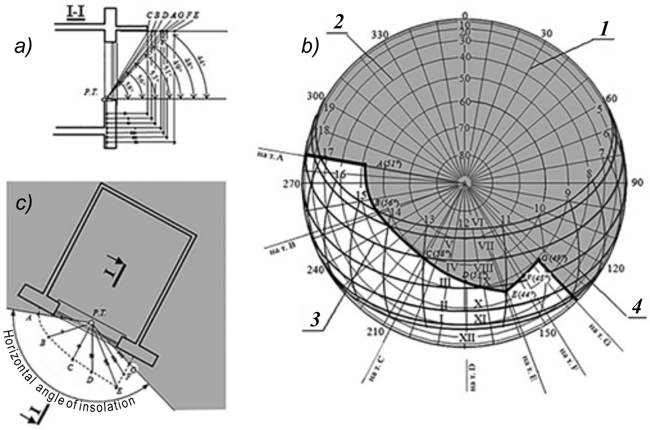


Fig. 3. Determination of SPD shadow mask using a solar map: *a* – determination of insolation vertical angles; *b* – determination of horizontal insolation angle and of directions for construction of SPD shadow mask; *c* – shadow mask

For this purpose, a vertical secant plane I–I is drawn through a protection screen point, for example through point *N* (Fig. 3b). On the window section (Fig. 3a), the angular height is determined for the ray passing through point *N* and reference point *RP*. Using almucantarats, a point is found along direction *C* on the solar map (Fig. 3c) corresponding to point *C* on the protection screen. By a similar method, other shadow mask points are also constructed on the solar map corresponding to the protection screen selected points.

It should be noted that the solution of a converse task allows designing SPD configuration by the shadow mask covering the solar map area, which is undesirable in terms of a room overheating.

Solar maps are useful when calculating room insolation duration with SPDs.

Some SPDs consisting of plain elements (as though plane compartments), and their shadow masks are presented in Fig. 4 [1]. Near to the SPD axonometry and structure cross section its

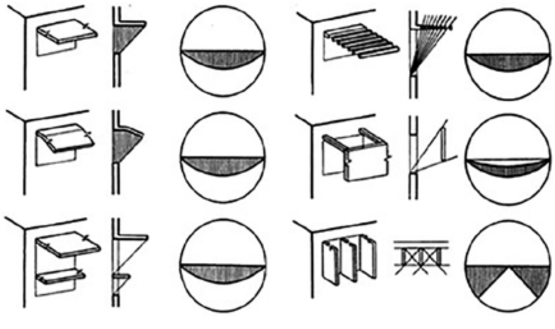

Fig. 4. Some types of sun protection devices and their shadow masks

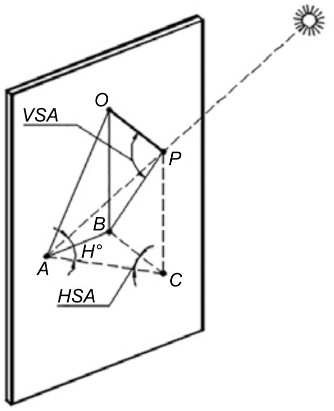


Fig. 5. Shadow angles:
*OP* – perpendicular to the wall; *HSA* – horizontal shadow angle; *VSA* – vertical shadow angle; *H*° –angular altitude of a solar ray

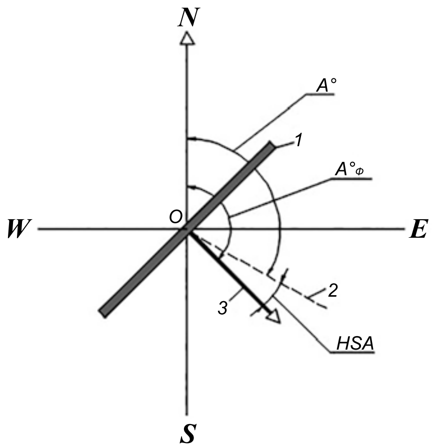


Fig. 6. Azimuthal angles:
1 – wall; 2 – sun ray; 3 – perpendicular to the wall; *A*° – solar azimuth; $A^{\circ}_{\Phi}$ – facade azimuth

shadow mask is shown, which can be used when calculating insolation duration by superimposing it on the solar map.

The centre of the shadow mask should be coincided with the solar map centre, and the solar map should be orientated according to the window orientation.

***Using horizontal and vertical shadow angles***

In work [1], an SPD shaping method using horizontal and vertical shadow angles is proposed. When designing shadowing systems of optimum configuration, using the sun's altitude and azimuth is not entirely convenient [1]. It is more convenient to use the sun position angles measured from perpendicular to the facade in horizontal and vertical planes named horizontal and vertical shadow angles.

Horizontal shadow angle *HSA* is determined as the angle between the solar azimuth *A*° and facade azimuth $A^{\circ}_{\Phi}$ (Fig. 5 and 6).

$$HSA = A^{\circ} - A^{\circ}_{\Phi}.$$

Vertical shadow angle *VSA* is an angle between *CR* perpendicular to the wall and *BP* projection of its shade within the vertical plane, in which *CR* perpendicular is placed.

Using elementary trigonometrical ratios, we obtain:

$$\mathrm{tg}VSA = OB / OP = PC / BC = \\ = (PC / AC)(AC / BC) = \mathrm{tg}H^{\circ}\sec HSA.$$

Fig. 7 shows rectangular projections of the SPD, which consist of a vertical cylinder with an arbitrary horizontal projection designated as *FKRKBDA*. This example is considered in book [1] for 32° S. Horizontal and vertical shadow angles are determined by DCSR for the 26th May, and 19th July, which are days of the building cooling period in the southern hemisphere and symmetric relative to the 22nd June. The Table only shows several of the angles used and characteristic points taken into consideration when designing.

For contour form shaping, it is necessary to remove the superfluous cylinder part so that the winter sun penetrates into the room. The cut out line is determined by means of horizontal and vertical shadow angles from the Table corresponding to the selected period from May 26th to July 19th (Fig. 7). With these angles, the rays are constructed on the rectangular projections.

Points of intersection of these rays with the SPD cylindrical surface appertain to the cut out line.

A necessary condition for the application of this method is a good knowledge of descriptive geometry. Its disadvantages are an awkwardness of construction and complexity associated with the calculation.

