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On the Competition of Scientific and Technical Journals

In early 2017, the Ministry of Education announced the All-Russian competition of Scientific and Technical Journals. Winners should receive state financial support for three years: 2018–2020.

The competition was held in three rounds, and after the first round there were to remain 500 journals (out of 2500 issues presented at the contest). After the second round – there were only 100 journals that went to the last decisive third round.

It should be noted that during the last round of the competition, the remaining 100 editions were additionally subjected to a very rigorous examination of two specialists singled out for this purpose by the organizers of the contest. The experts carefully considered the programs submitted by each editorial board for their development in 2018 with financial justification for each of the points of the submitted programs. Our program was forced in a number of cases to disagree with the expertise and provided additional justification for the proposed program (its individual items). It's nice to note that the commission that examined the documents submitted for the third round basically agreed with our arguments. Unfortunately, the amount of anticipated state funding for 2018 was cut three times and amounted to only 1, 000, 000 rub what means, including VAT – 847457. 63 rub.

It can be assumed that one of the most important pledges of our success was the following circumstances:

– Provided full processing of the site in Russian and English languages and access to automatic mode of the site;

– The foundation 26 years ago in New York of the English version of the "Light & Engineering" Journal, the relocation of its publication in Moscow in 1999 and the transformation of it over the years into an international journal;

– The issue has been endorsed by CIE Board of Administration as one of the three best lighting journals that meet the CIE requirements and criteria (Leukos, Light & Engineering / Svetotechnika, Lighting Research & Technology), and for many years our editorial board cooperates directly with international scientometric agencies, such as Web of Science and Scopus.

None of the competitor's participants had such a history with access to the international arena.

It also seems that the establishment of a network of foreign correspondent points in countries such as Argentina, India, Turkey, Slovenia, as well as Israel, Iran, South Korea and Finland played an important role in this plan.

But most importantly, in our opinion, this is the active position of our journal, its role in uniting specialists working in various branches of the national economy in the field of illumination, conducting systematic discussions on the most important problems of the development of science and technology, increasing the scientific and technical level in the field of light and engineering in the hundreds specialists who do not have lighting engineering education, systematic expansion of the authors' team and assistance to new authors in the preparation of materials for publication.

Thus, at present the Journal "Light & Engineering" is one of the in-demand lighting technical journals in the world and it is in a group of the best scientific and technical journals of the Russian Federation.

We are proud of the victory in such a large-scale competition. However, there is a big and difficult work ahead to implement the approved program and preserve our leading positions for our favourite issue.

J.B. Aizenberg

N.S. Sherri

V.P. Budak

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

LIGHT & ENGINEERING СВЕТОТЕХНИКА

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Scientific Editors:

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.

To promote the work of the Journal, the editorial staff is in active communication with Thomson Scientific (Citation index) and other international publishing houses and agencies, such as Elsevier and EBSCO Publishing.

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THE NATURE OF THE PHOTON AND QUANTUM OPTICS

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Everything has to be made so simple, as possible, but not easier
A. Einstein

ABSTRACT

In a concise, but accessible for the first acquaintance form the procedure for the quantization of linear oscillator is set out. By analogy with this procedure the procedure of quantization (second quantization) of classical Maxwell's electrodynamics is set up. The physical sense of the wave functions arguments of transverse electromagnetic field and its Fourier transformation is set up. One pay attention as for quantum coherent (almost a classic) states of the electromagnetic field and for photonics Fock states. Attention is drawn to the fact of absence the power of the universal content of such concepts as field amplitude, phase and number of particles (photons), which are used by experimenter's to describe the states of a quantized field. The semi quantitative description the interaction processes of a quantum electromagnetic field with substance is set up. Specified situations are shown in which the discrepancy between the predictions of classical and quantum electrodynamics is noticeable at the macroscopic level.

Keywords: classical electrodynamics, quantum electrodynamics, quantum coherent states, Fock states, photon

1. INTRODUCTION

About a hundred years ago, a famous French physicist L. de Broglie (1892–1987) posed the problem to describe the diffraction and interference photon properties, which existence was theoretically predicted by M. Planck (1858–1947) in 1905. On the basis of his theory [1] de Broglie put the then-known equations $E = \hbar\omega$ and $E = mc^2$. This way led him to the conclusion that the photon possesses a small, but a finite mass. At the same time it remains unclear what are the principal differences between the photon and the other "massive" elementary particles. And then de Broglie came up to the brilliant idea: if the fundamental differences between the particles are absent than, on the contrary, all "massive particles" like a photon have to possess the wave properties. In such way the quantum mechanics of particles of the final mass was constructed. But formulated above the primary problem hasn't been fulfilled by de Broglie. The theory of a photon possessing both corpuscular and wave properties, was constructed later, in five years, by the work of other scientists. This theory turned out to be rather rich and complex, requiring the common efforts of many people. Below in elementary terms one presents its main concepts.

The idea of the light and its internal structure by the development of scientific knowledge has undergone dramatic perturbations. The concept of "ray of light" has ancient origin. There are two author of the law of refraction: V. Snellius (1580–1626) and R. Descartes (1596–1650). In works of C. Huygens (1629–1695), R. Hooke (1635–1703), and particle I. Newton (1643–1727) was opened the wave nature of light. But the date of establishment of this theory should considered the 1865, when J.C. Maxwell (1831–1879) got from his theory of electricity and magnetism the conclusion of the existence of electromagnetic waves. Describing by electric E^{ν} (r,t) and magnetic $H^{\nu}(r,t)$ strength posed at each point of space *r* at any time *t*, these waves perfectly definite quantity the interference, diffraction and the polarization of light. As for radiation and absorption of light, this theory is coming across the difficulties.

Investigating this question, firstly from thermodynamic point of view, and then developing the hypothesis of L. Bolsman (1844–1906) about the inevitability in the nature of the jump-figurative processes, M. Planck introduced the concept "photon" into the theory, which was reported by him at a meeting in German Physical Society 14 December 1905 year. Introduction the "photon" has made possible the understanding of atomic phenomena. As for the properties of the photon until the end of the twentieth years of last century one know nothing apart the expressions for its energy $\hbar\omega$ (ω is the frequency) and momentum $\hbar\mathbf{k}$ (**k** is the wave vector). As soon as one speaks about the photons, he/she had to forget about the attributes of Maxwell theory $E^{\nu}(r,t)$ and $H^{\nu}(r,t)$. So the Planck's constant $\hbar = 1{,}05\cdot 10^{-27}$ '$erg\cdot s$ came to the theory. But rather soon it became clear that this constant is applicable not to light only, but also to bodies of finite mass.

In the works in the first place N. Bohr (1885–1962), L. de Broglie, W. Heisenberg (1901–1976) and E. Schrödinger (1887–1961) the quantum mechanics of particles of final mass was constructed. It was this theory that pointed the way and the need of building a consistent quantum theory of optical phenomena. The necessity of such theory directly follows from the definition of electric strength $E^{\nu}(r,t)$ as the force acting from the force on a single point charge. In quantum theory, any charged body describes by the wave function, the concept of localization blurs. Together with it, the classical concept of electric strength is blurred. The quantum theory of the electromagnetic field was built in the papers of P. Dirac (1902–1984), V. Heisenberg, V. Pauli (1900–1958), P. Jordan (1902–1980) and E. Fermi (1901–1954) in the period from 1927 to 1930. This theory combines classical (wave) and quantum (corpuscular) properties of photons. On a question "What is a photon?" this theory gives a clear answer: "Photon is an electromagnetic object described by its wave function". The explicit form of the wave function is well known, whereas with her interpretation the situation is more complicated. Here are stored all problems, characteristic of quantum mechanics wave function of particles of finite mass, often discussed up to now [2]. But at the same time be more questions about the methods of its calculation. In spite of the fact that such a theory is now well developed, in engineering practice it still has not found its application. This review aims to introduce the reader to enter into the nontrivial circle of quantum theory of electromagnetic field ideas. I want to believe that, if the reader with pencils in hand will review the proposed review of more than one under consideration, it will significantly facilitate him /her further acquaintance with voluminous manuals [3] on the subject.

2. THE CLASSICAL ELECTROMAGNETIC FIELD AND THE QUANTUM OSCILLATOR

According to Maxwell's equations, electromagnetic waves characterizing the propagation of light in the vacuum can be described by introducing the vector potential $A^{\nu}(r,t)$ that satisfy the wave equations [4]:

$$\nabla^2 A^{\nu}(r,t) - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}A^{\nu}(r,t) = 0. \quad (1)$$

Instead of the vector potential one traditionally use vectors

$$E^{\nu}(r,t) = -\frac{1}{c}\frac{\partial}{\partial t}A^{\nu}(r,t) \text{ and } \\ H^{\nu}(r,t) = rotA^{\nu}(r,t). \quad (2)$$

The solution of equation (1) can be represented in the form of superposition of plane waves

$$A^{\nu}(r,t) = \sum_{\mathbf{k}\lambda} e^{\nu}_{\mathbf{k}\lambda}\gamma_k\left(\alpha_{\mathbf{k}\lambda}e^{i\mathbf{kr}-ikct} + \alpha^{*}_{\mathbf{k}\lambda}e^{-i\mathbf{kr}+ikct}\right), \quad (3)$$

where **k** is the wave vector with components $\{k_x, k_y, k_z\}$, $\alpha_{\mathbf{k}\lambda}$ is dimensionless constants that depends on wavelength $ƛ = 2\pi/k$ and the index of transverse $(ke_{k\lambda}) = 0$ polarization $\lambda = 1,2$. By $e^{\nu}_{\mathbf{k}\lambda}$ the unit vectors are designated perpendicular to the direction of wave propagation that is to vector **k** . Next, c is the speed of light in vacuum, and the functions γ_k, having the dimension of a vector potential are introduced for the convenience of further consideration. If one put $\alpha_{\mathbf{k}\lambda} = |\alpha_{\mathbf{k}\lambda}|\exp(i\vartheta_{\mathbf{k}\lambda})$ we get:

$$A^{\nu}(\mathrm{r},t) = \sum_{\mathbf{k}\lambda} e^{\nu}_{\mathbf{k}\lambda} A_{\mathbf{k}\lambda} \cos\left(\mathbf{kr} - kct + \vartheta_{\mathbf{k}\lambda}\right), \quad A_{\mathbf{k}\lambda} = 2\left|\alpha_{\mathbf{k}\lambda}\right|\gamma_k. \tag{4}$$

According to (4) the classical electromagnetic waves described by entering the classical oscillator at each point of space $\mathbf{r}$, which performs the harmonic oscillations $A_{\mathbf{k}\lambda}\cos\left(\mathbf{kr} - kct + \vartheta_{\mathbf{k}\lambda}\right)$ with the frequency $\omega_k = kc$. This suggests that one describes the quantum the electromagnetic wave then the classical oscillators must be replaced by quantum one.

Recall that under the classical oscillator one means the material point with mass m, which coordinate $x(t)$ under the action of elastic forces $f(t) = -\chi x(t)$ performs the harmonic oscillations with the frequency ω. From the Newton's law $m\left(d^2/dt^2\right)x(t) = -\chi x(t)$ it follows that

$x(t) = x_0\cos\left(\omega t + \vartheta\right)$ where $\omega = \sqrt{\chi / m}$.

How to construct a quantum theory of the oscillator? In quantum theory is to replace the coordinate of the material x and its momentum p are given by operators $x \to \hat{x} \equiv x$ and $p \to \hat{p} = -i\hbar\partial/\partial x$. By such replacement the expression of classical point total energy E has to be replaced by operator expression named "Hamiltonian" or the total energy operator $\hat{H}$

$$E = \frac{p^2}{2m} + \frac{\chi}{2}x^2 = \\ = \frac{p^2}{2m} + \frac{m\omega^2}{2}x^2 \to -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + \frac{m\omega^2}{2}x^2 = \hat{H}.$$

In quantum mechanics the state of a quantum particle is described by the wave function $\psi(x)$ obeying the equation to the name of E. Schrödinger:

$$\left(-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + \frac{m\omega^2}{2}x^2\right)\psi(x) = E\psi(x) \text{ or} \quad \hat{H}\psi(x) = E\psi(x). \tag{5}$$

The square of the wave function $\psi^*(x)\psi(x)dx$ determines the probability of detection of the classical coordinates of the particle in the interval dx around the point x, if such experiment will be delivered. Therefore,

$$\int_{-\infty}^{\infty}\psi^*(x)\psi(x)\,dx = 1.$$

We write several formal properties of the quantum oscillator [5]. After the change the variables

$$\varsigma = x\beta,\ \beta = \sqrt{\frac{\omega m}{\hbar}},\ \lambda = \frac{2E}{\hbar\omega},$$

the Schrödinger equation (5) takes the form

$$\left(\varsigma^2 - \frac{d^2}{d\varsigma^2}\right)\psi(\varsigma) = \lambda\psi(\varsigma).$$

Of course, instead of $\psi(\varsigma)$ could be used $\psi\left(x\sqrt{m\omega/\hbar}\right)$, but it is inconvenient. The expression in brackets resembles an algebraic difference of squares. That is why is seems to be the natural to use the operators

$$\hat{\alpha} = \frac{1}{\sqrt{2}}\left(\varsigma + \frac{\partial}{\partial\varsigma}\right),\ \hat{\alpha}^+ = \frac{1}{\sqrt{2}}\left(\varsigma - \frac{\partial}{\partial\varsigma}\right).$$

By means of these operators the Schrödinger equation may be rewritten the form

$$\frac{\hbar\omega}{2}\left(\hat{\alpha}^+\hat{\alpha} + \hat{\alpha}\hat{\alpha}^+\right)\psi(\varsigma) = E\psi(\varsigma), \quad \hat{H} = \frac{\hbar\omega}{2}\left(\hat{\alpha}^+\hat{\alpha} + \hat{\alpha}\hat{\alpha}^+\right). \tag{6}$$

Under additional condition

$$\int_{-\infty}^{\infty}\psi^*(\varsigma)\psi(\varsigma)d\varsigma = 1$$

this equation has many solutions, determined by the index $n = 0,1,2,...$ Let us denote these solutions through $\varphi\left(\varsigma|n\right)$

$$\varphi(\varsigma|n) = H_n(\varsigma)e^{-\frac{\varsigma^2}{2}}, \quad H_n(\varsigma) = \frac{(-1)^n}{\sqrt{2^n n!\sqrt{\pi}}}e^{\varsigma^2}\frac{d^n}{d\varsigma^n}e^{-\varsigma^2}. \tag{7}$$

Function $H_n(\varsigma)$ is called the Hermit polynomials. To each solution $\varphi(\varsigma|n)$ its own parameter E corresponds, determing permissible discrete values of the oscillator energy $E_n = \hbar\omega\left(n + 1/2\right)$, if on it there are no external forces. Functions (7) are found to be real and possessing the following properties

$$\hat{\alpha}\varphi(\varsigma|n)=\sqrt{n}\varphi(\varsigma|n-1),$$
$$\hat{\alpha}^{+}\varphi(\varsigma|n)=\sqrt{n+1}\varphi(\varsigma|n+1), \tag{8}$$
$$\int_{-\infty}^{\infty}\varphi(\varsigma|n)\varphi(\varsigma|n')d\varsigma=\delta_{nn'}.$$

It follows from these equations that

$$\hat{\alpha}^{+}\hat{\alpha}\varphi(\varsigma|n)=n\varphi(\varsigma|n).$$

The operator $\hat{n}=\hat{\alpha}^{+}\hat{\alpha}$ denomination is operator number. With its help the photons operator number will be constructed. If the wave function $\psi(\varsigma)$ is not the same with any $\varphi(\varsigma|n)$, the number of photons in such state have not a specific meaning, and one can only talk about their average quantum number $\langle\hat{n}\rangle=\int_{-\infty}^{\infty}\psi^{*}(\varsigma)\hat{n}\psi(\varsigma)d\varsigma$. In General, if the oscillator is acting by externally force, then the wave function can essentially depends on time. Instead of equation (5), its behaviour is now defines a temporary Schrödinger equation:

$$i\hbar\frac{\partial\Psi(x,t)}{\partial t}=\hat{H}\Psi(x,t).$$

3. THE PROCEDURE OF QUANTIZATION OF THE ELECTROMAGNETIC FIELD

We will say that some set of parameters describes the state of any material object in some moment of time $t=0$, if this set is sufficient to the prediction of the results of any potential experiment carried out on this object in a future time $t>0$. In classical mechanics the state of a point particle in the one-dimensional space is described by coordinate x and momentum p. In the transition from classical mechanics to the quantum one the coordinate of a particle and the momentum are replaced by the corresponding operators. A similar situation arises in the field theory. In classical theory of electromagnetic field the state of the field is determines by its amplitude $A^{\nu}(\boldsymbol{r},t)$. It means that by the transition from classical optics to quantum one the field amplitude has to be replaced with an operator expression. The state of any system in quantum theory describes the wave function ψ satisfying to Schrödinger equation. The explicit form of the Hamiltonian in this equation will be predicted by procedure of quantization of classical oscillator with the replacement of electromagnetic energy by its quantum analogue. In classical physics, the energy of plane electromagnetic waves occupying the volume V is described by formula:

$$E=\int_{V}\frac{E^{2}(\boldsymbol{r},t)}{8\pi}d\boldsymbol{r}+\int_{V}\frac{H^{2}(\boldsymbol{r},t)}{8\pi}d\mathbf{r}=\int_{V}\frac{E^{2}(\boldsymbol{r},t)}{4\pi}d\boldsymbol{r}.$$

Here is taken into account that at plane electromagnetic waves the energy falling on the electric and magnetic components is equal to each other. Let us assume that electromagnetic field is placed in a cube with edge L and volume $V=L^{3}$. At the borders of the cube one use the periodic boundary conditions $\exp(ik_{x}L)=\exp(ik_{y}L)=\exp(ik_{z}L)=1$. In the case, using (2) and (3), we obtain

$$E=\sum_{\mathbf{k}\lambda}\frac{V\omega_{k}^{2}}{4\pi c^{2}}\gamma_{k}^{2}\left(\alpha_{\mathbf{k}\lambda}^{*}\alpha_{\mathbf{k}\lambda}+\alpha_{\mathbf{k}\lambda}\alpha_{\mathbf{k}\lambda}^{*}\right),\ \omega_{k}=ck. \tag{9}$$

This form of energy emphasizes its reality. The transition to infinite volume carries out by procedure $V\to\infty$. Comparison of expressions (6) and (9) indicates that the quantization procedure demands the replacement

$$\gamma_{k}\to\sqrt{\frac{2\pi\hbar c^{2}}{\omega_{k}V}},\ \alpha_{\mathbf{k}\lambda}\to\hat{\alpha}_{\mathbf{k}\lambda}=\frac{1}{\sqrt{2}}\left(\varsigma_{\mathbf{k}\lambda}+\frac{\partial}{\partial\varsigma_{\mathbf{k}\lambda}}\right),$$
$$\alpha_{\mathbf{k}\lambda}^{*}\to\hat{\alpha}_{\mathbf{k}\lambda}^{+}=\frac{1}{\sqrt{2}}\left(\varsigma_{\mathbf{k}\lambda}-\frac{\partial}{\partial\varsigma_{\mathbf{k}\lambda}}\right). \tag{10}$$

At the same time, vector potential (3) and total field energy (9) are replaced by operator expressions

$$\hat{A}^{\nu}(\boldsymbol{r},t)=\sum_{\mathbf{k}\lambda}e_{\mathbf{k}\lambda}^{\nu}\gamma_{k}\left(\hat{\alpha}_{\mathbf{k}\lambda}^{\ \ i\mathbf{kr}-ikct}+\hat{\alpha}_{\mathbf{k}\lambda}^{+}e^{-i\mathbf{kr}+ikct}\right),$$
$$\hat{H}=\sum_{\mathbf{k}\lambda}\frac{\hbar\omega_{k}}{2}\left(\hat{\alpha}_{\mathbf{k}\lambda}^{+}\hat{\alpha}_{\mathbf{k}\lambda}+\hat{\alpha}_{\mathbf{k}\lambda}\hat{\alpha}_{\mathbf{k}\lambda}^{+}\right). \tag{11}$$

View of the Schrödinger equation containing this operator $\hat{H}$ (Hamiltonian) was given above

$$\hat{H}\psi(\text{V}) = E\psi(\text{V}).$$

The solution to this equation is the product of functions

$$\varphi(\varsigma|\mathbf{N}) = \prod_{\mathbf{k}\lambda} \varphi(\varsigma_{\mathbf{k}\lambda}|n_{\mathbf{k}\lambda}),\ E_{\mathbf{k}\lambda} = \hbar\omega_k\left(n_{\mathbf{k}\lambda} + \frac{1}{2}\right),$$
$$E = \sum_{\mathbf{k}\lambda} E_{\mathbf{k}\lambda}.$$

Here, the multidimensional vector ς means a set of arguments ....,$\varsigma_{\mathbf{k}\lambda}$,... with varyous $(\mathbf{k},\lambda)$, the multidimensional vector **N** means a set of numbers ...,$n_{\mathbf{k}\lambda}$,.... Function $\varphi(\varsigma_{\mathbf{k}\lambda}|n_{\mathbf{k}\lambda})$ satisfies the equation

$$\frac{\hbar\omega_k}{2}\left(\hat{\alpha}^+_{\mathbf{k}\lambda}\hat{\alpha}_{\mathbf{k}\lambda} + \hat{\alpha}_{\mathbf{k}\lambda}\hat{\alpha}^+_{\mathbf{k}\lambda}\right)\varphi(\varphi_{\mathbf{k}\lambda}|n_{\mathbf{k}\lambda}) = E_{\mathbf{k}\lambda}\varphi(\varphi_{\mathbf{k}\lambda}|n_{\mathbf{k}\lambda}).$$

The energy $E_{\mathbf{k}\lambda} = \hbar\omega_k(n_{\mathbf{k}\lambda} + 1/2)$ corresponds to each solution φ $(\varphi_{\mathbf{k}\lambda}|n_{\mathbf{k}\lambda})$. Since we are always interested in energy difference

$$E - \sum_{\mathbf{k}\lambda}\hbar\omega_k/2 = \sum_{\mathbf{k}\lambda}\hbar\omega_k n_{\mathbf{k}\lambda}, \qquad (12)$$

then on the amount $\sum_{\mathbf{k}\lambda}\hbar\omega_k/2$ one could not pay attention. The sum in the left side of equality (12) is energy full electromagnetic fields associated with the specific set of numbers $n_{\mathbf{k}\lambda}$ that is, a specific set of photons, each with energy $\hbar\omega_k$. Thus $n_{\mathbf{k}\lambda}$ means number of photons in the mode $(\mathbf{k},\lambda)$.