***Based on the daily cone of solar rays***

This method is graph-analytic and consequently is easily implemented by means of [3] using for example the *3ds Max* program. Cuerrently,

**Table. Horizontal and vertical shadow angles**

| Solar time | | 10:00 | | | 16:30 |
|---|---|---|---|---|---|
| Shadow angles, grade | *HSA* | 22 | 40 | 52 | 61 |
| | *VSA* | 33 | 31 | 23 | 10 |
| Curves and points | | *RZF* curve | *K* | *L* | *BD* curve and *DA*' straight line |

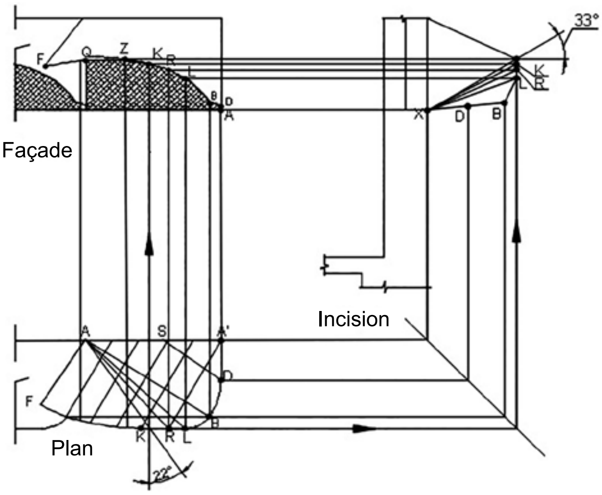


Fig. 7. SPD rectangular projections:
*QZKLBDA* – SPD contour; 33° – vertical shadow angle;
22° – horizontal shadow angle

there is a special software package under development, to simulate SPD configuration based on the DCSR. This is being developed at the the Crimean Federal University of V.I. Vernadsky and in the SRICPh of the RAACS

SPD configuration and position parameters are determined by the following algorithm:

1. An SPD spatial configuration is selected depending on the facade forms. For example, it can be cylindrical (Fig. 8).

2. The overheat period of the building is determined for the correspondent climate conditions (for example, daily average temperature of external air is higher than 21 °C, and superfluous solar radiation takes place). If the window shadowing period on southern facades in Simferopol is selected since April, 22nd to August, 22nd (the period is symmetric relative to June, 22nd), then DCSR for boundary days of this period is calculated as follows:

• day number from June, 22nd till August, 22nd is 62;

• angle *a* is determined according to formula (1). It is equal to 78°54/.

3. SPD sizes and contours are determined for the set shadowing period. For this purpose, a crossing line of SPD surface with DCSR is searched for boundary days of the shadowing period using the *3ds Max* program.

Fig. 8 shows SPD cylindrical configuration with a horizontal rotation axis.

This method is useful for the design of immovable SPDs as buildings in three-dimensional configuration. Its disadvantage is the symmetry of SPD surface, which does not fully account for overheat in the second half of a day.

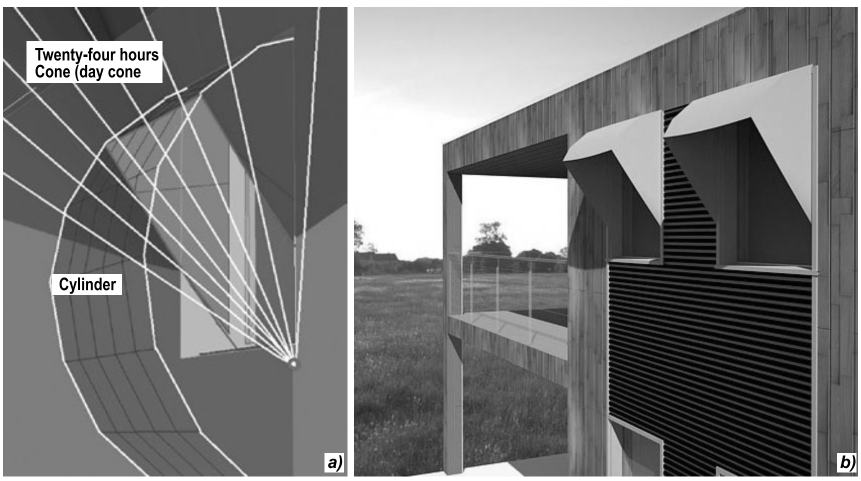


Fig. 8. SPD form shaping using daily cone of solar rays

## CONCLUSIONS

1. The article presented the main models for the building insolation process. These models are based on the solar geometry described by a solar ray daily cone, without knowledge of which a profession-

al design of energy efficient buildings and cities is impossible.

2. All of the proposed models can be implemented within *AutoCAD*, *ArchiCAD*, *3ds Max* and other graphic programs. The *INTEAR* and *Solaris* programs only allow calculating insolation duration in the first and last days of the insolation period and are not intended for SPD design. Special programs are being developed at present to design SPDs based on the DCSR.

3. For an optimum form shaping immovable SPD, which represent some spatial configurations (cylinder, cone, parallelepiped, etc.), a method based on the DCSR should be used, which is most easily implemented using computer software.

4. For insolation calculations and to design SPDs consisting of elements in the shape of planes or lamella compartments, a method based on solar maps is preferable because of its high information value and universal application.

## REFERENCES


1. Harkness E.L., Mehta M.L. Solar Radiation Control in Buildings. London: Applied Science Publishers Ltd, 1978, 170 P.

2. Podgorny A.L., Shchepetova I.M., Sergeichuk O.V., Zaitsev O.M., Protsyuk V.P. "Translucent building parapets" Under the editorship of A.L. Podgorny. Kiev.: Domashevska O.A., 2005, 281P.

3. Dvoretsky A.T., Avdonyev E. Ya., Morgunova M.A. "Form shaping of immovable sun-protective devices using daily cone of solar rays", Construction and reconstruction. 2015, #5 (61), pp. 70–76.

4. Rimshin V. I., Syomin S.A., Spiridonov A.V., Shubin I.L. "Practice of Rationing of Sun-protective Devices" Svetotekhnika. 2014, #6, pp. 27–31.

5. Sanitary Regulations and Rules 2.1.2.2645–10 (Revised as of 27.12.2010).

6. Kittler R., Mikler J. "Zaklady Vyuzivania Slnecneho Zarenia", Bratislava: VEDA, 1986, 152 P.

7. Steinberg A. Ya. "Sun protection of buildings" Under the editorship of A.L. Podgorny. Kiev: Budivelnik, 1986, 104 P.

8. Sergeichuk O.V., Buravchenko V.S., Antropov O.V., et al. ISO 13790: "Features of design procedure of solar comings in the national application for DSTU EN ISO 13790" Energy efficiency in construction and architecture: Science and technical collection. Kiev.: KNYBA, 2014, issue. 6, pp. 267–272.



***Alexander T. Dvoretsky,***
Prof., Doctor of Technical Science, graduated from the Donetsk Polytechnical Institute in 1971. At present, he is a Head of the chair "Geometrical and computer simulation of energy efficient buildings" of the Academy of Construction and Architecture of the Crimean Federal University of V.I. Vernadsky. An adviser of the RAACS

***Oleg V. Sergeichuk,***
Prof., Doctor of Technical Science, graduated from the Kiev National University of Construction and Architecture in 1975. The professor of the architectural department of the Kiev National University of Construction and Architecture

***Maria A. Morgunova,***
an architect, graduated from the Academy of construction and architecture of the Academy of Construction and Architecture of the Crimean Federal University of V.I. Vernadsky. A post-graduate student of the Chair "Geometrical and computer simulation of energy efficient buildings" of the Academy of Construction and Architecture of the Crimean Federal University of V.I. Vernadsky

***Alexander V. Spiridonov,***
Ph.D., graduated from Moscow Power Institute in 1975 as a specialist in light and engineering and in source of light, head of the "Energy saving in construction" laboratory at SRICPh of RACS, President of association of energy efficient windows manufactories, the winner of an award of the Government of the Russian Federation in the field of science and technique

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# RESEARCH INTO VISUAL WORKING CAPACITY AND FATIGUE WHEN OPERATING WITH BLACK TEXT AGAINST A COLOUR BACKGROUND

Sofia M. Kudryakova and Vladimir Yu. Snetkov

*The Moscow Power Institute National Research University FSBEI, Moscow*
*E-mail: sofiakudria@gmail.com*

## ABSTRACT

When working with text documents on a computer, most users select black texts against a white background. The authors determined that using a properly selected colour background instead of achromatic can improve the quality of the text work, raise working capacity and reduce fatigue. Qualitative recommendations are provided as to the choice of background colour for different levels of intensity, responsibility and duration of work with text work but also quantitative explanations of benefits of one over another.

**Keywords**: colour background, visual working capacity, visual fatigue, colour contrast

## STANDARD REQUIREMENTS

For today, according to the Russian standard [1], using a dark blue colour against dark backgrounds, red colour against dark backgrounds, as well as red colour against saturated dark blue backgrounds are not recommended.

It is recommended to think about the «depth» effect of the pictured space, which is not advised for long reading, when using extreme colours of the visible spectrum [2]. More detailed recommendations on choice of text background colours are not provided by the standard documents.

## RESEARCH

The authors estimated quality of work with text by levels of visual working capacity and visual fatigue using luminance adisparopia. Methods of calculating colour contrast between a black letter text and a colour background by chromaticity and luminosity were based on a system of uniform chromaticity developed by A.V. Matveyev and N.M. Belyaeva[1] [3]. All of the experiments were carried out in a classroom using a computer under artificial illumination conditions. The participants set the illumination conditions convenient for them: horizontal illuminance was equal to 1000 lx, and screen plane illuminance was 500 lx. As a result, the ripple factor of the luminous flux in the room didn't exceed 5 %, and the generalised discomfort parameter was not more than 15. There was no direct light from luminaires in the observers' field of vision. The text work was performed on a laptop screen. The screen was matte of transmitting type with light emitting diode back illumination manufactured using *IPS–ASS* technology.

In order to measure luminance and chromaticity co-ordinates, LS-100 luminance metre (*Konika Minolta*) and TKA-VD spectrocolorimeter were used. All participants of the experiment had normal chromatic sight.

To determine working capacity and fatigue, the *Test Vision* test program was used [4–7]. Visual working capacity and visual fatigue were tested using luminance adisparopia.

[1] This system takes into consideration adaptable and induction influence of surrounding object colour when calculating chromaticity co-ordinates connected by a hyperbolic dependence with the correspondent chromaticity co-ordinates of the RGB physiological system.

The visual working capacity test for one observer with one background lasted 30 minutes. During this time, in the heading and at a random point in the text, two characters appeared every five seconds, and the observer had to identify these pairs. The program calculated visual working capacity using the formula:

$$\eta = N_{ca} / (N_{sn} \cdot t_{av}),$$

where $N_{ca}$ is number of correct answers, $N_{sn}$ is stimulus exhibition number, $t_{av}$ is an average time, which the observer takes to process one example.

For the test of visual fatigue using luminance adisparopia, images of two adjoining achromatic semicircles were displayed against a grey background of 40 cd/m$^2$ luminance, the semicircles were approximately two times less in luminance. The semicircles differed by three luminance thresholds, and the button "don't see a difference any more" appeared. The observer looked at the centre of the adjoining semicircles (at the centre of the circle) and at the moment, when their luminance perception difference disappeared and they merged, the observer pressed the button "don't see a difference any more". By the results, the program calculated relative visual fatigue $Y_a$ according to the formula:

$$Y_a = (1 - t_2 / t_1) \cdot 100,$$

where $t_1$ is time of disappearance of luminance perception difference of the two circle halves before the research beginning for visual fatigue, and $t_2$ is time of disappearance of luminance perception difference of the two circle halves after visual fatigue research phase end.

The program calculated a comprehensive parametre $Q$ as well:

$$Q = 100 \cdot \eta / Y_a.$$

After chromaticity co-ordinates of the background colours on the computer screen were measured and their analysed on of A.V. Matveev's uniform chromaticity scale system diagram, the authors selected eleven colours for subsequent experiments.

Before the main experiment, ten observers were given a page of text to read against a colour background, to count number of the set combinations of two letters on each page and to estimate convenience of the work using a 5-point quality scale [8]. By the results of the preliminary test for each background, coefficient $k$ characterizing the observer's work quality was calculated. It was equal to the number of properly determined letter combinations relative to the total number of the proposed combinations. Six colours were selected, which had the greatest point and the higher work quality coefficient $k$. These colours and parameters listed above are presented in Table 1. Taking into consideration the pilot nature of this research, the evaluation of each observer was cleared by himself/herself at the end of the experiment. Therefore, figures in this Table are given ignoring the statistical dispersion of the evaluations.