So, the photon $(n_{\mathbf{k}\lambda} = 1)$ of the mode $(\mathbf{k},\lambda)$ is the state of the electromagnetic field to which corresponds the wave function

$$\begin{aligned}\varphi(\varsigma_{\mathbf{k}\lambda}|1) &= H_1(\text{V}_{\mathbf{k}\lambda})\exp(-\varsigma^2_{\mathbf{k}\lambda}/2) = \\ &= \sqrt{2}\pi^{-1/4}\varsigma_{\mathbf{k}\lambda}\exp(-\varsigma^2_{\mathbf{k}\lambda}/2).\end{aligned} \qquad (13)$$

This is the answer to the question in the title of this article. In infinite space, such states in its pure form cannot exist, as well as in the classical physics strictly monochromatic waves cannot exist. It's impossible just because monochromatic waves have no boundaries. But researching their properties is extremely fruitful, as soon as any really existing electromagnetic field can be represented in the form of their superposition. The same property is possessed by the photon states. Any realistically state of the field can be built of them, as from bricks.

To understand the physical meaning of a function (13), it is necessary to find out the physical meaning of arguments $\varsigma_{\mathbf{k}\lambda}$. The procedure of quantization of fields in accordance with (10) demands the replacement

$$\begin{aligned}\frac{\alpha_{\mathbf{k}\lambda} + \alpha^*_{\mathbf{k}\lambda}}{\sqrt{2}} &= \frac{A_{\mathbf{k}\lambda}}{\gamma_k\sqrt{2}}\cos\vartheta_{\mathbf{k}\lambda} \to \varsigma_{\mathbf{k}\lambda} \\ \frac{\alpha_{\mathbf{k}\lambda} - \alpha^*_{\mathbf{k}\lambda}}{\sqrt{2}} &= i\frac{A_{\mathbf{k}\lambda}}{\gamma_k\sqrt{2}}\sin\vartheta_{\mathbf{k}\lambda} \to \frac{\partial}{\partial\varsigma_{\mathbf{k}\lambda}}.\end{aligned} \qquad (14)$$

The argument of the wave function $\varsigma_{\mathbf{k}\lambda}$ corresponds to "classical value" $A_{\mathbf{k}\lambda}\cos\vartheta_{\mathbf{k}\lambda}/\gamma_k\sqrt{2}$. The word "classical" we take in inverted commas, because γ_k contents $\hbar$. Of course, it would be possible to write in such form $\varphi(A_{\mathbf{k}\lambda}\cos\vartheta_{\mathbf{k}\lambda}/\gamma_k\sqrt{2}|n_{\mathbf{k}\lambda})$, but this is inconvenient, so one is writing $\varphi(\varsigma_{\mathbf{k}\lambda}|n_{\mathbf{k}\lambda})$. According to quantum principles, construction $|\varphi(\varsigma_{\mathbf{k}\lambda}|n_{\mathbf{k}\lambda})|^2 d\varsigma_{\mathbf{k}\lambda}$ determines the probability about detection argument $\varsigma_{\mathbf{k}\lambda}$ (or "classical" construction $A_{\mathbf{k}\lambda}\cos\vartheta_{\mathbf{k}\lambda}/\gamma_k\sqrt{2}$) in the interval $d\varsigma_{\mathbf{k}\lambda}$, if such experiment will be delivered. In such a way one founds the distribution function of the "classical" variable $A_{\mathbf{k}\lambda}\cos\vartheta_{\mathbf{k}\lambda}/\gamma_k\sqrt{2}$.

We consider the Fourier transform (indices **k**, λ are omitted)

$$\varphi(\varsigma) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} e^{i\eta\varsigma}\tilde{\varphi}(\eta)d\eta,$$
$$\tilde{\varphi}(\eta) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} e^{-i\eta\varsigma}\varphi(\varsigma)d\varsigma.$$

From the properties of the Fourier transformation it follows that this procedure is accompanied by replacement

$$\varphi(\varsigma) \leftrightarrow \tilde{\varphi}(\eta),\ \varsigma \leftrightarrow i\frac{\partial}{\partial\eta},\ -i\frac{\partial}{\partial\varsigma} \leftrightarrow \eta$$

Therefore, instead of (14) as quantization rules of the electromagnetic fields can serve as the following:

$$\frac{\alpha_{\mathbf{k}\lambda}+\alpha^*_{\mathbf{k}\lambda}}{\sqrt{2}}=\frac{A_{\mathbf{k}\lambda}}{\gamma_k\sqrt{2}}\cos\vartheta_{\mathbf{k}\lambda}\to i\frac{\partial}{\partial\eta_{\mathbf{k}\lambda}},$$
$$\frac{\alpha_{\mathbf{k}\lambda}-\alpha^*_{\mathbf{k}\lambda}}{\sqrt{2}}=i\frac{A_{\mathbf{k}\lambda}}{\gamma_k\sqrt{2}}\sin\vartheta_{\mathbf{k}\lambda}\to i\eta_{\mathbf{k}\lambda}. \qquad (15)$$

Thus, the argument of the function $\tilde{\varphi}(\eta_{\mathbf{k}\lambda})$ meets the value of the classic $A_{\mathbf{k}\lambda}\sin\vartheta_{\mathbf{k}\lambda}/\gamma_k\sqrt{2}$. Construction $|\tilde{\varphi}(\eta_{\mathbf{k}\lambda})|^2$ determines the probability distribution "classical" values $A_{\mathbf{k}\lambda}\sin\vartheta_{\mathbf{k}\lambda}/\gamma_k\sqrt{2}$. Because the function $\tilde{\varphi}(\eta_{\mathbf{k}\lambda})$ follows from $\varphi(\varsigma_{\mathbf{k}\lambda})$ by a Fourier transformation, then according to (13)

$$\tilde{\varphi}(\eta_{\mathbf{k}\lambda}|1)=i\sqrt{2}\pi^{-1/4}\eta_{\mathbf{k}\lambda}\exp(-\eta^2_{\mathbf{k}\lambda}/2).$$

So, for one-photon states we have:

$$|\varphi(\varsigma_{\mathbf{k}\lambda}|1)|^2=\frac{2}{\sqrt{\pi}}\varsigma^2_{\mathbf{k}\lambda}\exp(-\varsigma^2_{\mathbf{k}\lambda}),$$
$$|\tilde{\varphi}(\eta_{\mathbf{k}\lambda}|1)|^2=\frac{2}{\sqrt{\pi}}\eta^2_{\mathbf{k}\lambda}\exp(-\eta^2_{\mathbf{k}\lambda}).$$

These are even functions of their arguments, so quantum averages

$$\langle\varsigma_{\mathbf{k}\lambda}\rangle=\langle\eta_{\mathbf{k}\lambda}\rangle=\int_{-\infty}^{\infty}\varsigma_{\mathbf{k}\lambda}|\varphi(\varsigma_{\mathbf{k}\lambda})|^2d\varsigma_{\mathbf{k}\lambda}=$$
$$=\int_{-\infty}^{\infty}\eta_{\mathbf{k}\lambda}|\tilde{\varphi}(\eta_{\mathbf{k}\lambda})|^2d\eta_{\mathbf{k}\lambda}=0$$

turned to zero. In other words, in one-photon states the quantum average $\langle A_{\mathbf{k}\lambda}\cos\vartheta_{\mathbf{k}\lambda}\rangle=\langle A_{\mathbf{k}\lambda}\sin\vartheta_{\mathbf{k}\lambda}\rangle=0$ is vanishing. For this reason, the classical parameters $A_{\mathbf{k}\lambda}$ and $\vartheta_{\mathbf{k}\lambda}$ cannot describe the single-photon states. Let's emphasize separately and once again that the single-photon state of the electromagnetic field do not has such attributes as amplitude $A_{\mathbf{k}\lambda}$ and phase $\vartheta_{\mathbf{k}\lambda}$.

But such property is inherent not only to one-photon states, but also to any states with precisely defined number of photons (Fock states). Really, after averaging over any defined by function $\varphi(\varsigma_{\mathbf{k}\lambda}|n_{\mathbf{k}\lambda})$ the quantum average of a vector potential (11)

$$\langle\hat{A}^\nu(\mathrm{r},t)\rangle=$$
$$=\sum_{\mathbf{k}\lambda}e^\nu_{\mathbf{k}\lambda}\gamma_k\left(\langle\hat{\alpha}_{\mathbf{k}\lambda}\rangle e^{i\mathbf{kr}-ikct}+\langle\hat{\alpha}^+_{\mathbf{k}\lambda}\rangle e^{-i\mathbf{kr}+ikct}\right)=0$$

turns to zero, which follows from the relations (8). But the quantum average $\langle\hat{A}^\nu(\mathbf{r},t)\rangle$ cannot be vanish, if we are dealing with superposition of wave functions with different numbers $n_{\mathbf{k}\lambda}$. It is among these superposition's necessary to find the wave function describing the quantum state that most closely approximates a classic field. Such a superposition is (again, we omit the indices $\mathbf{k},\lambda$):

$$\varphi(\varsigma|\alpha)=e^{-\frac{|\alpha|^2}{2}}\sum_{n=0}^{\infty}\frac{\alpha^n}{\sqrt{n!}}\varphi(\varsigma|n),$$
$$\int_{-\infty}^{\infty}\varphi^*(\varsigma|\alpha)\varphi(\varsigma|\alpha)d\varsigma=1,$$

where α is any number. It is customary to speak, that this superposition describes the "quantum coherent" state. It is easy to see that $\hat{\alpha}\varphi(\varsigma|\alpha)=\alpha\varphi(\varsigma|\alpha)$. If the operator $\hat{\alpha}$ to describe in explicit form (10), we get the equation $\frac{1}{\sqrt{2}}\left(\varsigma+\frac{\partial}{\partial\varsigma}\right)\varphi(\varsigma|\alpha)=\alpha\varphi(\varsigma|\alpha)$, the solution of which is a function

$$\varphi(\varsigma|\alpha)=\pi^{-1/4}\exp\left[-\frac{(\alpha+\alpha^*)^2}{4}+\sqrt{2}\alpha\varsigma-\frac{1}{2}\varsigma^2\right]. \qquad (16)$$

When working with quantum coherent states the following integral is useful:

$$\int_{-\infty}^{\infty}\exp(\delta\varsigma-\beta\varsigma^2)d\varsigma=\sqrt{\frac{\pi}{\beta}}\exp\left(\frac{\delta^2}{4\beta}\right).$$

Now, it is clear that $\int_{-\infty}^{\infty}\varphi^*(\varsigma|\alpha)\varphi(\varsigma|\alpha)d\varsigma=1$.

We use the Fourier transform

$$\tilde{\varphi}(\eta|\alpha) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-i\eta\varsigma} \varphi(\varsigma|\alpha) d\varsigma =$$

$$= \pi^{-1/4} \exp\left[-\frac{(\alpha+\alpha^*)^2}{4} + \alpha^2 - i\sqrt{2}\alpha\eta - \frac{1}{2}\eta^2 \right].$$

It follows from (16) and (17) that

$$|\varphi(\varsigma|\alpha)|^2 = \frac{1}{\sqrt{\pi}} \exp\left[-\left(\varsigma - \frac{\alpha+\alpha^*}{\sqrt{2}} \right)^2 \right],$$
$$|\hat{\varphi}(\eta|\alpha)|^2 = \frac{1}{\sqrt{\pi}} \exp\left[-\left(\eta - \frac{\alpha-\alpha^*}{i\sqrt{2}} \right)^2 \right]. \quad (18)$$

If one use the ideas $\alpha = |\alpha|\exp(i\vartheta)$ and $\alpha^* = |\alpha|\exp(-i\vartheta)$, then the most probable values of ς_{ex} and η_{ex} according to (14) and (15) will be:

$$\varsigma_{ex} = \left(A\cos\vartheta / \gamma_k \sqrt{2}\right)_{ex} = \frac{\alpha+\alpha^*}{\sqrt{2}} = \sqrt{2}|\alpha|\cos\vartheta,$$

$$\eta_{ex} = \left(A\sin\vartheta / \gamma_k \sqrt{2}\right)_{ex} = \frac{\alpha-\alpha^*}{i\sqrt{2}} = \sqrt{2}|\alpha|\sin\vartheta.$$

At $2\gamma_k|\alpha| = A$ from these ratios, the expressions followed which are valid for classical waves.

Next, we need an auxiliary equality

$$\langle n \rangle = \int_{-\infty}^{\infty} \varphi^*(\varsigma|\alpha)\hat{\alpha}^+\hat{\alpha}\varphi(\varsigma|\alpha)d\varsigma =$$

$$= \alpha \int_{-\infty}^{\infty} \varphi^*(\varsigma|\alpha)\hat{\alpha}^+\varphi(\varsigma|\alpha)d\varsigma =$$

$$= \alpha \int_{-\infty}^{\infty} \hat{\alpha}\varphi^*(\varsigma|\alpha)\, \varphi(\varsigma|\alpha)d\varsigma = \alpha\alpha^*.$$

Because the averaging on coherent states gets

$$\left\langle \hat{A}^\nu(\mathbf{r},t) \right\rangle = \sum_{\mathbf{k}\lambda} e^\nu_{\mathbf{k}\lambda}\gamma_k \left(\alpha_{\mathbf{k}\lambda} e^{i\mathbf{kr}-ikct} + \alpha^*_{\mathbf{k}\lambda} e^{-i\mathbf{kr}+ikct} \right),$$

$$\left\langle E^\nu(r,t) \right\rangle = -\frac{1}{c}\frac{\partial}{\partial t}\left\langle E^\nu(r,t) \right\rangle =$$

$$= \sum_{k\lambda} e^\nu_{k\lambda} E_{k\lambda} \sin(kr - kct + \vartheta) \ ,$$

$$E_{\mathbf{k}\lambda} = -2\sqrt{\frac{2\pi\hbar\omega_k}{V}}|\alpha_{\mathbf{k}\lambda}|,$$

so for these states, taking into account the auxiliary equality written in the form $|\alpha| = \sqrt{\langle n \rangle}$, one is finding $E^2_{\mathbf{k}\lambda} V / 8\pi = \hbar\omega_k \langle n_{\mathbf{k}\lambda} \rangle$. Introducing the concept of effective amplitude of the field $\bar{E}_{\mathbf{k}\lambda} = E_{\mathbf{k}\lambda}/\sqrt{2}$, we conclude $\bar{E}^2_{\mathbf{k}\lambda} V / 4\pi = \hbar\omega_k \langle n_{\mathbf{k}\lambda} \rangle$. So, if the electromagnetic wave is in a quantum coherent state, it does not possess a fixed number of photons, but its energy can be calculated as a quantum formula and classical one.

A quantum averages and the most probable parameters of the electromagnetic field coincide with their classical analogues, if the free field is in quantum coherent state. But that doesn't mean that each experiment will give the values of classical parameters. According to the distributions (18), there will be dispersion of points. The magnitude of this dispersion is determined by the dispersions of the distributions (18), which do not depend on the amplitudes of the fields. For this reason, if the amplitudes are large, then the dispersions can be neglected.

In this case, a flat electromagnetic wave, finding in the quantum coherent state, is described well by the classical theory. But that doesn't mean, that the result of the interaction of such waves with the environment always admits a classical description. Such example is set out below. Once again, emphasize that large value of the quantum coherent field by itself is not enough to use classical Maxwell equation.

It is useful to notice that in Fock state standing field with a large number of photons can to give a very high energy and destructive force, but the classical description of such a field does not exist.

4. THE INTERACTION OF THE ELECTROMAGNETIC FIELD WITH THE ENVIRONMENT

We will discuss examples showing that the evolution as strong as one wants and being in the quantum coherent state $\left\langle \hat{A}(\mathbf{r},t) \right\rangle \neq 0$ electromagnetic fields may not obey the laws of classical physics.

Consider a system consisting of excited atom and quantized electromagnetic field interacting each to another. For the sake of simplicity, we suppose, that the atom has one valence electron and two energy levels: ground and excited. The wave function of an electron in an excited atom denote by $\psi_{j_{ex}}(\boldsymbol{r})$, in the ground state via $\psi_{j_g}(\boldsymbol{r})$. Spin effects will neglect.

Let the atom, placed in an excited state-$\psi_{j_{ex}}(\boldsymbol{r})$ undergoes action of the single –mode $(\mathbf{k}_0\lambda_0)$ radiation, placed in a quantum coherent state $\varphi(\varsigma\,|\alpha)$. As a result of the scattering process, the total wave function atom-field system takes the form

$$\Psi(\mathrm{t}) = f_{j_{ex}}(\mathrm{t})\psi_{j_{ex}}(\boldsymbol{r}) + f_{j_g}(\mathrm{t})\psi_{j_g}(\boldsymbol{r}). \qquad (19)$$

Function $f_{ex}(\mathrm{t})$ describes the coherent channel of scattering, as a result of which the scattering atom remains in the initial excited state. Function $f_g(\mathrm{t})$ describes the scattering channel, as a result of which the atom of changes its state on ground state. This channel will be called incoherent. Since in the initial state electromagnetic field has "quantum average" value of the amplitude $\left\langle \hat{A}^{\nu}(\boldsymbol{r},t)\right\rangle$, then after scattering this construction will not turn to zero. Below, instead of operator $\hat{A}^{\nu}(\boldsymbol{r},t)$ one will use the operator of tension of the electric field

$$\hat{E}^{\nu}(k,t) = -\frac{1}{c}\frac{\partial\hat{A}^{\nu}(\boldsymbol{r},t)}{\partial t} =$$
$$= i\sum_{\mathbf{k}\lambda} e^{\nu}_{\mathbf{k}\lambda} k\gamma_k \left(\hat{\alpha}_{\mathbf{k}\lambda}{}^{i\mathbf{kr}-ikct} - \hat{\alpha}^{+}_{\mathbf{k}\lambda}e^{-i\mathbf{kr}+ikct}\right).$$

"Quantum average" of electric tension of electromagnetic field after scattering is calculating by conventional rule

$$\left\langle \hat{E}^{\nu}(\boldsymbol{r},t)\right\rangle = \left\langle \Psi\middle|\hat{E}^{\nu}(\boldsymbol{r},t)\middle|\Psi\right\rangle =$$
$$= \left\langle f_{ex}\psi_{j_{ex}}\middle|\hat{E}^{\nu}(\boldsymbol{r},t)\middle|f_{ex}\psi_{j_{ex}}\right\rangle +$$
$$+ \left\langle f_g\psi_{j_g}\middle|\hat{E}^{\nu}(\boldsymbol{r},t)\middle|f_g\psi_{j_g}\right\rangle =$$
$$= \left\langle f_{ex}\middle|\hat{E}^{\nu}(\boldsymbol{r},t)\middle|f_{ex}\right\rangle + \left\langle f_g\middle|\hat{E}^{\nu}(\boldsymbol{r},t)\middle|f_g\right\rangle =$$
$$= E^{\nu(\mathrm{c})}(\boldsymbol{r},t) + E^{\nu(\mathrm{n})}(\boldsymbol{r},t). \qquad (20)$$

Here in explicit form the function $\Psi(\mathrm{t})$ describing by expression (19) is shown, with the help of which the quantum averaging is performed, and it is taken into account that the operator $\hat{E}^{\nu}(\boldsymbol{r},t)$ does not change the mutually orthogonal $\left\langle\psi_j\middle|\psi_{j'}\right\rangle = = \int\psi^{*}_j(\boldsymbol{r})\psi_{j'}(\boldsymbol{r}) = \delta_{jj'}$ and normalized per unit the wave atoms functions. For these reasons, atomic functions fall out of this formulas, as well as fall out the interference term

$$\left\langle f_{ex}\psi_{j_{ex}}\middle|\hat{A}^{\nu}(\boldsymbol{r},t)\middle|f_g\psi_{j_g}\right\rangle = 0.$$

It is important to note that interference term turns to zero because of orthogonality of atomic functions, which eliminates the "quantum interference terms" of the electromagnetic field. The classical physics does not possess such property. Let's to say that coherent and incoherent channels of scattering are not quantum incoherent. But classical coherence in the form of summation of amplitudes with according to (20) is retained. From the coherent scattering channel the process of stimulated radiation that changes the state of the scattering atoms fall out. Thus, it should be distinguished two types of coherence: "quantum" depending on phase of full wave function of the system, and "classical", determined by the phase of averaged amplitude of the field. At the process of averaging the quantum phases disappear.