For the main experiment, the participant group was made up of six observers aged between 20 and 25. The experiment lasted for six working days, during which all observers were requested to keep to regular working hours and to sleep no less than seven hours a day. The observers were divided into two groups; the first group took the experimental tests between 10 am and 12 pm, and the

**Table 1. Results of the preliminary experiment**

| Sample background colour | Number of the sample background colour | Evaluation | Coefficient of the work quality $k$ |
|---|---|---|---|
| | 1 | 4.0 | 0.94 |
| | 3 | 3.9 | 0.95 |
| | 6 | 3.0 | 1.00 |
| | 8 | 4.0 | 0.96 |
| | 10 | 3.3 | 0.99 |
| | 0 | 4.5 | 0.93 |

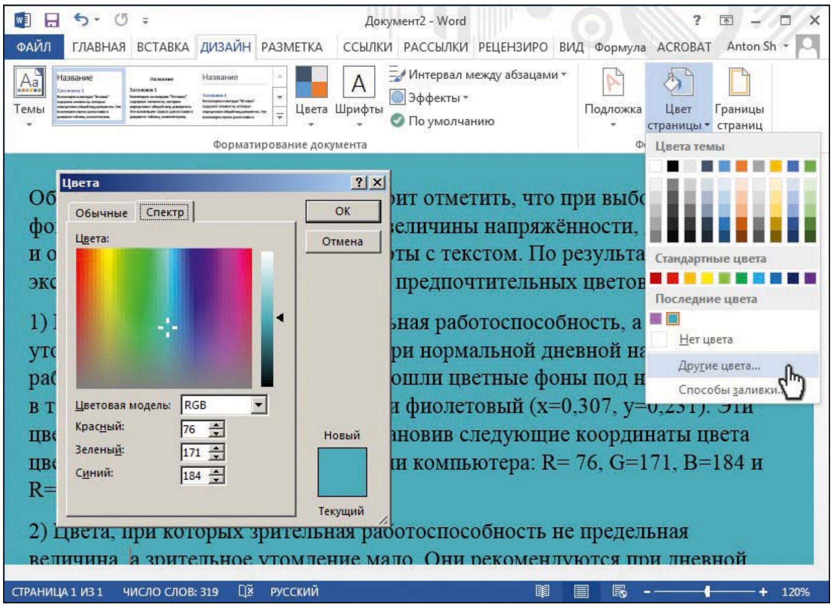


Fig. 1. Chromaticity co-ordinate selection on the computer chromatic system for the first group of the background colours

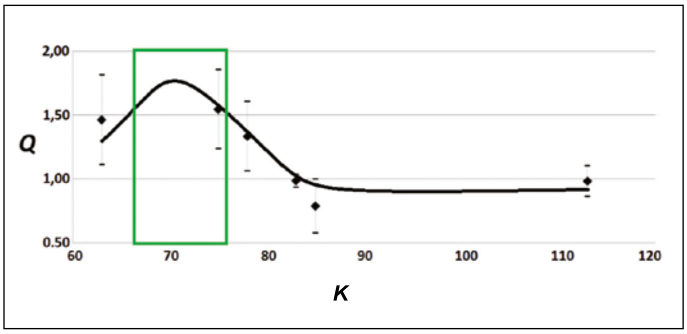


Fig. 2. Dependence of comprehensive parameters $Q$ averaged for six observers on the colour contrast in thresholds. Confidence intervals are calculated for $p = 0.95$ probability

second – from 4 pm to 6 pm: this was done because according to the available information [9], working capacity is at its highest during these intervals. For six days, every observer passed six tests with six different background colours, including white. Every test cycle consisted of an eight-minute preliminary test to allow for adaptation to the working conditions, followed by the main thirty-minute test for visual working capacity. Additionally, tests for visual fatigue were carried out before the test for visual working capacity, at 10 and 20 minutes during the test and after the end of the test.

During final interviews, all participants (observers) stated that they preferred working against a colour background to working against white. According to the observers, working with many colour backgrounds is more comfortable, and noticing character change in a text is easier. Blue, green and violet backgrounds were states to be the best.

When generalising the obtained results, it was noticed that in the process of choosing a colour background the important factors are intensity, duration and level of responsibility of the work with text. According to the experiment results, the authors named three groups of the preferable background colours:

- Colours, with which visual working capacity is high and visual fatigue is average, are recommended for a normal daytime text work loading. Background colours of numbers 3 and 8 (Table 1) are included in this group: blue ($x$ = 0.258. $y$ = 0.326) and violet ($x$ = 0.307. $y$ = 0.231). These colours can be generated on the screen and can be obtained by setting the following chromaticity co-ordinates on the computer: $R$ = 76. $G$ = 171. $B$ = 184 (Fig. 1) and $R$ = 177. $G$ = 109. $B$ = 191.
- Colours, with which visual working capacity is not limited and visual fatigue is low. They are recommended for daytime work for a user exceeding normal work load. Green background ($x$ = 0.386. $y$ = 0.491) relates to this group: #1 in Table 1. This colour can be geerated on the screen by setting the following chromaticity co-ordinates of the chromatic system on the computer: $R$ = 140. $G$=167. $B$=73.
- Colours, with which visual working capacity is high and visual fatigue is also high. This colour group is recommended to be used only in case of short-term work with a text. As an example, bright green saturated colour background can be given ($x$ = 0.338. $y$ = 0.613): #10 in Table 1. This colour can be generated on the screen by setting the following chromaticity co-ordinates on the computer are set: $R$=0. $G$=255. $B$=0.

**Table 2. Characteristics of the colours recommended for backgrounds**

| Colours | *x* | *y* | Background luminance of $L_{ф}$. cd/m² | Purity *p*.% |
|---|---|---|---|---|
| Blue | 0.21–0.26 | 0.30–0.40 | 65 – 120 | 20 – 40 |
| Green | 0.30–0.40 | 0.40–0.50 | | 30 – 50 |
| Violet | 0.21–0.31 | 0.20–0.25 | | 10 – 30 |
| Orange-yellow | 0.40–0.43 | 0.35–0.40 | | 20–50 |

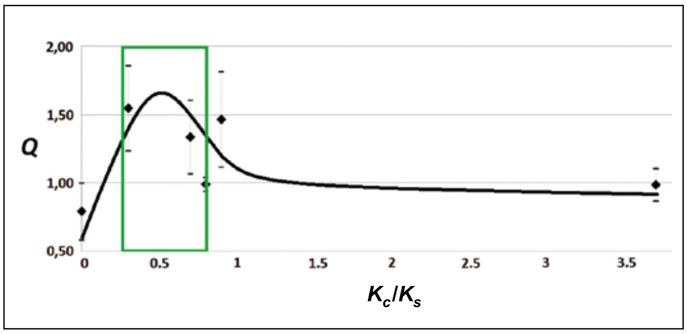


Fig. 3. Dependence of comprehensive parameter $Q$ averaged for six observers on the $K_c/K_s$. relationship. Confidence intervals are calculated for $p = 0.95$ probability

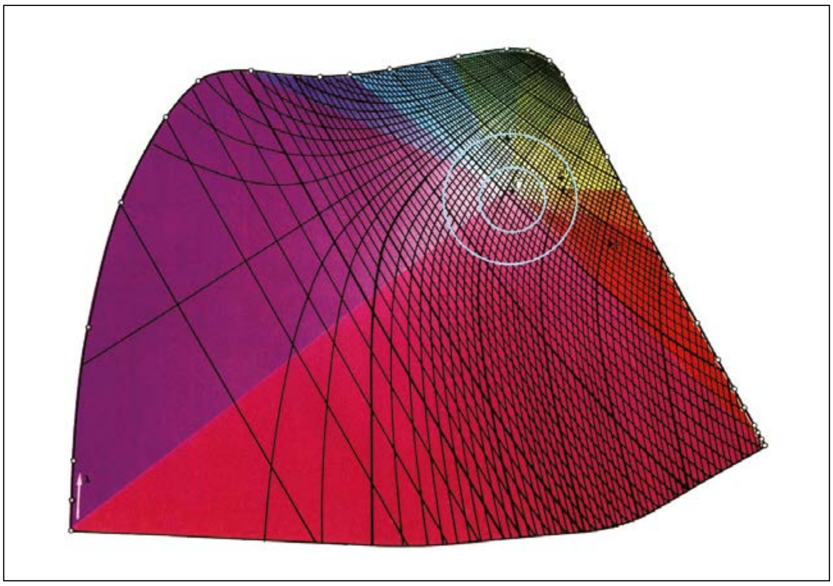

Fig. 4. Colour area with recommended $K_c$ chromaticity contrast values on the uniform chromaticity scale diagram of A.B. Matveev

An important characteristic is the relation of character contrast to the background by chromaticity ($K_c$) and luminosity ($K_s$). In Fig. 3 a dependence of the comprehensive parameter $Q$ on this relation ($K_c/K_s$) is presented. The interval for the best $K_c/K_s$ values is between 0.3 and 0.7. Acceptable $K_c$ and $K_s$ values were determined: from 50–75 to 20–50 thresholds accordingly.

Based on the $K_c$ values on the A.B. Matveev's uniform chromaticity scale diagram, an area of the best background colours was determined (Fig. 4). Red colours are also within this area, however, we suggest to exclude them, because they can have a negative impact on the psychological and physical state of a person [2, 10].

In Table 2 possible chromaticity co-ordinates ($x, y$), luminance intervals ($L_{ф}$) and colour purity ($p$) of the recommended backgrounds are presented when working with a black text on a computer screen for text letter luminance of 6 cd/m².

The experimental results are presented in Fig. 2. It can be seen that the preferable colour contrast area is located within an interval of 65 to 75 thresholds for the colour contrast. However, colour contrast is not determining, because white background colour can also have the same colour contrast with text characters.

## CONCLUSIONS

According to the data obtained during the work, use of colour backgrounds instead of white makes it possible to double visual working capacity, or to lower visual fatigue by a factor of 1.5. According to the authors, acceptable background colours for work with a black text can have $K_c$ and

$K_s$ ranging from 50–75 to 20–50 thresholds correspondingly. In this case, use of red colours as backgrounds is not recommended.

## REFERENCES

1. "Ergonomic requirements when accomplishing office works using video display terminals (VDT). Part 8. Requirements for displayed colours".

2. GOST P 50948–2001 "Facilities of displaying individual use information. General ergonomic requirements and safety requirements".

3. Sosnova T.L.. Frid Yu.V.. Sokolova Ye.G.. Loseva E.I. Chromatic decoration on the railway transport // Moscow: Transport, 1984,. 200 p.

4. Cherezova M.V.. Kudryavtseva M.V.. Snetkov V. Ju. Test program for evaluating quality of text images on a computer display // Theses of reports at the scientific and technical conference "Young light engineers of Russia". Moscow: Vigma, 2009, pp. 86–88.

5. Ataev A.E.. Bynina M.V.. Snetkov V. Ju. Determination of visual parameters of individual information displaying facilities // Vestnik of the Moscow Power Institute. 2012, # 2, pp. 122–125.

6. Grigorev A.A.. Bynina M.V. Snetkov V. Ju. Determination of an optimum contrast interval of a character with the background of individual information displaying facilities // Vestnik of the Moscow Power Institute. 2012,# 5, pp. 92–94.

7. Arkhangelsky V.D.. Snetkov V. Ju. Researchs of light influence on visual working capacity and fatigue of a person with due regard for his/her circadian rhythms // Vestnik of the Moscow Power Institute. 2012, # 6, pp. 219–224.

8. GOST 26320–84 Studio and extra studio television equipment "Methods of subjective quality evaluation of colour television images".

9. Human physiology. Under V.M. Pokrovsky and G.F. Korotko's edition, Moscow: Meditsina. 2001, 656 p.

10. Nikulova G.A. Chromatic decoration of teaching materials and its influence on perception of information // Vestnik of the Permsky State Humanitarian and Pedagogical University. Series: Information computer technologies in educations. 2006, #2, pp.77–83.