Suppose now we are interested in the energy characteristics of the scattered field, describing the "quantum averages" from the bilinear combinations of the field operators

$$\left\langle \hat{E}^{\nu}(\boldsymbol{r},t)\hat{E}^{\nu}(\boldsymbol{r},t)\right\rangle = \left\langle \Psi\middle|\hat{E}^{\nu}(\boldsymbol{r},t)\hat{E}^{\nu}(\boldsymbol{r},t)\middle|\Psi\right\rangle =$$
$$= \left\langle f_{ex}\psi_{j_{ex}}\middle|\hat{E}^{\nu}(\boldsymbol{r},t)\hat{E}^{\nu}(\boldsymbol{r},t)\middle|f_{ex}\psi_{j_{ex}}\right\rangle + \qquad (21)$$
$$+ \left\langle f_g\psi_{j_g}\middle|\hat{E}^{\nu}(\boldsymbol{r},t)\hat{E}^{\nu}(\boldsymbol{r},t)\middle|f_g\psi_{j_g}\right\rangle.$$

Here again and for the same reason there is no cross term. Both terms are positively determined.

Thus, the energy characteristics of the scattered field are determined independently by two channels of reactions and then algebraically add up. According to (21) the interference between channels is absent. Very important is to note that there is no interference between placed in the incoherent channel processes of induced radiation and scattering processes that do not change states of the atom system. In this sense, incoherent properties of induced processes, which rarely stressed, can significantly change the macroscopic pattern of the scattered field.

The value of the averaged bilinear structures (21) it is convenient to estimate using the well-known inequality

$$\left\langle \hat{B}\hat{B} \right\rangle \gg \left\langle \hat{B}\hat{B} \right\rangle \left\langle \hat{B}\hat{B} \right\rangle,$$

true for any operators and any procedure of averaging. Applying this inequality to both terms equality (21), we obtain the lower estimate for the research construction

$$\begin{gathered} \left\langle \hat{E}^{\nu}(\boldsymbol{r},t)\hat{E}^{\nu}(\boldsymbol{r},t) \right\rangle \gg \\ \gg E^{\nu(\mathrm{c})}(\boldsymbol{r},t)E^{\nu(\mathrm{c})}(\boldsymbol{r},t) + E^{\nu(\mathrm{n})}(\boldsymbol{r},t)E^{\nu(\mathrm{n})}(\boldsymbol{r},t). \end{gathered} \quad (22)$$

If only the non-coherent channel (and the processes of induced radiation) are absent or on any reason the coherent channel of scattering is absent, the energy of the scattered electromagnetic field is determined by the squared of scattering amplitude, which resemble equality, at in classic field. In other words, the classical physics can correctly describe the scattering process of resonant radiation only in exceptional cases. In general, if the scattering radiation is almost classical and is in a quantum coherent state the scattered radiation loses this property. According to (22), the energy of the scattered radiation consists of two terms that are defined by different channels of scattering. Energy characteristics of these channels summed. “Quantum coherence states” do not obey such properties. One can say that in the scattered radiation, along the quantum coherent component the “Fock’s” component appears. The value of “Fock’s” component can reach rather hundred percents of the total radiation. Such radiation in the representations of classical physics can’t be described. This is the case with Fresnel reflection of resonance radiation from excited media [6]. They say that in these cases we have dealing with the discrepancy between the predictions of the classical and quantum physics at a macroscopic level.

5. CONCLUSION

Pay attention to the equality

$$\varphi(\varsigma|\alpha) = \pi^{-1/4}\exp\left[-\frac{\left(\alpha+\alpha^*\right)^2}{4} + \sqrt{2}\alpha\varsigma - \frac{1}{2}\varsigma^2\right] = = e^{-\frac{|\alpha|^2}{2}}\sum_{n=0}^{\infty}\frac{\alpha^n}{\sqrt{n!}}\varphi(\varsigma|n),$$

which is indicating that the closest to the classical presentation the concepts of “quantum coherence states” of electromagnetic field can be represented as a sum of photons (Fock states) states having no classical analogues. It is a “quantum coherent state” $\varphi(\varsigma|\alpha)$ can be described verbally with the help of concepts “amplitude”, “phase” and “dispersions” of these quantities, then as photons (Fock) states $\varphi(\varsigma|n)$ of these attributes lack. In Fock states we use the adoption of a “photon”. There is also an inverse relationship [7]:

$$\varphi(\varsigma|n) = \frac{1}{\pi}\iint\frac{\alpha^{*n}}{\sqrt{n!}}e^{-\frac{1}{2}|\alpha|^2}\varphi(\varsigma|\alpha)d^2\alpha,$$

$$d^2\alpha = d(\mathrm{Re}\,\alpha)\,d(\mathrm{Im}\,\alpha),$$

which is indicating that photons (Fock) states, incognizant the concepts of “phase” and “amplitude”, can be present in the form of a superposition of “quantum coherent states”, which are characterized by such concepts. One can speak that we solve the problem in photon (Fock) or in a coherent representation. Therefore, the objective characteristic of the electromagnetic field is its state described by the wave function. For depending on the mathematical background chosen by us, the specific view of this function can be strongly various. It may be representing by the series of functions $\varphi(\varsigma|n)$ as well as functions $\varphi(\varsigma|n)$.

The attributes such as amplitude, phase, and number of photons, are inherent to concrete representations and are not invariant with respect to the choice that depends on us. Thus, these attributes do not follow absolutely sense and do not possess universal meaning.

The need for quantization of the electromagnetic field follows from logical considerations and from different results of calculations using quantized and classical fields that qualitatively demonstrated above on some examples.

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THE PROBABILITY OF DETECTING COLOURED OBJECTS ON COLOURED BACKGROUNDS BASED ON A STATISTICAL MODEL OF THE THRESHOLD OF COLOUR VISION

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ABSTRACT

Using a statistical model of the threshold of colour vision, a new expression is obtained to calculate the detection probability of colour objects against colour backgrounds. The method shows that in the day sight area, this probability is completely determined by the individual criterion of decision making about an object's presence, by addition functions of the RGB colorimetric system, by radiance spectral concentrations of the object and background, and by the angular dimensions of the object.

Keywords: visual system of a person, theory of statistical solutions, optimum receiver, detection probability, direct and reverse problems

1. INTRODUCTION AND PROBLEM FORMULATION

The existing theories of colour vision focus on the explanation of the psychophysical aspects of colour perception [1], in particular on an observer's ability to equalise colours visually. Theories explaining the reasons for the existence of colour discrimination thresholds, which allow calculating the probability of detection of colour objects, were not identified in the existing literature.

Modern methods of calculating colour detection thresholds are based on an empirical approach, which does not explain why colour discrimination threshold arise.

Since the effectiveness of the application of the statistical solution theory to the calculation of the detection thresholds of monochrome images in [2–4] has been proved, it can be considered a natural generalisation of the statistical approach to the processes of detecting coloured objects, i.e. there is scope for developing a statistical theory of the threshold of colour sight.

As the statistical approach is based on the spectral sensitivity of radiation receivers, and the most appropriate theory of colour sight is three-component theory of Young-Helmholtz [1], the most sound approach is to develop a statistical theory based on the RGB physiological colorimetric system. This approach is both fundamental and practical. The International Commission on Illumination (CIE) recommends using the general colour rendering index [5] to evaluate the quality of colour rendition when developing new illumination devices. In accordance with [6, 7], calculations of a general colour rendition index are carried out in the CIE uniform-chromaticity-scale system 1964 U*V*W*. These R_a calculations use von Kries coefficients to exclude a systematic error arising due to the different colour adaptation of the visual system (VS) to the reference and examined light sources. These are also calculated in the RGB colorimetric system. The calculation of colour co-ordinates is performed according to the classical radiation expressions [6, 7]:

$$\Xi = \int_{380}^{780} L_{e\lambda}(\lambda)\bar{\xi}(\lambda)d\lambda\,, \qquad (1)$$

here $\Xi = \{R, G, B\}$, $L_{e\lambda}(\lambda)$ is radiance spectral concentration, λ is radiation wavelength, so the error in the definition of the addition functions

$\bar{\xi}(\lambda) = \left\{\bar{r}(\lambda),\ \bar{g}(\lambda),\ \bar{b}(\lambda)\right\}$ inevitably affects the

reliability of the obtained values of the general colour rendering index.

As has been shown in [8], classical methods for determining specific colour coordinates of the RGB colorimetric system, based on experiments with dichromate, lead to unpredictable errors. Therefore it becomes necessary to determine the curve for a subject with normal vision under natural eye adaptation conditions. The first step is to derive expressions for the detection probability of colour objects on colour backgrounds at specific RGB colour coordinates. Since such probabilities can be obtained through experimental studies of visual systems, solving this mathematically for a subject with normal colour vision can identify specific RGB colour coordinates.

This paper is devoted to solving the problem at hand and assumes that the known functions of the RGB colorimetric system are known.

2. METHOD OF SOLVING THE FORMULATED PROBLEM

Works [2–4], consider threshold characteristics of a human visual system in detail, based on a statistical approach. The main limitations of the methods they propose is that it can be only used for low levels of adaptation luminance and for observation of one-colour images, when only the rods apparatus of the visual system works. The first successful attempts to apply a statistical approach to explanation of colour thresholds of visual system were made in [9, 10], however this only addressed the detection of thresholds for monochromatic objects against white backgrounds. Obtaining calculation expressions for detection probability of arbitrary colour objects against colour backgrounds requires further study.

With regard to solving problems of single-colour image detection by the human visual system, a block diagram of the VS mathematical model is provided in [4, Fig. 1], based on an optimal statistical receiver [11]. A fundamental difference of the threshold colour vision mathematical model (TCVMM) from that given in [4] is the three receiver types (*R*, *G* and *B)* with reactions μ_{ri}, μ_{gi}, μ_{bi} and with a nonlinear dependence of these reactions on adaptation luminance.

According to the block diagram, a person's field of vision can have either an image of a coloured object on a colour background, or an image of a coloured background, differing only in chromaticity and luminance from the image of the object. Random output signals *R*, *G* and *B* of receptors (μ_{ri}, μ_{gi}, μ_{bi}) are transmitted via optic nerve fibres to the brain, which is represented in the block diagram by memory, analysis device (AD) and decision-making device (DMD), which decided whether an object is present or not in the visual field.

According to the theory of the optimum statistical receiver [4, 11], on which TCVMM is based, the analysis device (AD) calculates one-dimensional function of the credibility relation (Λ) equal to the relation of emergence probability (*P* [Y/S]) of random two-dimensional distributions of signals μ_{ri}, μ_{gi}, μ_{bi} (random *Y* implementation) at the output of radiation receivers matrix (RR) under the condition of emergence of the studied colour object against a colour background in the visual field, to emergence probability of (*P* [Y/0]) of the same *Y* implementation under the condition of colour background emergence without an object in the visual field.

$$\Lambda = \frac{p}{q}\frac{P[Y/S]}{P[Y/0]}, \qquad (2)$$

where *p* and *q* are priori probabilities of object and background emergence ($p + q = 1$).

The decision-making device (threshold device ThD) makes a decision on the presence of a colour object against a colour background in the visual field every time the calculated value Λ exceeds threshold value Λ_{th}. Otherwise, it makes the decision on the presence a background without an object in the visual field. The optimum receiver algorithm allows using the results of the previous work detecting one-colour objects [4] for analysing the threshold of colour sight as a mathematical model.

Using the results of [4], it is simple to obtain an expression to determine the logarithm of credibility relation (Z) in problems of calculating detection probability of a colour object against a colour backgrounds for the distribution law (*P*[*Z*]):

$$P[Z] = \frac{1}{2\pi\sigma_\Lambda}\exp\left(-\frac{(Z-m_\Lambda)^2}{2\sigma_\Lambda^2}\right), \qquad (3)$$

where $Z = \ln\Lambda = \sum_{i=1}^{N}\mu_i \ln\left(\frac{X_{oi}}{X_{\phi i}}\right) - \sum_{i=1}^{N}(X_{oi} - X_{\phi i})$,

μ_i is the totality of random output signals of the radiation receiver (RR): μ_{ri}, μ_{gi}, μ_{bi}; X_{oi}, $X_{\phi i}$ are mathematical expectations of matrix i RR output signal under the condition that a colour object is observed on a colour background and respectively that a colour background is observed without an object.

For statistically independent RRs, it is simple to obtain expressions [4] for mathematical expectation m_Λ and for dispersions σ_Λ^2 of the credibility relation logarithm provided that an object is in visual field:

$$m_\Lambda = \sum_{i=1}^{N} X_{oi}\ln\left(\frac{X_{oi}}{X_{\phi i}}\right) - \sum_{i=1}^{N}(X_{oi} - X_{\phi i}),$$
$$\sigma_\Lambda^2 = \sum_{i=1}^{N} X_{oi}\ln^2\left(\frac{X_{oi}}{X_{\phi i}}\right), \quad (4)$$

where N is number of RGB receivers in the RR matrix.

As the optimum receiver makes a decision on the presence of an object, if $\Lambda \geq \Lambda_п$, then taking into consideration the monotony of the logarithmic function provided that an object is within the visual field, the probability of correct detection is determined by the integration of the conventional distribution law ln(Λ) over values area ln(Λ) from $\ln(\Lambda_п)$ to infinity:

$$P_{det} = \frac{1}{2\pi\sigma_\Lambda}\int_{\ln\Lambda_п}^{\infty}\exp\left(-\frac{(Z - m_\Lambda)^2}{2\sigma_\Lambda^2}\right)dZ = \Phi(y), \quad (5)$$

$$y = \frac{m_\Lambda - \ln\Lambda_ï}{\sigma_\Lambda}, \quad (6)$$

where $\Phi(y) = \frac{1}{2\pi}\int_{-\infty}^{y} e^{-t^2/2}dt$ is probability integral [12].

According to [13], with increasing luminance, the relation of "action current" pulse frequency at the receptor output of the visual system to the photon flux incident on the receptors decreases. Therefore, the effective transformation coefficient used in [4] for determining the receptor signal distribution law will be much less than one with daylight luminance. This makes it possible to use Poisson distribution law to descript receptor reactions in TCSMM as well. In this case, at $p = q$, the expression for credibility relation [2] will be as follows:

$$\Lambda = \prod_{i=1}^{N}\left(\frac{X_{oi}}{X_{эi}}\right)^{\mu_i}\exp\left(-(X_{oi} - X_{эi})\right). \quad (7)$$

As it was noted already, human colour vision is connected with presence of three types of receptors in the visual system with output signals μ_{ri}, μ_{gi}, μ_{bi} generating μ_i. Therefore, these signals should be explicitly added to the expression. With statistically independent (under the threshold conditions) RRs, we will group (similar to [10]) reactions of *R*, *G* and *B* receptors. Then expression (7) for the credibility relation will be as follows:

$$\Lambda = \prod_{i=1}^{n}\left(\frac{X_{oкi}}{X_{\phi кi}}\right)^{\mu_{кi}}\left(\frac{X_{oзi}}{X_{\phi зi}}\right)^{\mu_{зi}}\left(\frac{X_{oci}}{X_{\phi ci}}\right)^{\mu_{ci}}$$
$$\exp\left(\begin{matrix}-(X_{oкi} - X_{\phi кi}) - (X_{oзi} - X_{\phi зi}) - \\ -(X_{oci} - X_{\phi ci})\end{matrix}\right), \quad (8)$$

where n is the number of *RGB* triads in whole number N of model receivers, and $X_{oкi}$, $X_{oзi}$, X_{oci}, $X_{\phi кi}$, $X_{\phi зi}$, $X_{\phi ci}$ are conventional mathematical expectations of *R*, *G*, *B* receptors output signals in the presence of an object and background in visual field respectively.

After taking the logarithm of the left and right parts (8), we will obtain an expression for ln(Λ) as:

$$\ln(\Lambda) = \ln\left(\prod_{i=1}^{n}\Lambda_к\Lambda_з\Lambda_с\right) =$$
$$= \ln(\Lambda_к) + \ln(\Lambda_з) + \ln(\Lambda_с), \quad (9)$$

where Λ_r, Λ_g, Λ_b are particular credibility relations calculated for reactions of *R, G, B* receptors;

$$\Lambda_\xi = \prod_{i=1}^{n}\left(\frac{X_{o\xi i}}{X_{э\xi i}}\right)^{\mu_{к\xi i}}$$
$$\exp\left(-(X_{o\xi i} - X_{э\xi i})\right), \quad \xi = \{r, g, b\}. \quad (10)$$

Thus, the detection probability of an object by chromaticity or luminance against a colour background will be determined by expressions (5) – (6), in which parameters of the distribution law ln(Λ) are specified by expressions:

$$m_\Lambda = m_{\Lambda r} + m_{\Lambda g} + m_{\Lambda b}, \quad \sigma_\Lambda^2 = \sigma_{\Lambda r}^2 + \sigma_{\Lambda g}^2 + \sigma_{\Lambda b}^2, \quad (11)$$

where

$$m_{\Lambda\xi} = \sum_{i=1}^{N} X_{o\xi i} \ln\left(\frac{X_{o\xi i}}{X_{\text{ф}\xi i}}\right) - \sum_{i=1}^{N} (X_{o\xi i} - X_{\text{ф}\xi i}),$$
$$\sigma_{\Lambda\xi}^2 = \sum_{i=1}^{N} X_{o\xi i} \ln^2\left(\frac{X_{o\xi i}}{X_{\text{ф}\xi i}}\right), \quad \xi = \{r, g, b\}. \quad (12)$$

3. DETERMINATION OF TCVMM RECEPTOR REACTION DEPENDENCE ON THE OBSERVED LUMINANCE

To derive an expression for the detection probability of colour objects, we need to find the mathematical model receiver output reaction dependence on the visionable luminance. This is not straight forwards, as the receptor is nonlinear within the day sight area ($L_v \geq 10$ cd/m^2), i.e. with a nonlinear dependence of the "action current" pulse frequency in the fibres of the optic nerve [13] on photon radiation flux. This leads to the fact that the photometric contrast of the observed objects differs from the signal contrast of the mathematical model RR output. In [3, 10] an RR reaction's dependence on the sought luminance is presented, however it is obtained for only one type of receptor, which is insufficient for a colour sight model.

One of the basic colorimetric principles asserts that in daytime vision the chromaticity of permanent spectral composition objects does not depend on the changing luminance of the objects [7]. According to expression (1) reactions of *R*, *G* and *B* receptors ($X_\text{к}, X_\text{з}, X_c$) are proportional to colour co-ordinates of the *RGB* physiological colorimetric system. It follows from this:

$$\frac{X_r}{X_r + X_g + X_b} = \xi \to X_\xi = \xi X, \quad \xi = \{r, g, b\}, \quad (13)$$

where $X = X_r + X_g + X_b$ is the sum of *R*, *G*, *B* receptor reactions depending on background luminance, and *r*, *g*, *b* are colour co-ordinates independent of luminance.

Using expression (13) one can determine the contrast connection at the receptor $KR = \Delta X/X$ output with photometric contrast $K = \Delta L_v/L_v$:

$$K_R = \frac{X_{\text{îê}} + X_{\text{îç}} + X_{\text{îñ}} - X_{\text{ôê}} - X_{\text{ôç}} - X_{\text{ôñ}}}{X_{\text{ôê}} + X_{\text{ôç}} + X_{\text{ôñ}}}, \quad (14)$$

where X_{or}, X_{og}, X_{ob} and $X_{\text{ф}r}, X_{\text{ф}g}, X_{\text{ф}b}$ are mathematical expectations of output reactions of any *R*, *G* and *B* receptor sought an area within object contour under the condition of observing a colour object against a background and colour background only, respectively.

With due regard for (14) it is simple to derive:

$$K_R = \frac{X_o - X_\text{ф}}{X_\text{ф}}, \quad (15)$$

where X_o, $X_\text{ф}$ are sums of mathematical expectations of receiver signals under the condition of sighting of an object and background respectively.

Standard objects, which are used in colorimetry, have angular dimensions from two to ten degrees. With such angular dimensions and with an adaptive luminance greater than 10 cd/m^2, values of threshold luminance contrasts on any background and any object chromaticity, as well as signal contrast values at the receptor output, are much less than one [7].

This allows limiting by two terms of Taylor's series expansion of function $X_{\hat{\imath}}(L)$ [12] in expression (15) at vicinity $X=X_\text{ф}$. Then:

$$K_R = \frac{dX}{dL_v}\frac{\Delta L_v}{X} = \frac{dX}{dL_v}\frac{L_v}{X}K. \quad (16)$$

Use of this expression in TCVMM makes it possible to derive a differential equation for $X(L_v)$ dependence. Let's now transform expressions (12) for m_Λ and σ_Λ^2 as well, having used difference of the receiver signals (ΔX_i) sighting object and background:

$$m_\Lambda = \sum_{i=1}^{n}(X_i + \Delta X_i)\ln\left(1 + \frac{\Delta X_i}{X_i}\right) - \sum_{i=1}^{n}\Delta X_i,$$
$$\sigma_\Lambda^2 = \sum_{i=1}^{n}(X_i + \Delta X_i)\ln^2\left(\frac{X_i + \Delta X_i}{X_i}\right). \quad (17)$$

Having expanded logarithm in (17) into Taylor's series in vicinity of one, we will be limited by two expansion terms and consider a frequent case of observing equally-bright objects against a uniform background. Under these conditions, out of object contour $\Delta Xi = 0$ and within it, the difference of receiver signals has a constant value ΔX.

Within the object contour, X_i doesn't depend on the receiver number as well and is equal to X. Therefore, expressions (17) become simpler:

$$m_\Lambda = \frac{1}{2}\sum_{i=1}^{n}\frac{(\Delta X_i)^2}{X_i} = \frac{1}{2}t\frac{(\Delta X)^2}{X},\qquad \sigma_\Lambda^2 = \sum_{i=1}^{n}\frac{(\Delta X_i)^2}{X_i} = t\frac{(\Delta X)^2}{X}, \tag{18}$$

where t is number of RRs sighting a space area within the object contour.