***Sofia M. Kudryakova,***
master of engineering and technologies of the electronics and microelectronics direction and of the theoretical and applied light engineering program, graduated from the Moscow Power Institute National Research University in 2015, specialising in Light and Engineering and light sources, assistant engineer on light equipment of Artemide Agency (Open Company), Moscow

***VladimirYu. Snetkov,***
*Ph.D,* a senior lecturer of the Light and Engineering chair of the Moscow Power Institute National Research University, graduated from the Moscow Power Institute in 1974 (Light and Engineering and light source specialty)

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# DEVELOPMENT AND OPTIMISATION OF A POWER SUPPLY FOR FLEXIBLE ELECTROLUMINESCENCE PANELS

Igor N. Goncharov, Alexander M. Kabyshev, Evgeny N. Kozyrev, and Alan I. Maldzigati

*The North Caucasian Mining and Smelting Institute (State Technological University) and Gran Open Company, Vladikavkaz*
*E-mail: maldzigati@mail.ru*

## ABSTRACT

The requirements applicable to operating modes of power supplies for flexible electroluminescence panels are considered. The results of research into the influence of current configuration on the operational parameters of these products are presented. A power supply circuit is developed for electroluminescence panels and its optimisation is described. The influence of source operating modes on the operational parameters of the electroluminescence panels is considered. Currents and voltage oscillograms illustrating operating modes of the electrofluorescence panels are obtained.

**Keywords:** electroluminescence panel, frequency, equivalent circuit, phosphor, throttle, autonomous voltage inverter, transistor keys, oscillograms, luminance

## INTRODUCTION

An electroluminescence panel (ELP) represents a flexible source of optical radiation of a large area, the spectrum of which depends on the phosphor composition and on frequency of alternating current flowing through the ELP.

Such radiation sources are used for illumination of device panels of stationary and mobile installations, in signal and emergency illumination which must work continuously for a long time, as well as for decorative and advertising purposes [1].

ELPs differ by the composition of the materials used and by spatial location of their thin-film structure layers [1–5].

The most widespread ELPs contain as part of their structure the following list of layers: mylar film; transparent conductor *ITO* layer (10 % $SnO$ + 90 % $In_2O_3$); fluorescent layer, which is composed of a phosphor suspension and dielectric; dielectric layer consisting of a dielectric binder and barium titanate ($BaTiO_3$); an opaque electrode.

An ELP is in operation when the working layer glows; it consists of zink sulphide phosphor and dielectric as a binding component. The phosphor radiates photons under the influence of an alternating electric field and works in the pre-breakdown electroluminescence mode.

The fluorescent layer consists of a phosphor and polymeric dielectric also performing the function of a binding material. The dielectric creates barrier areas and thereby concentrates the electric field at the phosphor grain boundaries. The binding dielectric should be transparent for visible light, and have good adhesion to the adjacent layers, a sufficient level of breakdown voltage, chemical inertness relative to the filler and electrode materials, as well as stable electro physical and optical characteristics. The dielectric binder, being part of the dielectric layer, should have a high dielectric permeability $\varepsilon$ and low dielectric losses $tg\ \delta$. For this purpose, up to 40 % of ferroelectric material $BaTiO_3$ is added to its composition.

In order to excite a glow on the electroluminescence panel, an alternating voltage is required

[1, 6]. In this case the ELP phosphor emits light quanta during both voltage half-cycles, and its instant luminance is a periodic function of time.

At present, to increase operational ELP parameter values, work is carried out intended not only to perfect the ELP structure and manufacturing technology, but also to optimise electric energy converters needed for the power supply of the optical radiation flexible sources [1, 3, 4, 6].

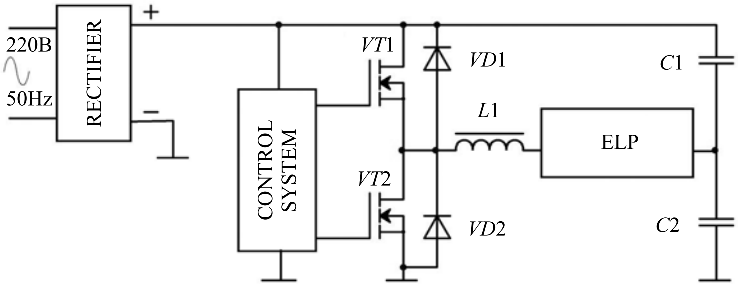

Fig. 1. Function circuit of the ELP power supply: *VT*1, *VT*2 – transistor keys; *VD*1, *VD*2 – diodes; *L*1 – throttle; ELP – electroluminescence panel; *C*1, *C*2 – capacitors

The purpose of this work was to investigate the influence of current configuration generated by the power supply unit on the main operational ELP characteristics (luminance and working temperature) and to develop a small-sized power supply assuring the effective operation of the ELP. In the relevant literature, there is almost no information on the influence of the current configuration on ELP operation, which is especially important when developing small-sized power supplies providing high operational ELP parameters.

## DESCRIPTION OF THE EXPERIMENT TECHNIQUE

ELP for power supplies is a loading, in which the capacitor component prevails [2, 6]. Knowing the operating voltage $U$ and current $I$, their frequency $f$ and neglecting active resistance of the dielectric layers, which are a part of ELP structure, one can approximately determine ELP electric capacitance $C_{ELP}$:

$$C_{ELP} = I/(2\pi fU)$$

For example, for *A3* ELP format with $U$ = 120 V, $I$ = 377mA, $f$ =1 000 Hz, $S_{ELP}$ amounts to 0.5 μF.

$C_{ELP}$ value influences current value and configuration and consequently ELP luminance and power supply operating mode.

Fig. 1 shows a functional flow diagram of the developed small-sized network electric energy converter intended for ELP power supply. Elements *VT*1, *VT*2, *VD*1, *VD*2, *C*1 and *C*2 are a part of the half-bridge autonomous voltage inverter (AVI). Capacitors *C*1 and *C*2 represent a voltage divider forming an average point of the half-bridge AVI power supply. Rectifier transforms power line alternating voltage to unipolar voltage (rectified voltage). The AVI based on the direct voltage delivered to its input, forms an alternating voltage of 1000 Hz frequency. A control system (CS) sets algorithm of transistor keys *VT*1 and *VT*2 work, as well as frequency and voltage at the AVI output. The work of these keys can be accomplished using a pulse-width modulation (PWM) algorithm or a pulse-width control (PWC) algorithm [7].

Work [6] shows that it is possible to operate an ELP power supply based on the PWM algorithm, which allows obtaining an optimum harmonious composition of AVI output voltage close to the harmonious composition of sinusoidal voltage due to a high-frequency switching of transistor keys with opened and closed state of their duration modulation by sinusoidal law. However in this case, AVI switching losses increase and circuit efficiency decreases [7].