With little differences ΔX typical for threshold contrasts of big angular size objects, it can be expressed by a derivative of searched dependence of receiver reaction X of background luminance L_v in the form of $\Delta X = \Delta L_v\, dX/dL_v$, where ΔL_v is object – background luminance difference. Then expression (6) for probability integral argument determining probability of object detection will be as follows:

$$y = \frac{m_\Lambda - \ln\Lambda_п}{\sqrt{2m_\Lambda}}. \tag{19}$$

According to experimental studies of luminance threshold contrasts [7], with angular object dimensions greater than 2° and background luminance greater than 10 cd/m^2, Weber-Fechner law is valid, i.e. when the background luminance changes, threshold contrast remains constant. This means that detection probability also does not depend on background luminance, so derivative $dy/dL_v = 0$. As under the threshold conditions ($P_{ob} = 0.5$) argument of the probability integral is equal to zero [12], then from expression (19) a differential equation for X dependence on luminance L_v can be obtained:

$$\frac{t}{2}\frac{d}{dL_v}\left[K^2\left(\frac{dX}{dL_v}L_v\right)^2\Big/X\right] = 0. \tag{20}$$

As photometric contrast $K = \Delta L_v/L_v$ in the Weber-Fechner area does not depend on luminance, solution (20) is a function of luminance square logarithm:

$$X = C_1\ln^2(C_2L_v), \tag{21}$$

where C_1 *and* C_2 are arbitrary integration constants not dependent on luminance.

With due regard for (13), the obtained result allows drawing the conclusion that nonlinearity of all three types of cones is identical and is determined by expression (21) with different C_1 values and coinciding C_2 values.

4. CALCULATION RATIO FOR DETECTION PROBABILITY OF A COLOUR OBJECT AGAINST A COLOUR BACKGROUND

Detection probability of a colour object against a colour background is determined by expressions (5) and (6). The expression for probability integral argument (6) can be transformed in accordance with (11) and (18) as follows:

$$y = \frac{\sum_\xi \Pi_\xi - \ln\Lambda_п}{\sqrt{2\sum_\xi \Pi_\xi}},\qquad \Pi_\xi = \frac{t\left(\Delta L_\xi\, dX_\xi/dL_\xi\right)^2}{2X_\xi},\ \xi=\{r,g,b\}. \tag{22}$$

Taking into account the obtained dependence of RR reactions on luminance (21), components Π_j of expression (22) will be as follows:

$$\Pi_\xi = 2tC_{1\xi}\left(\frac{\Delta L_\xi}{L_\xi}\right)^2, \tag{23}$$

where according to [7],

$$L_\xi = 683\beta_\xi\int_{380}^{780}L_{e\lambda}(\lambda)\bar{\xi}(\lambda)d\lambda, \tag{24}$$

$$\Delta L_\xi = 683\beta_\xi\int_{380}^{780}\left(L_{e\lambda o}(\lambda) - L_{e\lambda}(\lambda)\right)\bar{\xi}(\lambda)d\lambda, \tag{25}$$

where $L_{e\lambda o}(\lambda)$ object, $L_{e\lambda}(\lambda)$ is radiance spectral concentration of the background, β_ξ are luminance coefficients of RGB colorimetric system, $\xi = \{r, g, b\}$, $\bar{\xi}(\lambda) = \{\bar{r}(\lambda), \bar{g}(\lambda), \bar{b}(\lambda)\}$, C_{1r}, C_{1g}, C_{1b} are constants not dependent either on the object and background spectrum or on the object angular size.

If to introduce solid angles Ω of the object and of instant visual field ω of any RR, then the number of R, G, B triads of the receivers in RR matrix sighting an area within the object contour will be determined by the following expression:

$$t = \frac{\Omega}{3\omega}. \quad (26)$$

Formulas (22) – (26) completely determine calculation expression for *y*.

5. CONCLUSIONS

Applying the optimum statistical receiver theory to the detection processes of a colour object against a colour background allowed obtaining a calculation expression for the probability of its detection which showed the following:

1. Luminance coefficients of primary colours of the RGB colorimetric system do not influence the detection probability of colour objects against colour backgrounds. When detecting a colour object, the influence of addition functions of the RGB colorimetric system is principal, and maximum values of addition functions also do not influence the detection probability.

2. In case addition functions are known, the detection probability of colour objects on a colour background is unambiguously determined by value $\Lambda_п$, by spectral luminance distributions over surfaces of the object and background and by angular dimensions of the object.

3. Constant coefficients of the mathematical model, including a criterion for decision making by a person (the criterion is determined by $\ln(\Lambda_п)$ value), do not depend on the angular size of the object and on the spectral luminance distribution over the object and background and can be determined when normalising the mathematical model.

4. The obtained expression allows calculating the detection probability of colour objects on colour backgrounds with arbitrary spectra (chromaticities) of the objects and backgrounds.

5. However, to solve a reverse problem of finding $\bar{r}(\lambda)$, $\bar{g}(\lambda)$, $\bar{b}(\lambda)$ values experimentally studying the detection probability of colour objects using expressions (5) and (22) – (26), the development of a special protocol and criteria for the experimental installation are required.

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A HYBRID ILLUMINATION COMPLEX FOR COMBINED ILLUMINATION SYSTEMS: CONCEPTS, STATE OF THE PROBLEM, PRACTICAL EXPERIENCE

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ABSTRACT

Hybrid illumination complexes for systems of combined illumination are considered, including the concept of their development as a structural element of high energy efficiency and high quality light environment. The first practical application experience is described, of the project installed in a building of the MEGA Adygea Family Shopping Centre.

Keywords: combined illumination system, automatic control system, hybrid illumination complex, natural light, artificial light, hollow tubular light guide, artificial light LED unit

INTRODUCTION

In 2015–2016, a pilot project of the combined illumination system (CIS) based on the hybrid illumination complex (HIC) was installed in the MEGA Adygea Family Shopping Centre [1] (FSC) building. The entrance complex of the FSC "ASHAN" store served as the object of the illumination system reconstruction. Commissioning an illumination system reconstruction using innovative illumination technology naturally raises caution exacerbated by the relatively high capital costs of CIS construction. Without doubt, convincing and objective information about the prospects of CIS on the basis of HIC, their technical advantages and favourable economic indicators, in particular, their attractive payback period for innovative lighting systems, should play a decisive role in dispelling doubts and influencing the right decision.

HIC Concept for CISs

A significant increase in the economic, environmental and social efficiency of lighting, together with increased safety and comfort, can be achieved through the use of new and improved innovative technologies. HICs are especially attractive because they realise the potential of costless natural light. Engineering and technological approaches to realising natural light potential include advanced facilities of light transmission using hollow tubular light guides (HTLG)[1, 2]. Their use in buildings becomes a source of creative inspiration for architects and designers. Using a combination of natural light resources with energy efficient artificial light powered by automatic control systems (ACS), together forms CISs. Their distinctive criterion is stability of light environment characteristics due to compensation of the natural component changing in time by a correspondent correction using the artificial component (electric illumination). CISs based on HIC offer a holistic solution for modern architectural approaches to high energy efficiency illumination systems. The advantages of HICs in comparison with traditional solutions offer the challenge of their ap-

[1] MEGA Adygea FSC address: Republic Adygeya, Takhtamukaysky district, Novayaew Adygea aul

plication: a compactness of architectural and design structural solutions; a comfortable light environment; high energy efficiency; a dynamic control parameter of a room's light environment.

The flexibility and high energy efficiency of CISs have inspired very original engineering solutions [3–7]. A natural result of the evolution of a computer-controlled CIS is that the three interconnected components: an HTLG (natural light), an LED light source (artificial light) and an ACS [8–11], determine the characteristics of the system only when acting in unison. Such a system is correspondent to the HIC term and according to GOST [12], the following definition is applicable: HIC is a device intended for a combined illumination uniting two light source types (natural and artificial) integrated into one whole structure together with an automatic control system and with general technological documentation ensuring a combined illumination and performing its functions to the consumer in the assembled condition.

HICs combine a hollow tubular light guide (HTLG) and an artificial light unit (ALU) with radiators which are "built-in LED modules with a built-in control device" [13]. Photometric techniques, metrological concepts and lighting characteristics of illumination devices are applicable to HICs in accordance with GOST [13].

The relevance of CISs based on HIC increases with new trends of architecture and of buildings with limited natural illumination (sporting, shopping, civil, industrial, agricultural buildings and underground spaces associated with new urban policies). Large new build projects usually fail to provide for effective natural illumination solutions when meeting microclimate requirements. Standard solutions for light openings (vertical windows, skylights, transparent roof) fulfil standard requirements for illumination but do not solve the problem of optimising the room's energy balance. A suitable alternative to a standard light opening is a HIC based on HTLG, which has the advantages of lighting- and heat-engineering characteristics [14–16]. Development and introduction of CISs based on HICs is an important step in the evolution of high-quality and energy-effecient illumination technology. Each HIC component is simultaneously autonomous, and interdependent, and its energy saving capabilities provide critical efficiencies to the complex:

- Natural illumination based on HTLGs – (50–75) %;
- Artificial illumination of a high energy efficiency based on LED light sources – (20–70) %;
- Automatic control system – (30–70) %.

A Review of CISs and Development of the Concept

In its primitive version, CISs are present at any room with an outside outlet, because they contain at least two components: a system of natural illumination (vertical or top light openings) and illumination devices (ID) of artificial light. These CISs operate along natural light cycles, and their efficiency depends completely on the parameters and quality of the light openings, on efficiency and rationality of the ID. For such systems, low efficiency IDs and their irrational use due to a lack or randomness of control are typical.

As an example of a first attempt to implement a computer-controlled CIS, a combination of roof lights and luminaires with fluorescent lamps can be considered [3]. With an obvious imperfection, such illumination systems nevertheless produce an energy saving effect and confirm the benefits of the CIS concept.

A large-scale project of a heliostat-and-light guide illumination system of a school recreation halls in Saint-Gallen, Switzerland (the *Heliobus* system) demonstrated the huge potential of a computer-controlled CIS through the quality of the created light environment and its energy savings [1, 5, 6].

The development of HTLGs with their unique characteristics was a new stage in CIS evolution. Several engineering solutions of HICs based on HTLGs are known: *LED + Solarspot* [10], *Monodraught* [11, 14] and *Solatube M74 Smart LED* [9]. Every solution has its merits and drawbacks but all of them confirm the potential of the integrated illumination system concept, the important advantages of which are an almost complete lack of heat loss and heat input. The latter is an important advantage in comparison with standard light opening solutions.

Application of such HICs as *LED + Solarspot* [10, 17] for office room illumination tangibly reduces power consumption with an almost complete reduction of heat loss and of heat inputs. A feature of the *LED + Solarspot* HIC structure is that

Fig. 1. *LED + Solarspot* hybrid illumination complex (light guide diameter is 375 mm). Installed in 2010 by *Solarspot International S.r.l* Company

its ALU consists of light emitting diodes placed on the external circular contour of the HTLG diffuser (Fig. 1). Disadvantages of the *LED + Solarspot* luminaire are their blinding and perhaps phototoxic effects in office rooms with low ceilings because of a high dimensional luminance of the LEDs, as well as maintenance challenges when installed at height. (Specifications of the five *LED + Solarspot* HIC model types are given in [10].)

The *Monodraught* HICs are similar to the *LED + Solarspot* in their structure of light-emitting diode ALU but the blinding effect is eliminated by the *LuxLoop* LED panels (Fig. 2). However, the *Monodraught* HIC range [11] is limited by the light guide's diameter (530 mm), by ALU power (30 W) and by luminous flux, which is less than 4000 lm. These limitations restrict the application field of these HICs in rooms with high ceilings.

The above described *LED + Solarspot* and *Monodraught* HICs have a peculiar design, which is not favoured by all users, and the luminous body geometry changes depending on the time of day. In the day-time it looks like a central disc of the HTLG diffuser, and in the night-time it is a LED ring around the dark diffuser (Fig. 2). During transition periods, luminous parts are the diffuser central disc and the ALU ring surrounding it, which change luminance dynamically. A common disadvantage of these HICs is that the combined illumination is created visually by an observable radiation of two separate light sources: HTLG and ALU, the spectral characteristics and luminance of which are different. Furthermore, a transition from natural light to artificial and vice versa is followed by significant changes of HIC light distribution creating a continuously changing light environment and indoor discomfort. It was likely these limitations which led to the restriction on the use of CIS specified by standard documents: СП 251.1325800.2016 and СП 52.13330.2016.

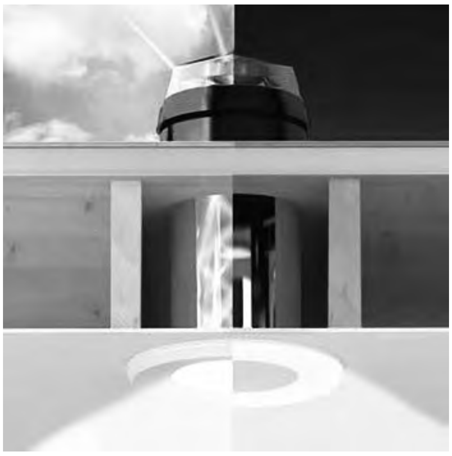

Fig. 2. *Monodraught* HIC. Operating modes under day and night time conditions are shown (the left half of the picture is day-time: natural light penetrates through the diffuser) and night-time, when the LED panel radiates (the right half of the picture: HTLG diffuser as a dark disc)

The *Solatube M74 Smart LED* HIC [9] based on the *Solatube*® HTLG is an optimal structure in terms of lighting characteristics, size, and of design. Blinding and phototoxic effects of the HICs were completely eliminated by a decreases dimensional luminance of the LEDs using diffusers. Depending on room parameters, different diameter *Solatube*® HTLGs and ALUs of different power can be installed. A powerful HIC model based on the *Solatube® M74* HTLG – the *SkyVault* [2] series (tube diameter is 740 mm), deserves special attention as the new generation roof light, providing some advanced solutions beyond those of its competitors. Natural light is very important in buildings with large areas and high ceilings – this supports the application of high efficiency and power CISs.

Advanced features of the *Solatube® M74* HTLG structure and respectively of the *Solatube M74 Smart LED* HIC are its collector and collimator

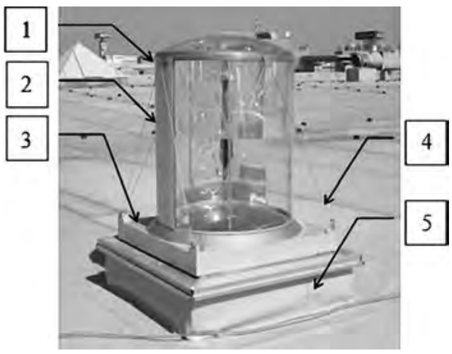

Fig. 3. Input HIC node on the FSC roof:
1 –collector; *2* – *LightTracker*™ reflecting plate; *3* – border flashing; *4* – cable of anti-wind loading; *5* – border

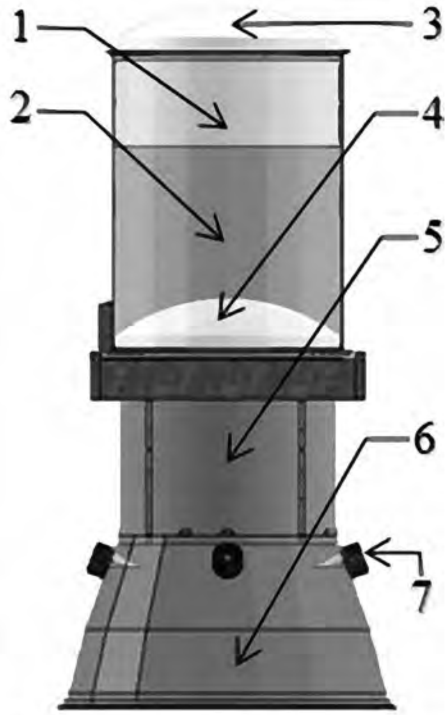

Fig. 4. General view of *Solatube Smart LED* HIC based on HTLG *Solatube® M74*: *1* – collector; *2* – *LightTracker*™ reflecting plate; *3* – collector dome; *4* – light guide dome; *5* –light guide tube; *6* – collimator; *7* – LED module, built in collimator.
Complex parameters: collector height is 1067 mm; tube diameter is 740 mm; diffuser diameter is 949 mm; collimator height is 600 mm; tube potential length is up to 30 m; installation height is from 6 to 20 m; luminous flux of the natural light is 18–35 klm; luminous flux of the artificial light unit is up to 9700 lm

[9]. The collector (Fig. 3 and 4) considerably expands the captured area increasing the efficiency of light collection. It is a cylinder made out of transparent material. In the collector, on the inner surface of the semi-cylinder, the *LightTracker*™ plate with the *Spectralight® Infinity* high-reflecting coating is placed. In comparison with systems without collectors, the collector optical cylinder increase triple light collection, because of the large area of the reflecting plate equal to 1/2 area of inner side surface of the cylinder and its large volume.

The cone-shaped collimator of the *Solatube® M74* HTLG [2, 9] is convenient for placing an ALU, which in the *Solatube M74 Smart LED* HIC structure consists of four radiating elements built into the collimator plates (Fig. 4 and 5).

In HICs of any structure, the basic element is the HTLG, which is a finished industrial product brought to perfection. Having analysed different models of HIC by leading manufacturers, we selected the *Solatube M74 Smart LED* HIC as an analogue for development of domestic *Solar-LED* HICs, and a project of FSC illumination reconstruction using the *Solar-LED* was developed.

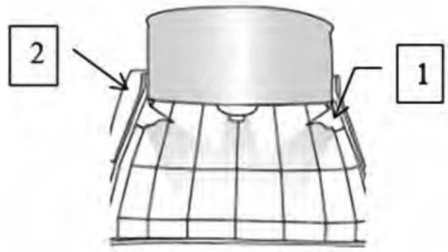

Fig. 5. A layout of placing four radiating elements (LED modules) of *Solatube Smart LED* HICs on the inner surface of the collimator and special transparent caps lenses *1* directing light to the diffuser plane. On the collimator external surface *2*, power supply and control units, as well as cooling radiators of the specified elements are installed

Fig. 6. The illumination system before reconstruction – permanent artificial light IDs. Light sources are HP MHLs

Initial State and Characteristics of the Lighting System

Before the reconstruction, the project's 1920 m^2 area was mainly illuminated with artificial light IDs of 6.6 kW installed power containing bell-shaped luminaires with MHLs of average illuminance ≤ 140 lx (Fig. 6). Natural illumination added ≤ 20 lx and came from four roof lights.

The reconstruction specifications required the following:

– Increase of average illuminance of the combined illumination at the entrance area pier level of the Ashan shop FSC up to 300 lx (in day-time mainly from natural light);

– Maintaining illumination at a constant level during the FSC's full working hours by means of an ACS;

– Support of good colour rendition (R_a > 80);

Fig. 7. A hall view after illumination system reconstruction using *Solar-LED* HICs

– Increased energy efficiency compared with the baseline MHL IDs, up to 60 %;
– Increased reliability and durability.

Design Solution

The solution solved the problem of illumination fo the object using eighteen *Solar-LED* HICs (Fig. 7). Structurally the HIC unites the *Solatube M74* hollow tubular light guide, a LED unit of the preset power artificial light, an ACS (including a light sensor, a controller, a controlled power supply unit of the LED modules) and a fixture for HIC assembling and for fastening functional units around the collimator (Fig. 8). The installed CIS design parameters are given in Table 1.

HIC Efficiency Factor

A parameter was introduced which allows estimating the economic efficiency of an illumination system, in order to evaluate the costs and efficiencies of the CIS at the design stage and inform a reasoned decision. This parameter is especially important, as the published works [1–8] dedicated to HICs do not discuss parameters needed to estimate CIS economic efficiency. This is a normal situation arising as a rule: when describing innovation products or technologies, one should move away from standard terms and definitions. This is connected with the fact that luminous efficacy being a standard evaluation factor of energy efficiency of an illumination device do not describe in full all innovation properties of the product. The CISs and their components HICs are such new products in the light engineering field.

Hence, to evaluate energy efficiency, it is proposed to adapt for inner illumination the relative specific power factor of utilitarian external illumination device according to СП 52.13330.2016. The formula for calculation of CIS average annual relative specific power based on HIC, taking into account a specific character of the component operation, can be expressed as:

$$D_p = P_r \cdot K_d \,/\, (E_{ni} \cdot A),$$

where D_p is the average annual relative specific power of an illumination system, W/(m^2 · lx); P_r is rated power of an illumination system, W; K_d is average annual coefficient of ALU light-emitting diode power demand; E_{ni} is normalised illuminance on the working surface (it has a constant value maintained

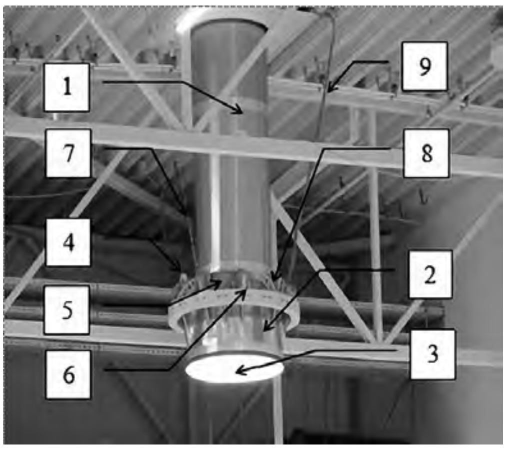

Fig. 8. *Solar-LED* HIC in the FSC:
1 –*Solatube®M74* tube; *2* – collimator; *3* – diffuser luminant disc; *4* –illuminanse sensor; 5 – LED module power supply unit; 6 – assembly ring; *7* – suspension cable; *8* – reinforcement and joint ribs of the collimator with the assembly ring; *9* – power supply and control cables

Table 1. Design Factors of the CIS Object

Factor name			Factor value
Calculation rated capacity (installed power) #, P_{inst}, *kW*			max. 9.45
Applicability for emergency illumination			4.9
Repairability of HIS ****			0.30–0.45
Electric power of ALU HIC, P_{HICmax}, W			max. 500
HIC Power factor (cosφ)			0.95
Electric power supply circuit			220/380 V, 50 Hz
Controllability of HIC (interval of luminous flux change),%			(0–10) – 100 compatible with ACS
Energy saving effect **,%			≥ 60
Luminous flux of the complex	HTLG (natural), lm		max. 35000
	LED ALU (artificial), lm		max. 49000
	HTLG + ALU + ACS*** (combined), lm		≥35000
Average illuminance of the object	HTLG (natural), lx		≥300
	LED ALU (artificial), lx		≥300
	HTLG + ALU + ACS*** (combined), lx		≥300
Quality of colour rendition in ALU mode, R_a / T_c			> 80 / 3500–4000 *K*
Lifetime, years/hours		HTLG	30
		LED ALU	10 / 50000
Warranty operation period, years		HTLG	10
		LED ALU	5
ALU protection degree from external environment exposure, *IP*			42
Operation temperature interval, ˚*C*			- 20 – + 40
Applicability for emergency illumination			Yes
HIC repairability ****			High
Control mode			Automatic

Notes:

Due to natural light, the power demand coefficient in the illumination system is equal to 0.30–0.45. Therefore, power consumption decreases more than twice in comparison with the baseline;comparison with IDs with MHL luminaires; ***during the periods of natural illuminance decrease lower than 300 lx;**** The HIS has unit (block) structure; #according to Table 2.*

Table 2. An Example of D_p Calculation for Various Illumination Installations

<table>
<tr><th>ID type</th><th>P_r, kW</th><th>K_d</th><th>E_{ni}, lx</th><th>A, m^2</th><th>T, h</th><th>t, h</th><th>$D_p \cdot 10^3$, W/(m$^2 \cdot$lx)</th></tr>
<tr><td>CIS based on HIC</td><td>9.45</td><td>0.3</td><td rowspan="4">300</td><td rowspan="4">1920</td><td rowspan="4">4380</td><td>1230</td><td>4.9</td></tr>
<tr><td>IDs with LED luminaires</td><td>12.6</td><td rowspan="3">1</td><td rowspan="3">4380</td><td>21.8</td></tr>
<tr><td>IDs with MHL luminaires</td><td>16.5</td><td>28.6</td></tr>
<tr><td>IDs with IL luminaires</td><td>137.5</td><td>238.7</td></tr>
</table>

by ACS at a preset level), lx; A is area of the illuminated surface, m^2.

K_d value is determined as

$$K_d = (1/T)\int_0^t k_d(\tau)d\tau,$$

where k_d is light-emitting diode ALU power demand coefficient changing in time dependent on the object natural illumination level and set by ACS from 0 to 1; t is use duration of the CIS artificial component during a time cycle, h**;** T is CIS use duration during a time cycle, h.

The D_p calculation technique assumes determining the annual resource of natural light within the location according to meteorological observation data, its change over time, as well as an operation schedule for the HIC artificial component. Calculation parameters of average annual relative specific power for the described object (MEGA Adygeya FSC) for various illumination systems are given in Table 2.

Implementation of the CIS Project Based on Hybrid Illumination Complexes

In December 2016, the upgraded CIS with the reached design parameters was commissioned (Fig. 7). The light environment parameters of the installation (as of April 2017) are as follows: average horizontal illuminance E_{av} = 493 lx and illuminance uniformity coefficient $E_{min}/E_{av} \geq 0.4$ during the daytime, natural E_{av} in fine weather were ≥ 400 lx. The ACS monitored natural E_{av} outside changes depending on the weather and time of day maintaining the design E_{av} level for the combined illumination inside the FSC so that it would be more than 300 lx. Input node and appearance of the HIC with mounting elements, general view of the FSC roof (with installed collectors and HIC) respectively, are shown in Figs. 3, 8 and 9.

Fig. 9. General view of the FSC roof

The CIS ACS is functionally separated into seven groups (there are from 2 to 4 HICs in a group) according to the illuminated area zoning principle. Within the groups, a group control is included. ACS of each group consists of the *DALI-Sensor02 5DPI 41sr* light sensor with remote control, a controller and the HIC ALU controlled power supply units for light-emitting diode modules. ACS adjustment is performed for a HIC group using radio link after the illumination system is mounted.

After the IDs are switched on, the ACS reaches an equilibrium and provides a constant standard illumination level of the space.

To provide the rooms with systems of emergency and evacuation illumination, three HICs are included in their operative circuits. During the light part of a day, CIS HTLGs provide comfortable illumination in case of the FSC electric power supply emergency conditions.

Energy savings are achieved due to a greater luminous efficacy of the light emitting diode ALU than of luminaires with MHLs and because of a decrease of ID power demand coefficient (Table 2) owing to an effective use of natural light.

A comparative analysis[2] of the CISs based on HICs and of light opening standard solutions of upper natural illumination for the implemented project in the MEGA Adygea FSC has revealed higher light- and heat-engineering characteristics of HICs and their indisputable advantage both during warm year period (small solar radiation heat input), and in cold period (low thermal losses).

In the process of implementing a pilot project of the combined illumination system based on the HICs, the experience of designing and installing a hybrid illumination systems was obtained, which has allowed developing a new HIC series[3] free from the disadvantages of the first. The most tangible disadvantage of the implemented CIS is a bright glow of the collectors because of a high level of the reflected light. According to the calculations it is about 22 %. This is an indicator of the ALU optical path imperfection. Another disadvantage of this CIS is the challenge of installing and servicing the HIC, as the ALU and ACS diffusers are mounted high.

CONCLUSION

The conceptual solution of CISs based on HIC structural construction proposed in this article has many advantages compared with traditional systems of general artificial illumination and with the standard openings for natural light. High quality and efficiency parameters and the holistic solution are prerequisites for a widespread introduction of HICs into illumination systems, where the main determining factors are light comfort and energy savings. Based on an analysis of HIC models by leading manufacturers, as comparator for domestic HICs, the *Solatube M74 Smart LED* HIC was selected. Based on its designed structure, a domestic *Solar-LED* HIC was created, and illumination project was developed to illuminate MEGA Adygeya FSC rooms. The project implementation phase has confirmed the main design parameters of the illumination system and revealed some disadvantages, which allowed formulating principles of designing new and improved HICs.

The authors of the CIS project for the Mega-Adygea FSC are grateful to the international IKEA Corporation for an opportunity to implement the project, as well as to Yu.B. Aizenberg and A.A. Korobko for constructive discussion of the article.

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ASSESSMENT OF THE CURRENT STATE AND PROSPECTS FOR DEVELOPMENT OF IRRADIATION SYSTEMS IN MODERN GREENHOUSE FACILITIES

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ABSTRACT

An analysis of the artificial irradiation system used in modern greenhouses using photoculture is conducted. An assessment of the prospects for the introduction of irradiators with LEDs into this system is given, taking into account the payback period in comparison with traditional irradiators with specular sodium HP lamps.

Keywords: greenhouse irradiation, photoculture, discharge sodium lamps, sodium specular lamps (SSL), light emitting diodes, effective systems of irradiation, irradiating installations, pay-off period

Industrial vegetable cultivation in protected soil is a key segment of the agro-industrial complex of the domestic economy; it is currently undergoing a period of rapid development.

According to the Greenhouse Association of Russia, the total area of industrial greenhouses in the country is at 2500 hectares, with more than 500 hectares equipped with systems of technological irradiation, providing year-round vegetables cultivation, Fig. 1. Intensive construction of new greenhouses is enabled by growing consumer demand for fresh vegetables out of season and a state ban on the import of greenhouse vegetables to Russia. The programme of agricultural development in Russia for the period 2013–2020 includes projects creating and developing of greenhouse facilities with artificial irradiation. These projects are a part of a list of actions with priority financing. Just in 2017, the size of the photoculture enabled area grew by 150 %.

Amongst the photoculture enabled greenhouse cultivation, cucumbers represent 60 % of all cultivation, tomatoes account for 30 %, and 10 % is covered by leaf vegetables, i.e. salad cultures. Cucumbers are most sensitive to change in the level of irradiation. Upgrading greenhouses with irradiation systems increases cucumber yield from (40–50) kg/m^2 to (120–150) kg/m^2. The main increase comes in the winter period, when prices for fresh vegetables are at their highest.

Greenhouse irradiation is one of the most energy-intensive uses of light. To provide for the normal growth of plants and achieve a high yield capacity, a high illuminance level is required: from 10 to 30 klx. Large-scale greenhouse facilities are compara-

Fig. 1. Winter greenhouse using artificial irradiation systems (Maysky greenhouse facility, Kazan)

Fig. 2. Cucumber photoculture

Fig. 3. Irradiator and HP specula sodium lamp *Reflux* SSL

ble with small cities or settlements by their energy consumption,. Their light can be seen at a distance of many kilometres. It is obvious that with such power consumption, the cost of electricity is a considerable part of the product cost, reaching as much as (30–40)%. Consequently, raising the efficiency of the radiation sources (RS) and irradiator optical equipment becomes a critical challenge for lighting manufacturers for the greenhouse industry.

More than 20 years ago, a Russian greenhouse facility (GF) called Maysky in Kazan pioneered experiments with various systems of preliminary irradiation for plant cultivation. The managers were interested in specular *Reflux* HP sodium lamps (HPSLs), which had just appeared on the greenhouse market. The first batch of lamps showed good results and became the main RSs for plant irradiation at this facility. Specular HPSLs of *Reflux* LLC production are still used at Maysky GF today. More than 120,000 irradiators with *Reflux* specular sodium lamps (SSL) HPSLs of 600 W are installed there today.

After Maysky, other greenhouse facilities also caught on to the economic benefits, and began to introduce artificial irradiation. The development of photoculture evolved an effective process which is based on the use of irradiators with HPSLs of 600 and 1000 W. This process is applied today by an absolute majority of greenhouse facilities in Russia and around the world. Using this technology, leading domestic greenhouse enterprises like LipetskAgro, Vyborzhets, Novosibirsky, Churilovo, Teplichny and Yaroslavskyl harvest cucumber yields of (130–150) kg/m^2 every year, and Maysky GF is the greenhouse industry leader, collecting up to 180 kg/m^2, Fig. 2.

It should be noted that the use of irradiating installations (II) with HPSLs in the GF not only raises the yield capacity, but also ensures higher levels of profitability demonstrated by GF economic indicators.

Today about 80 % of Russian GFs use effective irradiation systems based on specular *Reflux* SSL HPSLs, exclusive to Russia, Fig. 3.

Due to the design features of the*Reflux* SSL HPSL, (its reflector is a specularised part of a spe-

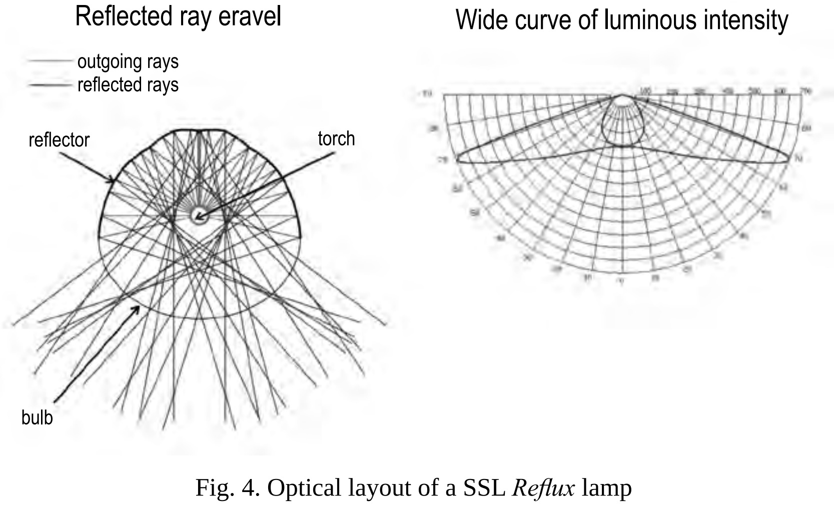

Fig. 4. Optical layout of a SSL *Reflux* lamp

cial configuration envelope on the inner surface) these lamps of identical rated capacity generate a higher irradiance compared with normal HPSLs. The envelope is designed in such a way that reflected rays do not reflect back onto the torch. This provides a high efficiency (more than 95 %), a stable luminous efficacy and a long lifetime of the *Reflux* SSL HPSLs, Fig. 4.

Specular HPSLs have a wide luminous intensity distribution curve (LIDC) in the transverse plane, Fig. 4, which makes the irradiation uniform and extensive. This type of irradiation facilitates a strong plant growth and development. This is especially important for tall plants, such as cucumbers and tomatoes, because as the plant grows the effective penetration of vertical radiation abruptly decreases as each lower leaf receives five times less radiation than the upper leaves. Taking into consideration the direction of growth and leaf structure, most effective type of irradiation for these plants combines vertically directed upper radiation and lateral penetrating into the growing plant uniformly and deeply. Specular HPSLs with a wide luminous intensity curve in the transverse plane, installed above the spaces between each row, create rays, which fall not only from the top but also laterally onto the external surface of a leaf at an angle close to 90º, whilst not overheating the plants. In this case, extra lamps in the spaces between the rows are not needed, Fig. 5.

The inner surface of the lamp is itself a reflector in a vacuum and loses none of its properties, avoiding oxidation and dust pollution, which can decrease the luminous flux. The deposition material for the *Reflux/Ag 600W/400V* lamps is made of fine silver with the highest reflection factor of 99.9.

Fig. 5. *Reflux* SSL lamps in a greenhouse

Additional benefits of *Reflux* HPSLs arise from the use of electron ballasts with at least 96 % efficiency.

Greenhouse installations use highly efficient irradiators enabling high yield and profitability. Irradiators in use today have electron ballasts and (mainly specular) HPSLs with passive optical systems. They have a luminous efficacy of up to 150 lm/W, radiation efficiency factor (Φ_{PPF}/P_W) equal to 2 μmol/s·W and a lifetime of over 20,000 h.

However, technologies continue to change and evolve, and today there is an active search for new

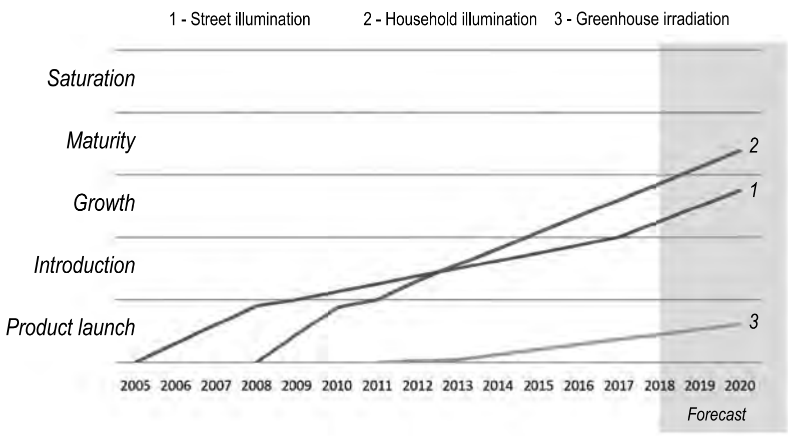

Fig. 6. Stages of light emitting diodes introduction by directions

Fig. 7. LED irradiators for plant cultivation

effective radiation sources (RSs) on the greenhouse irradiation market. LED RSs are competitors in this race for improved methods.

The introduction of LED light sources is an iterative process, which involves promoting them on the market, whilst simultaneously improving their performance and driving down their cost. Logically, those market segments where LEDs can bring the greatest economies are first to respond to these new technologies.

According to the theory of product service life, market capture occurs in six steps: introduction to the market, implantation, growth, maturity, saturation and decay, Fig. 6.

Fig. 6 shows that the development of LED RS in the three applications mentioned above is at different stages; this largely depends on the competitiveness of traditional RSs forced out by LED RSs. The replacement process is most successful where energy inefficient RSs are replaced: incandescent lamps in household illumination or mercury arc lamps (MAL) in street illumination. However, in the greenhouse irradiation space, where massive radiation is required, LED RSs have a very strong competitor in HPSLs, which lose slightly to LED RSs by their performance features, but are significantly cheaper.

Currently, in the sphere of greenhouse irradiation LED RSs are at the initial stage of market introduction, which implies many experimental application projects, with a high uncertainty of success. At this stage, it is difficult to determine the likely economic benefit. The products are expensive due to their continuing modernisation and a limited scale of production. There is also a need to dramatically improve and adapt their output characteristics to the requirements of the market. These are the processes taking place today in the sphere of greenhouse irradiation.

LED manufacturers propose different types of LED irradiators, promising considerable electric energy savings, increased harvest yields, or both. Many greenhouse facilities have taken an interest in irradiation using these RSs, and experiment with their installation, so far with mixed results, Fig. 7.

Considering the tangible interest in this technology expressed in the greenhouse industry, the following section attempts to compare payback periods for artificial irradiation with traditional HPSLs and LEDs, and estimates the prospect LED RS introduction.

As there are no objective economic results of the commercial use of LED irradiators available, only approximate evaluations based on generalised expert estimates are possible.

We will consider a hypothetical case, when managers of a modern greenhouse facility decide to introduce an artificial plant irradiation system to increase the profitability of growing cucumbers during winter and spring periods.

Photoculture technology increases yield during winter periods by an average of 60 kg per 1m^2 of greenhouse area per year. With a price of 80 roubles for 1 kg, the assumed additional income for the greenhouse can be around 4800 roubles per 1m^2.

As a rule, achieving this level of yield increase needs about 200 W/m^2 of irradiance or photosynthesis photon flux density (PPFI) of about 300 µmol / m^2·s. This can be generated by irradiator type ЖСП 25 with electron ballast and complete with a lamp type *Reflux/Ag 600W/400V*. The cost of equipment per 1m^2 in this case is 2500 roubles, as one SSL RS irradiates 3m^2 area and costs 7500 roubles.

For the comparison we will take an irradiator set of the *GreenPower LED* series by Philips used for upper irradiation and for inter-row reirradiation. According to the manufacturer, the *GreenPower LED* irradiators surpass HPSL irradiators by 25 % in respect of photosynthesis photon flux (PPF). These irradiator sets would cost greenhouses about 25,000 roubles per 1m^2, based on average market prices.

If the cost of electricity for these facilities, taking into account depreciation and operational costs, is 2.5 rub/kW·h and the operating time is 4000 h per

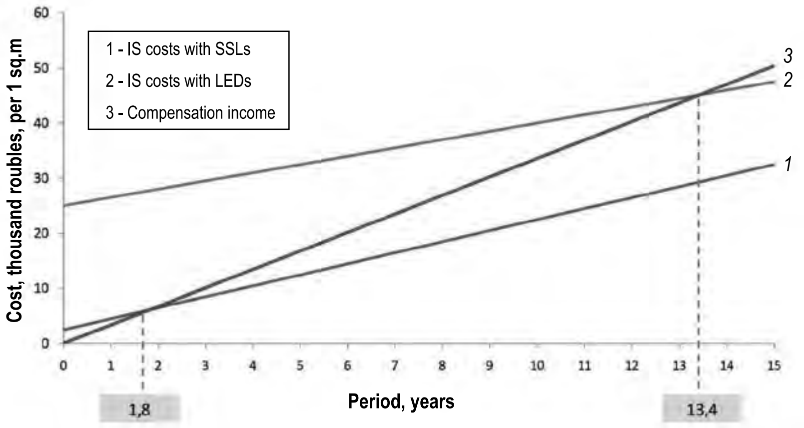

Fig. 8. An evaluation of irradiating installation pay-off period in greenhouse irradiation

year, then the annual specific cost of electricity is as follows:

- For an irradiator with *Reflux/Ag 600/400* SSL:

200 W/m^2 · 2.5 rub/kW·h · 4000 h = 2000 rub/m^2;

- For an irradiator with *Philips GreenPower LED*:

2000 rub/m^2 · 0.75 = 1500 rub/m^2.

Assuming that about 30 % of the additional income generated as a result of the introduction of photoculture covers the expenses for product cost, not related to irradiation, 70 % is the available to pay back on capital expenditure and electricity costs. This is equal to 3360 rub/m^2 per year, and represents a compensation income (I_{comp}).

Irradiation expenditure consist of capital expenditure for the purchasing of equipment and of electricity costs. In this calculation, SSL replacement and the decrease of radiation flux of LED irradiators, as well as assembly cost and expendable material cost for light point installation are not accounted for as they are approximately identical in both cases.

The pay back period of the project finishes when capital and operational costs for the adoption of artificial irradiation in a greenhouse are covered by an additional (compensation) income I_{comp} accumulated for a certain period:

$$C + E \cdot T_{pay\text{-}off} = I_{comp} \cdot T_{pay\text{-}off,}$$

where C is equipment capital expenditure; E is annual electricity costs; $T_{pay\text{-}off}$ is pay-off period, years.