PWC makes it possible to accomplish a simpler algorithm of the AVI transistor key control. In case of single fold switching of the keys for a half-cycle, they open in turn, once during the half-cycle, and between intervals of transistor conductivity, a “dead time” (time interval, when both transistors are closed) is added. Switching energy losses decrease and so maximum circuit efficiency is achieved. The natural configuration of the AVI output alternating voltage when using such a control algorithm is rectangular [7].

ELP is a capacitor loading for the AVI and consequently to limit amplitude of the charge current pulses of the capacitor formed by the ELP electric capacitance, throttle *L*1 is installed at the AVI output. The throttle inductance value influ-

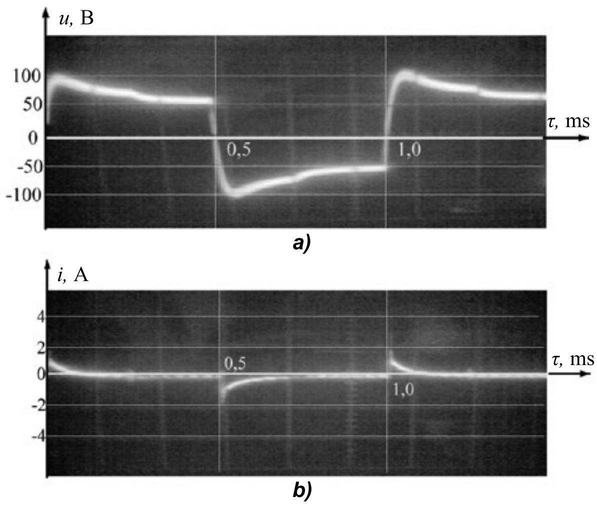


Fig. 2. Voltage (a) and current (b) oscillograms with inductance ($L$) of throttle $L1$ equal to 10 μH

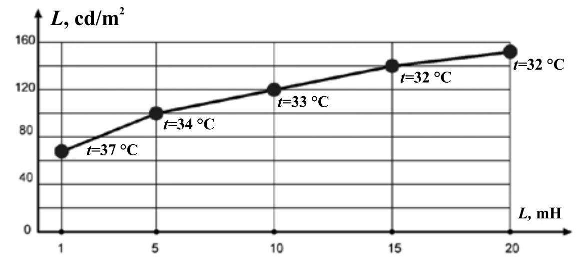


Fig. 3. ELP $L_v$ luminance dependence on inductance ($L$) of throttle $L1$

ences the configuration and value of the current flowing through the ELP and AVI transistor keys.

Fig. 2 shows an ELP oscillograms of voltage *u (τ)* and of current *i (τ)* flowing through it when using throttle $L1$ with $L$ = 10 μH inductance in the circuit. It is seen that the current has a configuration of short pulses with an amplitude higher than 2 A.

It is seen from Fig 2 b that the current has a configuration of short pulses, the amplitude value of which exceeds 2A and is only limited by the active resistance of the ELP power supply circuit and by the throttle of inductive resistance. In this operating mode, *A3* format ELP luminance does not exceed 35 cd/m$^2$. A considerable rise in temperature (up to 55°C) can be noticed, which in case of an ELP's long operation leads to its degradation and destruction. These oscillograms are obtained when using a PWC control algorithm by AVI transistor keys (*VT*1 and *VT*2).

Obviously, it is necessary to try to limit current pulse amplitude and consequently, to improve

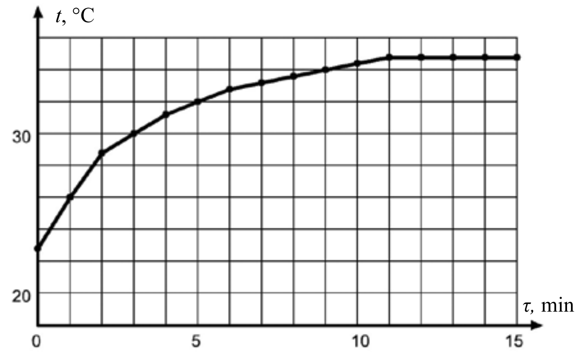


Fig. 4. ELP temperature $t$ time dependence of throttle $L1$ inductance ($L$) equal to 15 μH

ELP thermal mode. This problem can be solved, if throttle $L$ inductance value will compensate the ELP equivalent resistance capacitor component. The full compensation occurs with equality of the circuit reactive element resistances:

$$2\pi fL = 1/(2\pi fC_{ELP})$$

For example, with $f$ = 1000 Hz and $C_{ELP}$ = 0.5 μF, $L$ = 50.7 μH.

To optimise $L$, an experiment is carried out to find out ELP luminance $L_v$ dependence on $L$. Fig. 3 shows ELP (format *A3*) $L_v$ and working temperature $t$ dependences on $L$. Temperature $t$ for each point is specified, which is measured in five minutes after switching on the power supply, and initial (for each point) $t$ corresponds to the ambient temperature (23°C). The choice of five-minute time measurement interval allows recording a gradual temperature increase. A greater interval is undesirable, because at small $L$ values, an abnormal warming-up of the panel takes place (Fig. 3). The measurements were performed using throttle $L1$ with winding active resistance of 2.6 Ohm. $L$ changed from 1 to 20 μH. A greater increase in $L$ is not desirable, because first, with $L$ > 15 μH, $L_v$ growth is slowed down (Fig. 3), and secondly, a bigger $L$ increase causes a deterioration of mass and dimension parameters of the power supply. With $L$ = 15 μH, $L_v$ = 140 cd/m$^2$, which meets most consumer requirements to ELPs [1].

The plotted time dependence of $t$ for operating mode with $L$ = 15 μH shows (Fig. 4) that beginning from the eleventh operation minute, a comfortable stable ELP temperature mode with

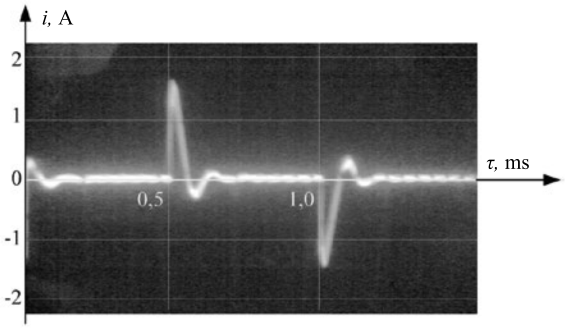


Fig. 5. Current oscillogram with throttle $L1$ inductance ($L$) equal to 1 μH

$t$ of about 35 °C is reached, and a further temperature rise almost does not occur.