It follows here from:

$$T_{pay\text{-}off} = C/(I_{comp} - E), \quad (1)$$

and incorporating C, I_{comp} and E values from the above, the results are:

- For *Reflux/Ag 600/400* SSL irradiators;

$T_{pay\text{-}off}$ = 2500 rub / (3,360 rub/year – 2000 rub/year) = 1.8 years;

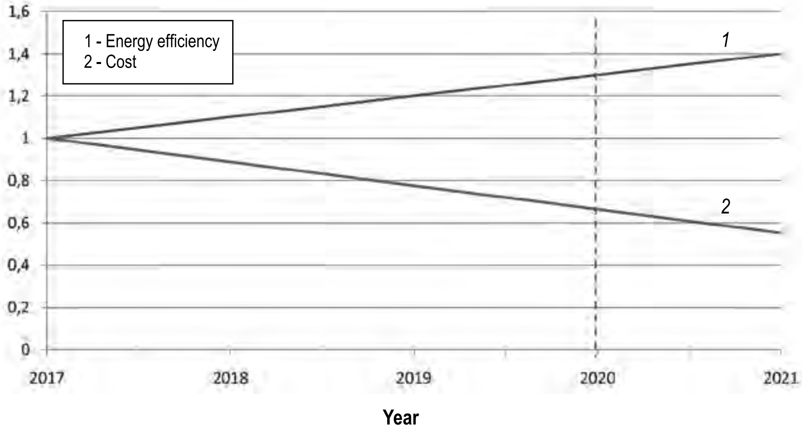

Fig. 9. An evaluation of relative dynamics of LED irradiating installation indicator change in greenhouse irradiation

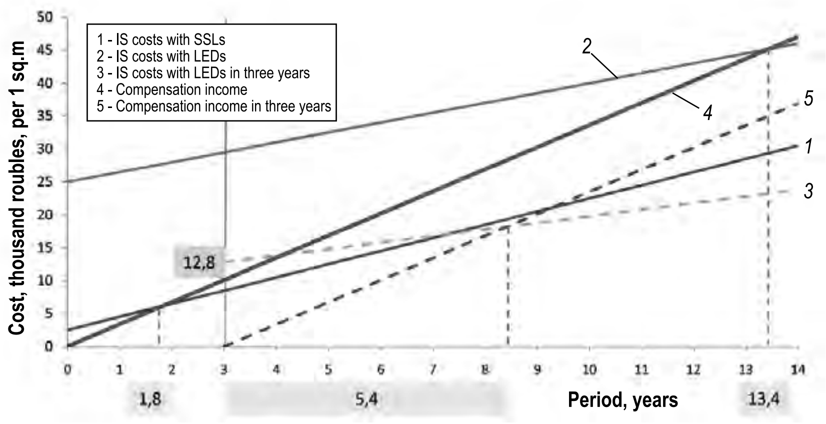

Fig. 10. An evaluation of irradiating installation payback periods in greenhouse irradiation, accounting for LED parameter change

- For *Philips GreenPower LED* irradiators

$T_{pay\text{-}off}$ = 25,000 rub/(3360 rub/year – 1500 rub/year) = 13.4 years.

Clearly, such a drastic difference in $T_{pay\text{-}off}$, Fig. 8, restricts the transition to LED irradiators for greenhouse facilities.

Nevertheless, LEDs for greenhouse irradiation are being developed, and in the years to come a considerable decrease in their cost can be expected, together with further gains in their efficiency, further reducing the annual electricity consumption and number of LED irradiators.

Taking Fig. 9 as the base assumption for cost reduction and efficiency gains, LED irradiator prices will fall by 1.5 times in three years, and their energy efficiency will increase by 1.3 times: based on preliminary estimates, this will allow saving up to 30 % on electricity costs (in this case it will cost about 1000 roubles per $1m^2$).

Taking into account the projected improvement in LED characteristics, a new capital expenditure level can be estimated using the following formula:

$$C_{new} = C_{base}/(1.5\cdot 1.3),$$

where C_{new} is capital expenditure in the context of improved LED parameters (in three years); C_{base} is capital expenditure today.

According to this expression, and to the values given above, C_{new} = 25,000 rub / (1.5 · 1.3) = 12,820 rub.

Therefore, the capital expenditure for LED irradiation will decrease almost twice in three years, Fig. 10.

Using these data, a new payback period $T_{pay\text{-}off\text{-}n}$ can be estimated taking into account the improved LED parameters with a formula similar to formula (1):

$$T_{pay\text{-}off\text{-}n} = C_{new} / (I_{comp} - E_{new}),$$

where E_{new} is electric energy cost a year taking into account improved LED parameters (in three years):

$T_{pay\text{-}off\text{-}n}$ = 12,800 rub / (3,360 rub/year-1000 rub/year) = 5.4 years.

It can be seen from Fig. 10 that LED irradiation equipment installed in three years' time will pay off twice as quickly, as and much earlier than any equipment bought and installed today.

Anyone in a big hurry to install now will lose out in the long term due to large investments and a long pay back period; they will miss out on the gains which will become available three or five years later. By waiting, it will be possible not only to pay off the LED irradiation source (IS) but also to generate profit once the LED IS pay back is reduced.

At present, the large-scale introduction of LED irradiators into greenhouse facilities implies unreasonable economic risks. But to become a pioneer in this industry requires the gradual introduction of these irradiators experimentally. In this case, the LED equipment manufacturer should take on all of the financial risk and compensate any incurred costs. If as a result an increased yield capacity is obtained and the economic benefit is obvious, then in due course the uptake of LED irradiators will increase.

In the case of a positive outcome, LED manufacturers will be interested in expanding their market outlet as much as possible. The greenhouse facilities participating in the experimental installation will gain a small increase in yield with great risks and labour expenditures, whilst their competitors will benefit from maintaining approved technology without additional costs and efforts. During this experimental phase, new LED irradiator models will appear, which will be twice as efficient and significantly cheaper. The competitors will install these models having avoided costs previously, and will reap the benefits over those who were first to market in their increased yields and energy efficiency, Fig. 10.

Financing such volatile market experiments can only be undertaken by large-scale LED equipment manufacturers, or by state investors ready to promote these products and to invest long term into the introduction of LEDs into greenhouse irradiation.

CONCLUSION

- The process of introducing light emitting diodes into greenhouse irradiation is significantly restricted by proven technologies, like HPSL irradiators with highly effective *Reflux/Ag* SSLs, the technological parameters of which are similar to LED irradiators, but their cost is ten times lower. A comparative evaluation of pay back periods gives evidence against LED ISs.
- With the present LED irradiator prices and performance characteristics, HPSL irradiator replacement with LED ISs is premature. Additional inter-row irradiation (reirradiation) options with upper radiation remaining as HPSL, for example for tomatoes, can be an option. However, this raises the capital expenditure without guaranteeing an tangible increase in harvest. LEDs can also be used to grow herbs, salads and other plants with a short vegetation period, as well as different types of seedlings using rack cultivation.
- LED irradiators have strong prospects in terms of their future efficiency and lifetime. But in order to become competitive in the greenhouse market, their profitability through reduced electricity costs must increase further, and their price must fall. Their technologies must be developed and approved. Intensive work is currently under way to achieve this, which allows predicting that significant gains will be made in the next three or five years. Until then, the commercial introduction of LEDs into greenhouse irradiation is a gamble, when business profits are at stake, and probability of success is not more than 10 %.

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HIGHLY EFFECTIVE COVERING MATERIALS WITH QUANTUM DOTS FOR GREENHOUSES

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ABSTRACT

The article considers the application of light-converting polymer films as cover materials for the cultivation of greenhouse crops in a covered soil. We analyse the impact of increasing the level of photosynthesis-active radiation (PAR) level in a greenhouse depending on the season, latitude, the angle of the sun, duration of daylight and on other parameters. The article presents some results of growing crops in greenhouse facilities located at the latitude of Moscow region. The results include a significant shorter vegetative stage, as well, as substantial increase in yield from 30 to 100 % in comparison with the reference conditions.

Keywords: quantum dots *CdSe/CdS/ZnS*, emission peak, exciton absorption peak, fluorescence layers, light transformation, photosynthesis, photosynthesis-active radiation, PAR

Most uses of solar energy are partially restricted by the fact that the radiation spectrum is not always radiating energy effectively. The crucial process of photosynthesis also does not always receive the full benefits of the Sun.

Modern agricultural science has identified a fundamental factor limiting photosynthetic efficiency of a green plant as the number of solar radiation quanta available to be absorbed by a green leaf. In the early 1900s K.A. Timiryazev came to the following fundamental conclusion: "We can give a plant any amount of fertilizer and water, we can protect it against the cold in the greenhouses and accelerate carbonic acid circulation, but we will never cultivate more organic substances than the solar energy that is absorbed by the plant. It is a limit which cannot be contravened by mankind. But once we understand this limit, we will obtain a real, strictly scientific measure for the productivity limit of each territory and region, and at the same time we will be able to judge to what extent our cultivation practice approaches perfection…"[1].

The study of the influence of light spectral composition on plant growth, undertaken in Russia and abroad since the 1950s has identified the impact of various spectral radiation intervals. Multiple experimental data, [1–4] for example, show that leaves absorb a lot of energy in the blue and near ultra-violet spectrum intervals (350–450) nm, and in the red visible interval (600–650) nm. Minimal absorption occurs in the green area (500–550) nm, and at wavelengths greater than 750 nm there is almost no radiant energy absorption. Some absorption occurs in the near IR interval, which is driven by the water content of the leaves.

The most physiologically important absorption is in the interval of (600–700) nm. Most of this affects the plant chlorophyll, with a small amount also absorbed by some other pigments, for example, in carotenoids. This area of the spectrum is the "photosynthesis-active radiation" (PAR). Typical absorption spectrum of green leaf chlorophyll is

[1] It is quoted according to [19]

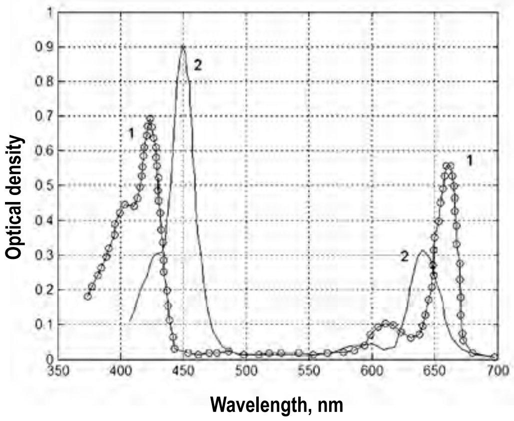

Fig. 1. Absorption spectrum of chlorophyll in the visible area: 1 – chlorophyll *a*; 2 – chlorophyll *b*

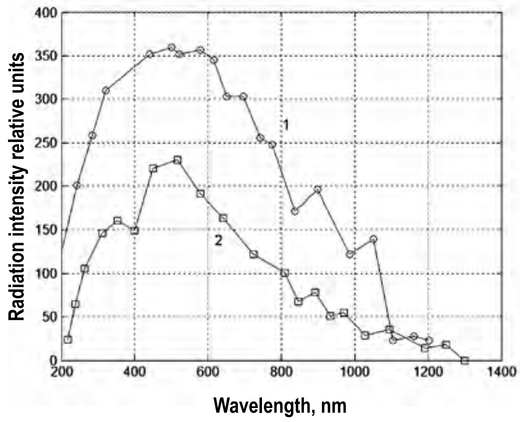

Fig. 2. Relative spectral intensity distributions of direct (1) and scattered (2) solar radiation

shown in Fig. 1. Further, Fig. 2 shows known spectral intensity distributions of direct and scattered solar radiation, and Fig. 3 shows diagrams of relative spectral distribution of photosynthesis efficiency according to McCree [5]. It can be inferred from the presented data that an increase in photosynthesis process efficiency can only happen by adding PAR spectral area radiation [6]. Comparing Figs. 1 and 3 with the solar spectrum given in Fig. 2 shows that maximum value of solar radiation intensity does not coincide either with either the chlorophyll absorption maximum value, or with action spectrum maximum area for photosynthesis. This work will not attempt to uncover the reasons of such evolutionary inefficiencies, which are still a mystery [4, 7]. The important fact remains that the most valuable radiation from the point of view of biological productivity is located in the red spectrum interval (600–670) nm.

In order to correct for the solar spectrum in such a way as to increase its photosynthesis efficiency, we have proposed to use a photoactive additive based on quantum dots of CdSe/CdS/ZnS high pressure polyethylene (HPPE) films as a covering material for greenhouses. These quantum dots are a new generation of phosphors with unique physical and optical properties.

Attempts to use phosphors to correct the solar spectrum were made in the 1980s by some institutes research of the Academy of Sciences of the USSR. In particular, films, containing inorganic and organic photo phosphors based on europium compounds (III), were developed [8]. These phosphors re-emit the ultraviolet component of the sunlight spectrum in the range (300–350) nm into the red visible part of the spectrum. However, these materials are not widely used in agriculture, due to their suboptimal spectral characteristics: narrow bands

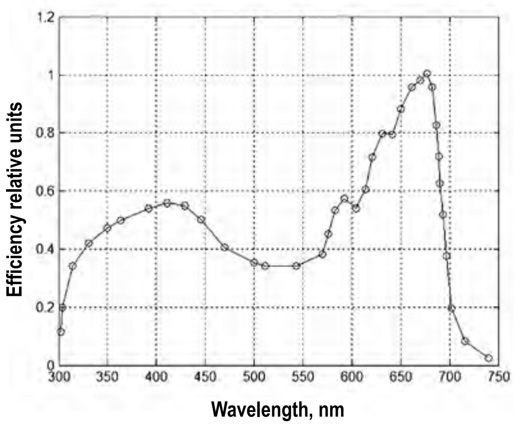

Fig. 3. Relative spectral distribution of radiation photosynthesis efficiency

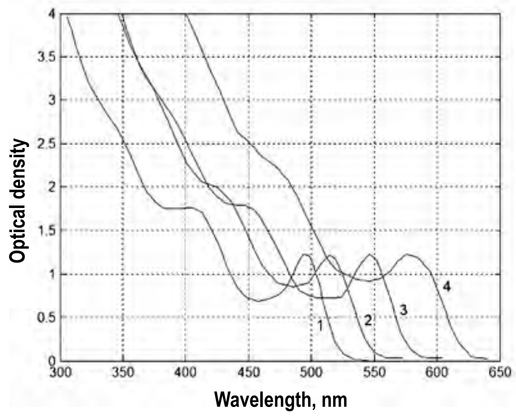

Fig. 4. Typical absorption spectra in the visible spectrum area of polyethylene films containing quantum dots of various size: 1–2.5 nm; 2–2.8 nm; 3–3.4 nm; 4–4.0 nm

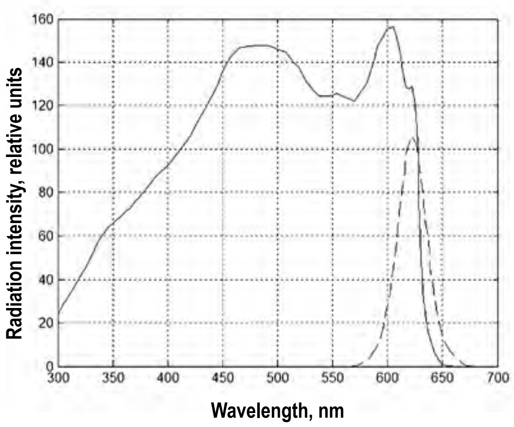

Fig. 5. Excitation spectra (solid line) and radiation spectra (dashed line) of *CdSe/CdS/ZnS* quantum dots

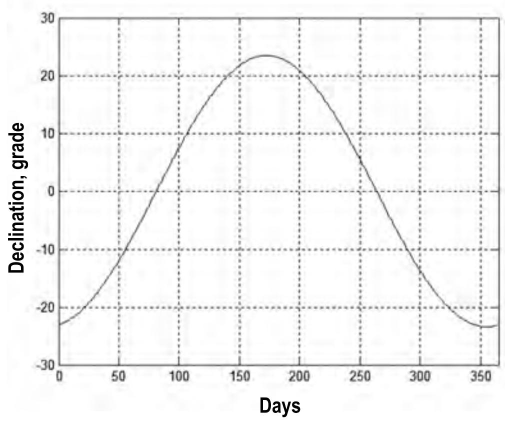

Fig. 6. Sun's declination angle at Moscow latitude (55.7° N)

of absorption and emission, an insufficient value of Stokes shift, a high level of light scattering and low photo stability as well, as a complexity of introducing them into polyethylene matrices.

The creation of a new generation of phosphor based on the CdSe/CdS/ZnS semiconductor colloidal materials has uncovered new possibilities in the development of light transformative materials [9]. Phosphors of this type have some unique optical and colloidal properties, which make them especially attractive for agriculture, because they are materials transforming light. In particular, they are characterised by a wide absorption spectrum in the blue and near ultraviolet regions, Fig. 4, and fluorescence in the form of a relatively narrow peak in practically any range of the visible spectrum.

The general principles of spectral transformation with phosphors were first formulated by S.I. Vavilov. The transformation efficiency is determined by fluorescence energy efficacy, which cannot be greater than 1. In case of anti-Stokes excitation, i.e. in case $\nu_{exit} < \bar{\nu}$, where $\bar{\nu}$ is frequency average value in the emission band, photo fluorescence and energy efficacy should decrease with an increase in the frequency difference ($\bar{\nu}$ - ν_{exit}) (10]. It should be noticed that fluorescence quantum efficacy of the considered materials is close to 1, which is much useful for practical application.

Along with quantum efficacy, an important factor determining the spectrum transformation efficiency is fluorescence energy efficacy. So, flux Φ_{ph} radiated by phosphor as a result of its excitation in some wide spectrum interval can be derived by the following expression:

$$\eta_{en} = \varphi_{ph}(\lambda)/\varphi_{exit}(\lambda), \quad (1)$$

where $\varphi_{ph}(\lambda)$ and $\varphi_{exit}(\lambda)$ are correspondent spectral radiation fluxes, η_{en} is fluorescence energy efficacy:

$$\Phi_{ph} = \int \phi_{ph}(\lambda)d\lambda = \int \phi_{exit}(\lambda)\eta_{en}(\lambda)d\lambda \ . \quad (2)$$

The ultimate goal of solar spectrum transformation is the increase of radiation flux in the photosynthesis active radiation (PAR) region [11]:

$$E_{PAR} = \int_{400}^{700} c(\lambda)I(\lambda)d\lambda \,, \quad (3)$$

where $c(\lambda)$ is the action spectrum for photosynthesis, $I(\lambda)$ is the spectral distribution of solar radiation strength. Comparing the quantum yield of photosynthesis, Fig. 3, and the spectra of excitation and emission of quantum dots, Fig. 5 clearly indicates the expediency of quantum dots for these purposes.

Under natural illumination conditions, PAR flux depends on a number of factors. First, as shown by the curves in Fig. 2, the spectra of direct and scattered natural radiation are substantially different. Direct radiation strikes the Earth's surface as a collimated flux. Scattered radiation falls on the Earth after its particles are reflected and dispersed by air, water droplets, by ice crystals and atmospheric impurities. Total flux includes both types of radiation, and the ratio of those components depends simultaneously on the state of the atmosphere and on the season, as well on the Sun's altitude above the horizon. For instance, scattered radiation strikes plants before sunrise, but with the increasing height of the Sun, the share of direct radiation increases, and the scattered share decreases.

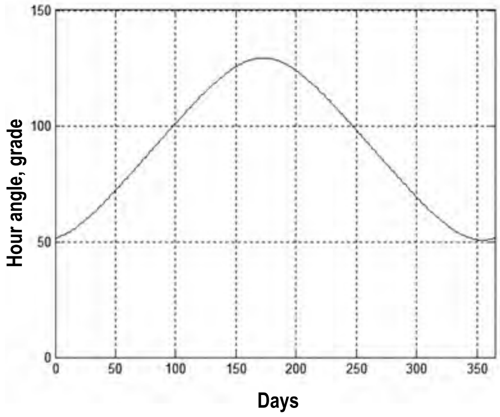

Fig. 7. Annual dependence of hour angle at sunset at Moscow latitude (55.7° N), days are counted from January 1

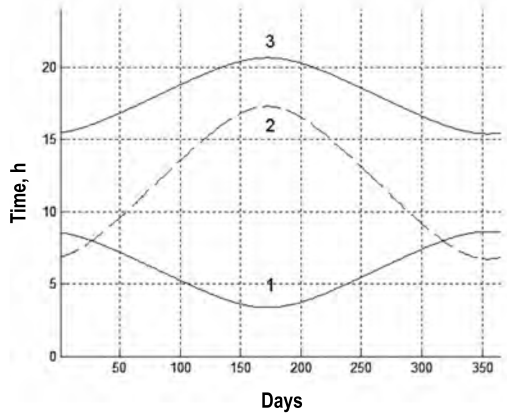

Fig. 8. Results of determining daylight duration, as well as sunrise and sunset time at Moscow latitude of (55.7° N) by average universal solar time: 1 – duration of daylight; 2 – sunrise time; 3 – sunset time

Secondly, the efficiency of radiation transformed by a phosphor layer depends on the irradiation conditions mentioned above, namely, on the ray angles incidence, which in their turn depend on the Sun declination, on daylight duration, on the scattered component share of flux and on other parameters. Studying the generic principles of fluorescence in optical layers in detail, which we have previously published in [13–15], determined some factors to be considered when predicting the light transformation process. As the "astronomic" aspects of solar radiation are widely known, we will use them to explain other observed patterns.

Total solar radiation flux (per unit area) falling upon a horizontal plane can be calculated by a formula similar to the one given in [11]:

$$H_0 = \left(\frac{t_s G_0}{\pi}\right)\begin{pmatrix}\cos\phi \cdot \cos\delta \cdot \sin W_s + \\ +\dfrac{2\pi W_s}{360}\sin\phi \cdot \sin\delta\end{pmatrix}, \qquad (4)$$

where G_0 is the solar constant (G_0 = 1.34 kW/m^2); φ is geographic locality latitude; t_s is daylight duration, s; δ is the Sun declination angle; W_s is hour angle of the Sun at sunset.

Further, declination of the Sun δ can be determined as

$$\delta = \delta_0 \sin\left[360 \cdot (284 + n)/365\right], \qquad (5)$$

where δ_0 = 23,5°, n is the number of the day of the year. Duration of daylight in hours can be calculated using the formula:

$$t_s = \frac{2}{15}\arccos\left(-\tan\phi \tan\delta\right). \qquad (6)$$

Sunset time (by average universal solar time) is calculated by the formula:

$$t_z = 6 + \frac{12}{\pi}\arcsin\left(\tan\phi \tan\delta\right). \qquad (7)$$

The results of the calculations according to formulas (5–7) are essential for evaluating the light transformation use efficiency. They are given in Figs. 6–8.

As Earth orbit is not circular but elliptic, ellipticity should be included using the formula [11]:

$$H = \left[1 + e \cdot \cos\left(\frac{360n}{365}\right)\right] H_0, \qquad (8)$$

where e = 0.333 is a constant, which reflects the Earth's orbit ellipticity.

It is considered that solar radiation reaches Earth surface as a sum of direct and scattered fluxes [11]. As direct and scattered fluxes have various spectral compositions, Fig. 2, this influences the efficiency of the light transformation process. Let's evaluate a "clarity index" k_T, which is a relation of the total daily solar radiation flux incident on the Earth's surface unit area of a horizontal site to the correspondent solar radiation flux outside the atmosphere.

$$k_T(n) = \frac{H_1(n)}{H(n)}, \qquad (9)$$

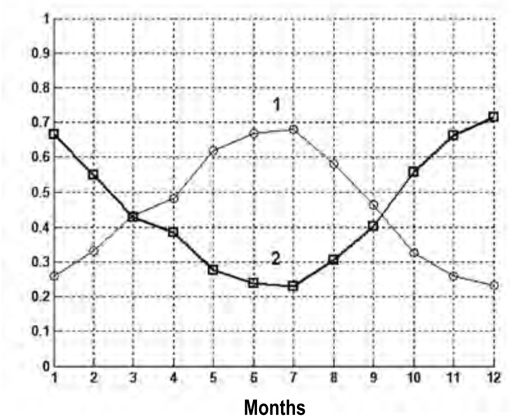

Fig. 9. Time change of clarity coefficient (1) and of scattered flux share (2), relative units

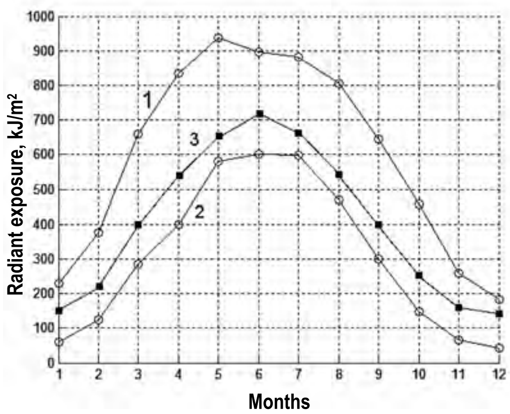

Fig. 10. Total exposure of solar radiation (1), exposure of scattered radiation (2), and total exposure of the transformed radiation in the PAR interval (3)

where $H_1(n)$ is value of solar radiation flux, which reaches the Earth's surface.

Further, diffuse radiation share H_D can be determined using the formula:

$$\frac{H_D}{H_1} = 1.39 - 4.03k_T + 5.53k_T^{\ 2} - 3.11k_T^{\ 3}. \quad (10)$$

In essence, the process of solar spectrum transformation constitutes emission (reradiation) at a certain light wavelength absorbed in a wide spectral interval. Examples of absorption spectra for the materials, which we have developed based on HPPE containing quantum dots of various dimensions, are given in Fig. 4. A unique feature of the quantum dot optics is a wide, almost continuous absorption spectrum in the blue and near ultra-violet ranges in an interval of wavelength lesser than the excitonic absorption peak. This is non-typical for traditional ceramic and organic phosphors, including rare-earths. Another feature of the developed materials is a dependence of spectrum transformation efficiency on the collimated solar radiation angle when passing through the fluorescence layer. This is caused both by a change of the physical properties of light (in particular, its spectral composition), and by the efficiency of the light transformation process itself by the layer with change of incidence angle *h*. Problems of light transformation efficiency connected with changing light ray angle when passing through the layer have been previously considered [13].

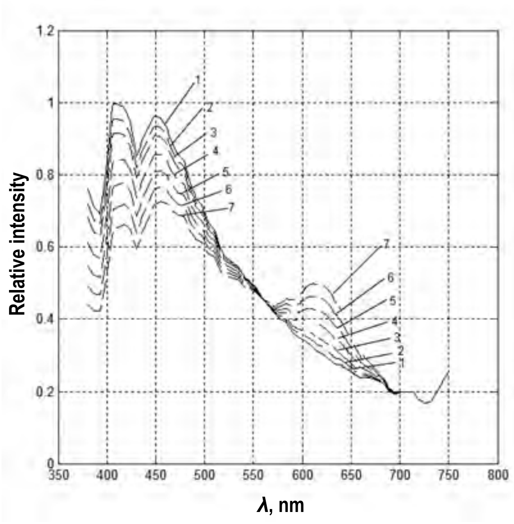

Fig. 11. Natural irradiance spectrum under HPPE film (50 µ thickness) containing various concentrations of a photoactive component: 1 – unmodified film, 2 – contains 0.1 mg/g of quantum dots, 3–0.2 mg/g, 3–0.4 mg/g, 5–0.6 mg/g, 6–0.8 mg/g, 7–1.0 mg/g

Further, incidence angle of collimated solar radiation is determined by a known formula [16]

$$\sin(h) = \sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)\cos(t). \quad (11)$$

The incidence angle of collimated solar radiation flux at Moscow latitude at noon is given in Fig. 6. Determination of the collimated and scattered fluxes ratio was carried out formerly based on the triple-flux approximation [16]. PAR increase is estimated depending on natural illumination conditions. A calculation of full PAR flux (or dose) was carried out using the formula:

$$\sum Q_{\Phi AP} = A\sum S + B\sum D + \Phi_{ph}, \quad (12)$$

where A = 0.6, B is transition coefficient from day-time sums of direct solar radiation to the day-time sums of direct PAR (Table 1); $\sum S$ is full flux of

Table 1. Effective transition coefficients from day sums of direct solar radiation to day sums of direct PAR for various latitudes [18]

Locality latitude, grade	Month							
	5	**6**	**7**	**8**	**9**	**10**	**11**	**12**
66	0.40	0.40	0.40	0.39	0.37			
50	0.41	0.42	0.42	0.41	0.405	0.385		
23	0.425	0.425	0.425	0.425	0.420	0.415	0.410	0.41

scattered radiation, $\sum D$ is full flux of direct radiation, Φ_{ph} is fluorescent flux.

Calculation results are given in Figs. 9, 10. Seasonal changes of clarity coefficient and of the share of scattered radiation are given in Fig. 9. Further, the experimental irradiance spectra obtained for a photoactive component based on quantum dots *CdSe/CdS/ZnS,* Fig. 11, using formula (12), the contribution of fluorescent flux Φ_{ph} to PAR was determined (Fig. 10, curve 3). It is seen that in the (600–650) nm PAR interval, radiation intensity increases by (15–65)% depending on the test time.

Experimentally, at first approximation, the efficiency of light transformation (χ) can be estimated by changes of integral intensity in the (400–550) nm and of (550–700) nm spectral range:

$$\chi = \int_{400}^{550} I(\lambda)d\lambda \,/ \int_{550}^{700} I(\lambda)d\lambda\,. \qquad (13)$$

Processing the experimental data given in Fig. 10 showed that 60 % of the radiation absorbed in the blue area is fluoresced in the red area. Radiation losses are no greater than 40 %. In order to correct the fluorescence spectrum, we also used mixtures of quantum dots dispersion with various maximum emission values. We have previously studied effective spectra of such mixtures in [14, 15].

It should be noticed that at Russia's midlatitudes, yield capacity is almost proportional to the meteorologically possible PAR flux [17–20]. Therefore, when increasing PAR flux by 50 %, a proportionate increase in photosynthetic intensity can be expected. This is illustrated by the spectrum under an HPPE film (50 μ thickness) containing various concentrations of a photoactive component (Fig 11). The figure shows a significant increase in radiation intensity in the PAR interval.

We have carried out tests of the developed material based on a HPPE film containing quantum dots at the same latitudes as Moscow region [21]. The following cultures were tested in protected soil: white cabbage (*Brassica oleracia var. capitata L.*), cauliflower (*Brassica oleracia var. botrytis L.*), lettuce (*Latuca sativa L.*), tomatoes (*Salanum lycopersicum erensuletum*), and cucumbers (*Cucumis sativus*). The results completely confirmed the assumptions.

The biomass of the *Brassica oleracia var. capitata L.* cabbage grown under the light transforming film, was (45–75)% higher than under the reference conditions (a non-fluorescence film). Biomass increase of the *Brassica oleracia var. botrytis L.* cabbage and of the *Latuca sativa L* lettuce was up by (30–40)% and (25–30)% respectively. Weight of the *Salanum lycopersicum erensuletum* tomato fruits and of the *Cucumis sativus* cucumber increased up to 35 % and 50 % respectively.

Some results of growing cucumbers of the Prestige and Miracle brands in protected ground under fluorescent films are given in Table 2. The yield increase in these experiments is significantly higher than the experiment statistical error. The results for the production capacity of the La-La-Fa brand of tomato (F_1 hybrid) are given in Table 3. It can be seen that production capacity depends on quantum dots concentration in the covering material, and that maximum productivity corresponds to the material quantum dots concentration of (3–5) mg/g.

CONCLUSIONS

1. Studying the optical properties of polymer films containing quantum dots as a photoactive component led to identifying the main features of the solar spectrum transformation process. It was found out that solar spectrum transformation efficiency depends both on fluorescent and optical film

Table 2. Cucumbers Yields (Prestige and Miracle brands) at 90 days of Age, Grown in Protected Ground Under the Developed Fluorescing Films

Brand	Experiment series	Yield, kg/m²	Number of fruits, piece/m²	Average fruit weight, g
Prestige	Reference	6.2	65	95
	Light transforming film, 2 mg/g *	21.0	140	150
Miracle	Reference	13.2	110	120
	Light transforming film, 2 mg/g *	20.8	160	130

* Concentration of the photoactive component

Table 3. Results of Studying Yield of the La – la – fa Brand Tomato (F_1 hybrid) Cultivated in Protected Ground Under a Light Transforming Film Containing Quantum Points in Various Concentrations

Coating	Concentration of a photoactive component in the film, mg/g				
	2.0	3.0	5.0	8.0	10.0
Yield, kg/m²	9.1	11.7	11.5	9.3	7.7
Yield increase,% in comparison with reference conditions	136	150	148	136	124

properties, and on some meteorological and astronomic factors. In particular, on latitude, the Sun declination, daylight duration, shares of direct and scattered solar flux.

2. The dependence of fluorescence flux on the Sun declination angle is mainly connected with the factor of radiation reflection from the geometric surface of angular dependence of the layer transforming light and to a lesser extent, on the scattered flux share in total flux of incident solar radiation.

3. It is found out that the additional impact of fluorescent flux to the natural PAR flux at Russia midland latitudes increases during autumn and winter seasons and decreases during the summer months. Similarly, the efficiency of light transformation increases with latitude. This allows to draw the conclusion that the use of light transforming materials in order to intensify the photosynthesis process is very effective for the midland region of Russia, where there is an obvious PAR, practically during the vegetative stage of crops. Therefore, the use of light transforming materials is expedient both during the basic (summer) harvest period, and during the autumn and winter periods.

4. The efficiency of light transformation can reach 50 %. There is very little loss (no more than 40 %) of radiant flux from absorption by the film in the blue and near ultraviolet regions of the spectrum, and it is of little value for photosynthesis.

5. Preliminary cultivation experiments made with some greenhouse cultures showed a significant increase both of the general biomass, and in the fruit mass caused by the general intensification of photosynthesis as a result of PAR flux increase.

6. The optimum concentration of quantum dots in the covering material is estimated to be between 3 and 5 mg/g.

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OPTIMIZATION OF CLASSROOM ILLUMINATION SYSTEM BASED ON NEURAL NETWORK ALGORITHM

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ABSTRACT

The optimization of classroom illumination system based on neural network algorithm was studied in order to optimize the classroom illumination system, which can effectively relieve the students ' visual fatigue and promote the learning efficiency. The neural network algorithm was used. First of all, on the basis of objective evaluation of classroom illumination system, the design algorithm of university illumination based on neural network was designed creatively. Secondly, the lower-machine program of intelligent Illumination system in university was designed, and the algorithm and model of the design at last were tested. Finally, the design algorithm and the model were tested. The results show that the design can play a good role in optimizing the classroom illumination system.

Keywords: neural network algorithm, classroom lighting, optimization design

1. INTRODUCTION

In recent years, the economic strength of our country has been greatly improved and the degree of civilization of the society is increasing, which is inseparable from the development of education. Education has also reached an unprecedented level of attention in the whole society [1]. The size and number of education for education is also rising, especially for higher education, carrying the culture for the motherland and the task of scientific research gave birth to a man of tremendous promise, which has attracted the attention of the whole society. Colleges and universities are not only large and more personnel, but also the distribution of personnel is more scattered [2]. Because most of the universities in our country are still taking traditional management, the waste of energy is still common. It is understood that the water and electricity expenditure of most colleges and universities in China can reach about twenty percent of the annual total expenditure of the school [3]. Especially for the consumption of electric energy, the proportion of total energy consumption is increasing, and the lighting system can make up more than fifty percent of the total energy consumption. Colleges and universities are different from primary and secondary schools, and the time and time of teaching and rest are relatively irregular [4]. And there are plenty of rooms; basically every classroom can not guarantee the people all day long. All day long in the classroom illumination in each period are different, so the lamp can not be timely closed waste of energy phenomenon, even “long light” phenomenon is still widespread there. Now most colleges and universities have adopted the way of multimedia teaching, using projectors to play slides instead of traditional teaching. Then you need to pull the curtains open lamps. The majority of colleges and universities teaching building for the first wave morning students turn on the lights, the class also no one thinks until the evening before the seal floor attendant uniform closed. Such a waste of energy not only brings a heavy burden to the running of colleges and universities, but also brings adverse effects to the development of public welfare activities of “energy saving and emission reduction” in the whole socie-

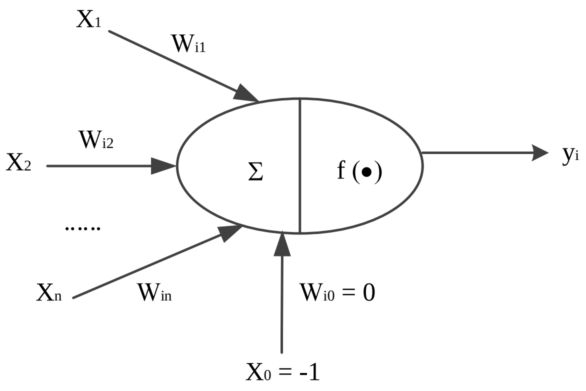


Fig.1. Neuronal structure

ty [5]. Therefore, how to effectively save energy has become a problem to be solved by the institutions of higher learning.

2. STATE OF THE ART

Intelligent lighting control system is an important part of intelligent building. With the continuous development of intelligent building, lighting system is no longer just for bringing light and simplicity to people, but is developing towards comfort and energy saving direction [6]. Especially for energy saving, for the important mission of intelligent lighting control system, it also takes on the task of building a saving society and promoting the sustainable development of the country. The main form of power generation at the present stage of our country is still thermal power generation. Especially in the north, if the intelligent lighting control system can be developed vigorously, the consumption of electricity can be reduced and the consumption of coal is reduced. This is of the same significance for improving the air quality and reducing the fog. In recent years, with the continuous development and mutual promotion of computer technology, automatic control technology, network communication technology and microelectronic technology, the development of intelligent lighting control system is also deepening [7]. According to the different environment, the users can make use of the intelligent lighting control system to set different requirements according to their own actual conditions. The environmental information is collected through the automatic acquisition system. The information is analyzed logically and inferred by the system, and the feedback processing signal is formed so as to achieve the best lighting control effect [8].

3. METHODOLOGY

3.1. Neural Network Based Lighting Design Algorithm for Colleges and Universities

Neural networks, also called artificial neural networks or neural computing, can be seen as the abstraction and modelling of a human brain or a biological neural network. In order to adapt to the environment and learning environment in the way of simulating biological interaction, it is an important part of artificial intelligence science and can solve all kinds of complex problems that human beings can't solve. The three main parts of the neural network are neuron, network topology and training algorithm. A neural network can be seen as a parallel processing system composed of many neurons or nodes connected by each other. The structure and function of single neuron seem simple, but the storage system formed by multiple neurons is distributed. Because of such characteristics, neural network has strong self-learning ability and high fault tolerance rate. The structure of the neuron is shown in Fig. 1.

Among them, x_1—x_n represent the input signal of the neuron. w_{ij} - represents the weight of the connection between the neuron *j* and the neuron *i*, *θ* stands for the threshold value also called bias. The expression of the relationship between the input and output of the neuron *i* is

$$net_i = \sum_{j=1}^{n} w_{ij} x_j - \theta \qquad y_i = f\left(net_i\right). \tag{1}$$

The output of the neuron *i* is y_1. *net* is called net activation. The function *f* is called an activation function. If the threshold value as the weight of a w_{i0} input to x_0 neurons in I, while type 1 can be simplified as

$$net_i = \sum_{j=1}^{n} w_{ij} x_j \qquad y_i = f\left(net_i\right). \tag{2}$$

If *X* is defined as an input vector, *W* is defined as a weight vector, then:

$$X = \left[x_0, x_1, x_2, \ldots, x_n\right], \tag{3}$$

$$\omega = \begin{bmatrix} \omega_{i0} \\ \omega_{i1} \\ \omega_{i2} \\ \cdot \\ \cdot \\ \cdot \\ \omega_{in} \end{bmatrix}. \quad (4)$$

The output of the neuron can be transformed into the product of the vector.

$$net_i = X\omega;$$
$$y_i = f\left(net_i\right) = f\left(X\omega\right). \quad (5)$$

If the net value of neurons is positive, it can be defined that neurons are in active state or excited state. If neuron net is negative, neurons can be defined as inhibitory state. Such as "threshold weighted and" neuron model is embodied in the form called M-P model (McCulloch-Pitts Model), also called the processing unit in a neural network (PE, Processing Element).

Network topology is divided into two types of feedforward and feedback networks in neural networks, including the structure of the network and the connection mode between neurons. Feedforward networks, when there is no feedback in the middle, each neuron outputs the input of the previous layer to the next layer. The feedback network refers to the existence of feedback loops between neurons. Training algorithm (also known as learning algorithm) refers to the way of adjusting weights in training process, which determines the initial weights of each connection neuron and can meet the performance of the network. The training algorithms can be roughly divided into two kinds of learning methods: supervised and unsupervised. Supervised learning can provide input mode and output mode to the network at the same time of training. And adjust weights through continuous input of different training modes so as to make output mode get closer to the expected mode. Unsupervised learning is to adjust its own parameters completely according to the input value, and the output value can accurately reflect the purpose of the characteristics of the input training sample.

3.2. Intelligent Lighting Program Design for Colleges and Universities Based on BP Neural Network Algorithm

The working process of the system determines the working state and the purpose of the system. Designing a correct and reasonable system workflow is also very important for the normal and stable operation of the system. The work flow chart can clearly reflect the design idea and the purpose that the designer wants to achieve for the whole system operation. The working mode and process of the system software are also determined according to the sequence of the system flow chart. This design has carried on the detailed exploration and selection to the system hardware equipment. Can we maximize the functions of this hardware, ensure the smooth operation of the hardware, and achieve the intelligent control requirements for the lighting system. The design of the work flow chart should be as accurate and reasonable as possible.

According to the related concepts of the module, the monitoring programs of the system generally include the two types of the command processing subroutine and the monitoring master program. The monitoring master can invoke a subroutine at any time. In general, when the system runs, multiple subroutines within the system can be called by the same main program at the same time. However, due to the low cost requirement of the design, the AT89S52 microcontroller may run in the running process, and the main program continuously calls the subroutine or even the dead cycle. In order to prevent the emergence of infinite circulation, we can match the main program of the slave machine into a large circular process according to a logical relationship. The functions of the lower machine in the process can be realized by calling various subroutines. In the process of designing the lower machine process, we should focus on the simple main program. The related functional modules in the system should be regarded as the subroutine under the main program. The function of the system is realized by calling the subroutine according to the design requirements. Therefore, it will become clearer and clearer to design the next machine software with this way of thinking. Even if there are any problems encountered during debugging, the causes can be found out and solved at the first time. The main program of the lower computer includes the initialization system, the related subroutine, the

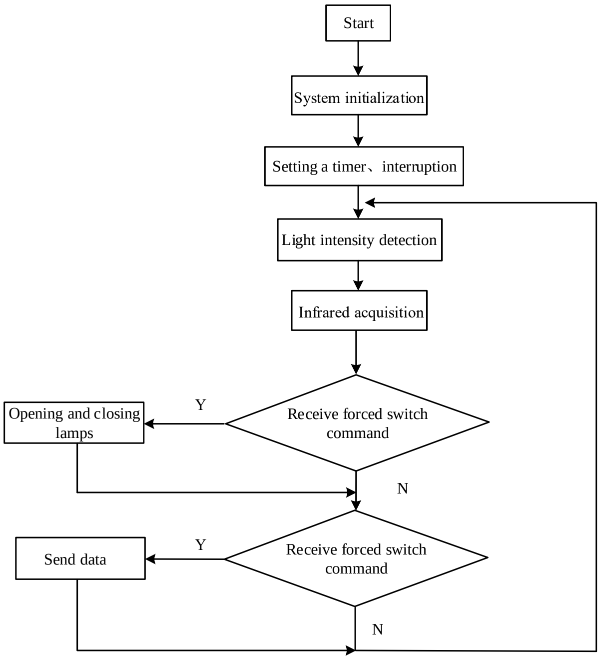


Fig.2. System work flow chart

input and output pin, the instant switch and so on. Besides the initialization and pin definition of the system, other subroutines of the system are executed repeatedly according to the workflow of the system, and each sub program will not interfere with each other. As a single chip computer program runs, it can be seen as a process to execute commands in a certain order. It is inevitable that there are some delays when running, but in fact, the speed of environment change and personnel flow in the classroom is relatively slow, and the delay of single-chip microcomputer can be ignored, which can meet the normal operation of the system. The flowchart of the main program of the lower machine is shown in Fig. 2.