The performed research shows that $L$ influences operational ELP parameters and the operating mode of the power supply. So in Fig. 5, a current oscillogram at the power supply output is given when using a throttle with $L$ = 1 μH in the circuit. It is seen from the oscillogram that the power supply works in an interrupted current mode, which leads to non-optimum by $L_v$ and $t$ ELP parameters. As it can be seen from Fig. 3, $L_v$ = 70 cd/m$^2$ with a relatively high $t$. Maximum amplitude of the current pulses is equal to 1.6 A, and I = 140 mA.

In Fig. 6, ELP voltage and current oscillograms obtained when using throttle $L1$ with $L$ = 15 μH in the power supply are given. It is seen that ELP current has a continuous nature, which positively affects $L_v$ level. And it follows from Fig. 3 that this operating mode provides a high $L_v$ (140 cd/m$^2$) and an acceptable temperature mode (Fig. 4). Maximum current amplitude is equal to 0.5 A, which as compared with the previous modes, reduces the circuit element loading. ELP current $I$ is 300 mA. The ELP voltage configuration is close to sinusoidal (Fig. 6,*)* and $U$= 126V.

Thus the performed research shows that to obtain good mass and dimension characteristics of the power unit and ELP operational parameters, it is useful to accept $L$ = 15 μH.

The developed power supply unit is a functionally finished module with the overall dimensions: 100×50×50 mm. Power of the source amounts to 200 VA, which allows using it as ELP power supply of a wide format range. To match the power unit parameters with ELP parameters, the format of which differs from *A3,* to obtain a required operating mode, one should include in series re-

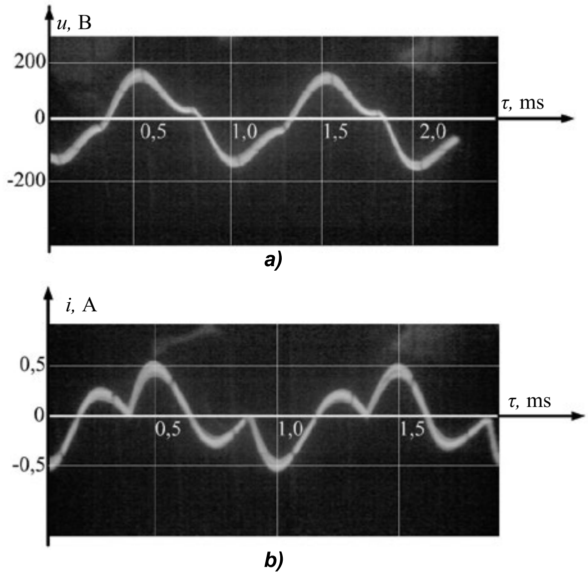


Fig. 6. Voltage and current oscillograms with throttle $L1$ inductance ($L$) equal to 15 μH

active elements of the required rated value into the power supply panel circuit (a throttle and a capacitor, which are not regular components of the power unit).

## CONCLUSION

ELP luminance, optimum temperature operating mode and durability are determined to a significant extent by the configuration and value of the current flowing through the ELP.

The considered principle of ELP power supply circuit construction and presented dependences and oscillograms allow developing converters of *electric energy for flexible ELP power supply units.* These converters have good mass and dimension, as well as power indicators and provide high operational characteristics of ELPs. The work was completed with a support of the Ministry of Education and Science of the Russian Federation (unique identifier is *RFMEFI57715X0196*).

## REFERENCES


1. Sushkov V. Ya. "Electroluminescence panels, don't pass by" Electronics: Science, Technology, Business. 2003. # 7 (49), pp. 54–57.

2. Gusev A.I., Samokhvalov M.K. "Electric characteristics of thin-film electroluminescence indicators" Ulyanovsk STU, 2006, 125 P.

3. Shubin N.E., Kozyrev E.N., Platova A.A, Brezhnev A.A, Maldzigati A.I. "Development and manufac-

ture of high-effective electroluminescence panels" Bulletin of the Voronezh State Technical University 2013, V.9, # 6–2, pp.74–77.

4. Goncharov I.N., Kozyrev E.N., Askerov R.O, Maldzigati A.I. "Research and increase of durability of radiation of electroluminescence panels" Radio engineering and electronics 2016, V.61, #1, pp. 89–92.

5. Bulany M.F., Kovalenko A.V., Polezhaev B.A. "Electroluminescence light sources based on ZnSe: Mn monocrystals with optimum luminance characteristics" The Technical Physics Journal, 2003, V. 73, Issue. 2, pp. 133–135.

6. Zhou Jia, Tong Ge, Linfei Guo, Ng Pei Jian Eileen, Huiqiao He, Joseph Chang "A high power driver IC for electroluminescent panel: design challenges and advantages of using the emerging LEES-SMART GaN-on-CMOS process" Procedia Engineering, 2016, V.141, pp. 91–93.

7. Rudenko V.S., Senko V. I, Chizhenko I.M. "Foundations of converter facilities" Moscow: Vyshaya Shkola, 1980, 424 P.

***Igor N. Goncharov,***
Prof., Doctor of Technical Science, a senior lecturer of the Electronic device chair of the North Caucasian Mining and Smelting Institute (State Technological University). Fields of scientific interest include modern sources of optical radiation, optical quantum generators, electron-optical converters

***Alexander M. Kabyshev,***
Ph.D. He is a senior lecturer of the Industrial electronics chair of the North Caucasian Mining and Smelting Institute (State Technological University). Fields of scientific interest include converters of electric energy

***Evgeny N. Kozyrev,***
Prof., Doctor of technical and economic science, the Head of the Electronic device chair of the North Caucasian Mining and Smelting Institute (State Technological University), and member of the Russian Academy of Natural Sciences and MANEB. His fields of scientific interest include photoelectronic and electron beam devices, solid-state devices and devices of the microwave interval

***Alan I. Maldzigati,***
an engineer. His position is a leading technology engineer of Gran Open Company. He is a post-graduate student. Fields of scientific interest include optoelectronic devices

# CONTENTS

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