The basic learning algorithm of the BP neural network is called the gradient maximum descent method. It is defined as the adjustment of weights to minimize the total error of the network, which is the gradient search technique. With expectation, the mean square error of the actual output value and the expected output value of the network is the smallest. Its network learning process can be regarded as a process of error correction and transmission coefficient correction. In the structure of BP neural network, the three layer network structure is composed of the input layer, the hidden layer and the output layer. There is no direct relationship between the hidden layer (middle layer) and the outside world, but the neuron state of the hidden layer can affect and change the input and output. The algorithm idea is the weight of network (ω_{ij}, T_{li}) and threshold (θ) revised, so that the error along the negative gradient direction is of continuous decline, finally we obtain the satisfactory results. The learning formula of the BP neural network is as follows: among them, ω_{ij} is the network weight value between the input node and the hidden layer node. T_{li} is the network weight value between the hidden node and the output node. t_1 is the expected value of the input node. The output node is O_l. W_e input in the input node x_j, the output of the middle node:

$$y_i = f\left(\sum \omega_{ij} x_j - \theta_i\right). \tag{6}$$

Output node:

$$O_l = f\left(\sum_i T_{ij} - \theta_l\right). \tag{7}$$

Among them, the connection weight value is ω_{ij}. The node domain value is θ_l. For the output layer, the output node expects to output t_1, and the error formula is as follows:

$$\delta_1 = (t_1 - o_1)(1 - o_1)o_1. \tag{8}$$

Error control:

$$E = \sum_{k=1}^{p} e_k < \in, \tag{9}$$

$$e_k = \sum_{l=1}^{n}\left[t_1^{(k)} - o_1^{(k)}\right]. \tag{10}$$

Weight correction:

$$T_{li}(k+1) = T_{li}(k) + \eta\delta_1 y_i, \tag{11}$$

where k is the number of iterations. The threshold value correction:

$$\theta_l(k+1) = \theta_i(k) + \eta\delta_1 y_i. \tag{12}$$

Among them, p is a sample number, E is a sample error, and n is the number of output nodes. For the correction formula of the middle layer (the input node to the intermediate node), the error formula:

$$\delta_i = y_i(1 - y_i)\sum_i \delta_l T_{li} \tag{13}$$

Weight correction formula:

Table 1. Classroom Lighting Monitoring Data

Input quantity		Output	
Standard of illumination (*h*)	**Luminaire power (*W*)**	**X axis coordinates (*cm*)**	**Y axis coordinates (*cm*)**
150	40	171	225
	30	133	180
	20	100	150
	15	92	82
200	40	200	150
	30	100	180
	20	75	150
	15	86	69
300	40	171	129
	30	100	129
	20	80	100
	15	50	82

Table 2. The Sample Data (for Table 1)

Input sample									Output sample	
H (10m)	φ (1041m)	A (102m^2)	η	K	P_c	P_f	P_w	E_{av} (103 lx)	N (10)	E_{av} (103 lx)
0.36	0.3112	1.08	0.7	1.3	0.55	0.26	0.35	0.35	28	0.304
0.36	0.2865	1.08	0.7	1.3	0.36	0.33	0.36	0.39	35	0.350
0.36	0.2553	1.08	0.7	1.3	0.39	0.36	0.37	0.299	36	0.318
0.36	0.2006	1.08	0.7	1.3	0.12	0.41	0.61	0.15	28	0.196

$$\omega_{ij}(k+1)=\omega_{ij}(k)+\eta\delta_i x_j. \quad (14)$$

The threshold value correction:

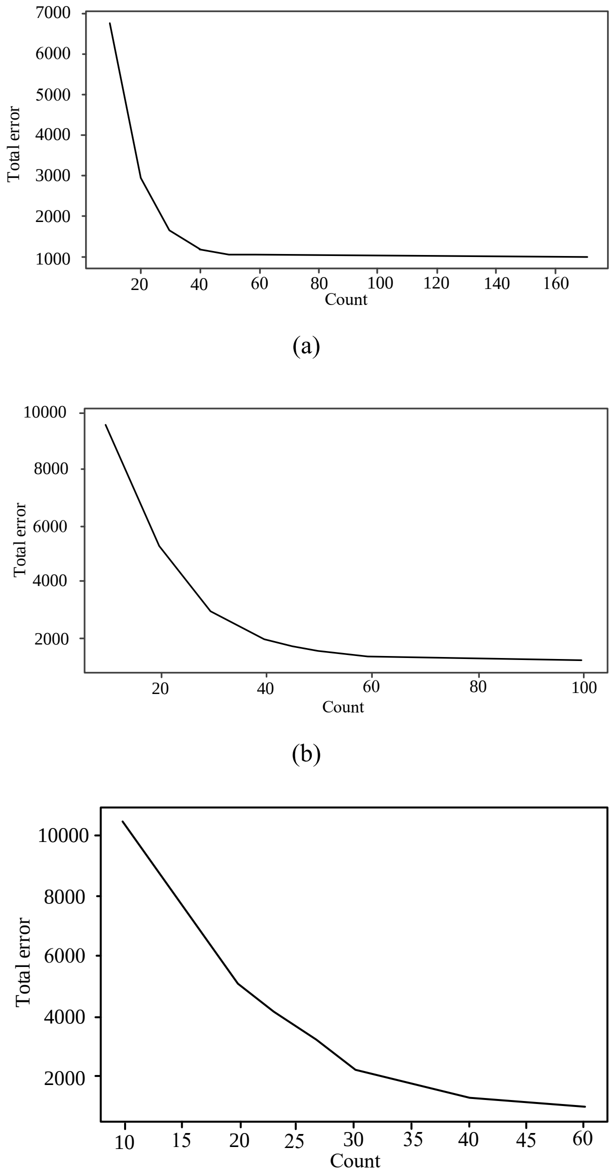
$$\theta_i(k+1)=\theta_i(k)+\eta\delta_i. \quad (15)$$

4. RESULT ANALYSIS AND DISCUSSION

4.1. Simulation Experiment of BP Neural Network

In order to satisfy the standard value of illuminance, the most energy-saving lamp installation scheme is designed, which can be simulated by BP neural network. Generally in different environment, the installation position and power of the lamps and lanterns will have a certain influence on the lighting effect. The model can be built through the BP neural network. The illuminance standard and the lamp power are defined as the input quantity, the installation position of the lamp is defined as the output, and the training is carried out. The experiment selected a classroom of the teaching building as the experimental object. The input data of the BP algorithm is normalized. The input and output parameters of the network are determined, and the selection and determination of the parameters are selected according to the actual situation. The distribution of lamps and lanterns in the classroom and the measured data are shown in Table 1, and the sample data are shown in Table 2.

P_e, P_f, and P_w are the characteristics of the lamp.



(c)
Fig.3. The BP neural network algorithm

The data used in the test show that the input amount is lighting luminance (*LC*) and luminaire power (*W*). The output is the minimum distance between the horizontal and vertical lights installed in a given classroom (the unit is cm). The default size of the classroom is 12m * 9m. For different sizes of classrooms, data can be modified by testing. The fluorescent lamp is used as the test lamp in the test. Because the 16W LED lamp in the design is basically the same with the 40W fluorescent lamp on the illumination, so the simulation results of 40W lamps in the test can be used as the basis for the installation location of lamps in the design. The total error of training obtained from many times is shown in Fig. 3 (a, b, c). The algorithm's error is displayed graphically, and there are shown every 10 iterations.

Then the test results are obtained. We can calculate the result of the test. Meeting the illumination requirement, if we choose 40W lamps, we can install 5 lamps in the 12m * 9m classroom in the range of X 9m. We can install 6 lamps in the scope of Y axis, and we need to install 30 lamps in the whole classroom.

4.2. Logical Relationship

Generally speaking, the intelligent lighting control system can be divided into three working modes: class mode, self-study mode and mandatory mode. The logical relationship between different modes is also different. When using class mode, there are two kinds of people in the classroom. There is a light intensity in the classroom. If the indoor light intensity is enough, no matter whether the indoor lights are on or off, they should be closed. If the intensity of the indoor light is insufficient, the lamps in the classroom should be open, and the lights in the unmanned classroom should be closed. When designing binary logic relationship, it should be consistent with the output signal of the illuminance acquisition module. When the illumination intensity is enough, it is set to "0", and when the illumination intensity is insufficient, it is set to "1". If indoor activity is set to "1", no indoor activity is set to "0", indoor lighting is set to "1", and indoor lighting is set to "0". According to the requirements of the design, the logical relationship is formed. When using the self-study mode, a certain priority can be set for the self-study room in order to save energy. If the indoor illumination of the highest priority classroom is insufficient and the room is detected, the luminaire will be in the open state. Secondly, the first class classroom will start the intelligent control system only if the upper level lamps are turned on. The human body detection module is used to decide whether someone is indoors or not, and then decides that lamps are still open for opening. In the design of a binary logic relationship, if someone in a high priority room can be set to "1" room, no one is set to "0". High priority indoor lamps and lanterns are set to "1", and the luminaire is set to "0". The next level of indoor lighting is set to "1", and the lamp closes to "0". According to the design requirements, a logical relationship is formed. When using coercive mode, the system will force the selected classroom lamps to be opened or closed to deal with all kinds of special situations. This control mode is only for simple opening and closing, and there is no logical relationship. There will be no more introductions here. In conclusion, the test results show that the design of this paper can optimize the lighting system of classroom, and classroom lighting should be optimized from lighting level, glare sensation, luminance distribution, lighting and indoor layout.

5. CONCLUSION

This paper took energy conservation as the starting point, takes such a large group of colleges and universities as the main research object, and took the electricity consumption in colleges and universities as the main research object. The classroom lighting system of teaching building, which is easy to cause waste, is the main research object. This paper put forward an intelligent lighting control system suitable for modern teaching buildings in colleges and universities. First of all, the algorithm and model used in this paper were described in detail. Secondly, in the overall design of the system, author learned the current development of intelligent control technology and the advantages, components, and development of intelligent lighting system by consulting related information. Based on the analysis of the existing intelligent lighting control system at home and abroad, and combined with the current situation of classroom lighting in colleges and universities in China, a classroom lighting optimization system based on neural network was constructed. In order to improve the efficiency of energy saving, the original fluorescent lamp was replaced by LED lamp. Finally, this paper simulated the best fixtures of lamps and lanterns through neural network algorithm. In short, classroom lighting: the level of illumination, glare, brightness distribution should be formed by the layout optimization of lighting and interior.

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OPTIMIZATION OF INTELLIGENT ILLUMINATION IN UNIVERSITY CLASSROOM BASED ON FMRAS CONTROL ALGORITHM

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ABSTRACT

Based on the FMRAS control algorithm, the optimization of the intelligent illumination in the classroom was studied, aiming at optimizing the classroom illumination and improving the energy utilization. The FMRAS control algorithm, based on technology, was used to design a fuzzy control system of intelligent illumination in college classroom. The analysis is based on the improved adaptive algorithm – FMRAS. After the PWM code is automatically generated, the system can automatically control the lighting of the lamps. Through the research, the result has been obtained: the method designed can meet the needs of the optimization of intelligent lighting in the classroom, and can further improve the efficiency and intelligence of classroom lighting in universities.

Keywords: fuzzy model reference adaptive system (FMRAS) control algorithm, college classrooms, intelligent lighting

1. INTRODUCTION

China has put energy saving work as the focus of the "11th Five-Year" work. The call for "building a conservation oriented society" was put forward. The Ministry of education has also actively responded to the call for "building a conservation oriented campus". As an important place for college teaching, the university classroom usually adopts the open management model. Students basically have no fixed classrooms and seats, while the building managers are only responsible for health or security [1]. Therefore, there is a waste of lights, unturned lights and less people because of the large number of lamps and lanterns in the classroom and the long time of use. The proportion of lighting in the whole school's electricity consumption has always been high. If a school has 200 classrooms in accordance with the 100m^2 [2], the intelligent lighting control is adopted to make the electricity saving rate of 30 %, and the electricity fee is saving from 150 to 200 thousand yuan per year. The above estimates are not including in the line loss and the ageing of the luminaire [3]. The above data show that the energy saving work in the classroom is a long-term and arduous task. The intelligent lighting control in university classrooms should not only meet the requirements of indoor lighting, but also prolong the life of lamps and lanterns, reduce operation costs, simplify distribution control devices and reduce wiring workload under the premise of energy saving [4]. A new wireless network technology with short distance, low speed, low complexity, low power consumption and low cost Zigbee technology has its unique advantages: power saving, reliability, short delay, large network capacity, high security, licensed frequency band, self-organization and so on [5]. It is very suitable for the wireless connection of the sensor nodes in the classroom. It not only conforms to the characteristics of the school network communication, but also saves a lot of manpower and material resources. Therefore, the research and Realization of intelligent lighting control system has very important practical significance.

2. STATE OF THE ART

The key technology of intelligent lighting system is information transmission and intelligent control. The power carrier technology, the integrated wiring technology and the wireless network technology are the three main technologies of the information transmission in the current intelligent lighting control system in China. The integrated wiring technology connects the central controller, the switch, and the terminal with the unshielded twisted pair and the optical cable as the medium [6]. The central controller transfers the wireless signals sent by the remote control to the terminals in a wired way, and the terminal completes the corresponding instructions. This method needs to set up the extra weak power control line to achieve the stable signal, which is more suitable for the large area control of the building and the district intelligence. But there are the following shortcomings: the specialized technical installation and maintenance large amount of engineering, long installation cycle, high cost, and poor compatibility of equipment. The wireless network realizes intercommunication and intelligent control of all kinds of electronic devices through infrared, Bluetooth, Zigbee and other technologies [7]. Wireless networks can provide greater mobility and convenience, which makes the use of space more flexible. The cost and energy spent on the generic cabling were saved. The application of wireless network technology to the school network has become an unstoppable trend. As a technology of low power consumption, low data rate and low cost, Zigbee is more suitable for classroom lighting automation system and low-cost equipment for low rate rate transmission. Zigbee is the best choice for intelligent lighting control system in Colleges and Universities [8].

3. METHODOLOGY

3.1. Design of Illumination Acquisition Module and Vibration Sensing Module

First of all, it is designed for the optical illumination acquisition module, which fully uses natural light. The combination of natural light and light is not only an effective way to save energy, but also to create a good visual effect. Therefore, a light illumination acquisition module is designed, and its structure diagram is shown in Fig. 1.

The module consists of three parts, which are data acquisition, data processing and PWM drive control. Among them, data processing and driving control are mainly completed by CC2430. The illuminance sensor is used by ON Company to produce a visible light sensor (ON9658). The sensor is an optoelectronic integrated sensor, with a built-in UNIKA sensor receiver, which automatically attenuates near infrared. The spectral response is close to the human eye function. It is highly sensitive in the visible range, and the output current varies linearly with illumination. The main function is to collect the bad illuminance signal of the classroom and send the signal to the data processing unit through the digital I/O pin P0.7 of the CC2430, whose circuit is realized as shown in Fig. 2.

As the core of data processing and driving control, Zigbee chip CC2430-F128 integrates ADC with 14 bit modulus / number conversion, and it can write the result of conversion to memory controller through DMA mode without CPU interference. This cannot only make the detection results more accurate, but also improve the overall efficiency of the system and reduce the power consumption. Configure the 16 bit timer of the CC2430, TIMER1.

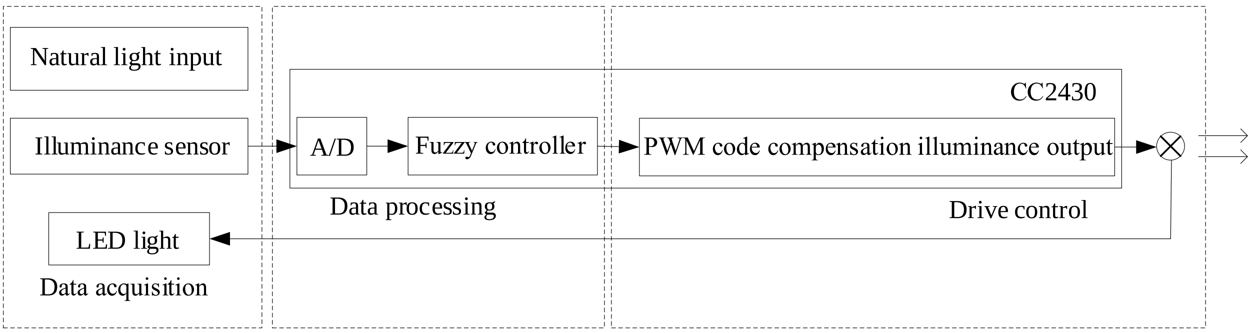


Fig.1. Structure diagram of illuminance acquisition module

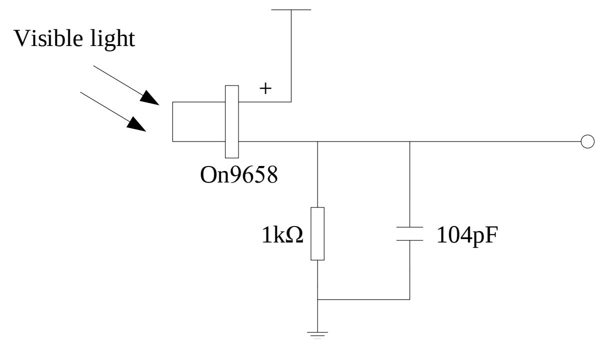


Fig.2. Optical illumination acquisition module circuit

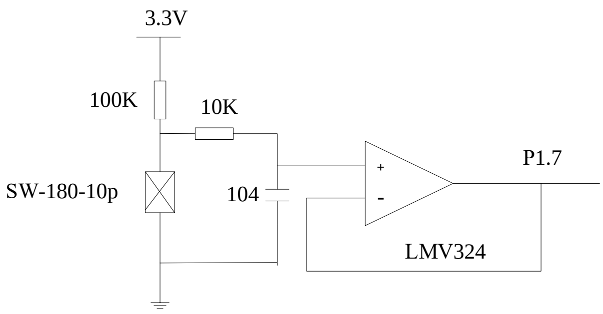


Fig.3. Vibration sensor module

The centre aligned PWM output can be generated. First, TIMER1 is selected as a positive count / down count mode, and the channel output comparison mode selects 5. Secondly, the period of the PWM signal is stored in the T1CC0. Finally, the PWM duty ratio is calculated according to the control changes of the fuzzy inference output. It is used to adjust the effective value of the output voltage to compensate the natural light illumination to stabilize the light environment of the classroom.

The second is the design of the vibration sensing module. At present, the multimedia classrooms in colleges and universities are quite common, and such classrooms have special requirements for the illumination. It is not only to meet the students' reading and note taking, but also to ensure the clarity of the projection screen. So, the vibration sensing module was designed and installed in the projector. When the fan is rotated, the module senses and determines that the classroom is in the projective state. At the same time, the lamp in the rostrum area is closed, while the reserved seat area keeps 50 % of the standard illuminance. The circuit diagram of this module is shown in Fig. 3.

In this design, the vibration sensing element, SW-180–10P, is used as a type of non-directional vibration induction device, which can be triggered at any angle. It is the open OFF state at any angle at rest. When the external force is collided or vibrate, the spring deformation and the contact of the central electrode make the two pins turn into the ON state instantaneously. When the external force is disappearing, the circuit is restored to the open OFF state. Considering the cost factor, the LMV324 operational amplifier is used as the comparator in this design. Its integration makes it smaller than the independent comparator occupying the circuit board, thus further saving the cost.

3.2. Adaptive FMRAS Algorithm Based on Fuzzy Control System Design

Fuzzy control is a kind of computer model based on fuzzy set theory; fuzzy language is variable and fuzzy logic reasoning. Fuzzy control system is a digital automatic control system based on fuzzy mathematics, fuzzy language form knowledge representation and fuzzy logic rule inference, and a closed loop structure with feedback channel, which is composed of computer control technology. The structural form of its system is shown in Fig. 4.

The fuzzy control system is usually composed of five parts, such as fuzzy controller, input / output interface, actuator, wave control object and detection device (sensor).

The basic structure of the fuzzy controller is shown in Fig. 5.

As shown in Fig. 5, in this system, fuzzy adaptive mechanism produces a fuzzy adaptive signal based on the difference between the output of YM and the output YF of the controlled system according to the reference model, controlling the output of the controlled system to the reference model output. However, in the actual situation, there will be changes in the object parameters, state interference

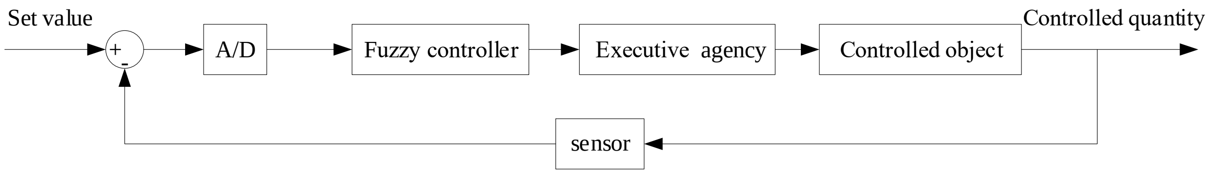


Fig.4. Structure block diagram of fuzzy control system

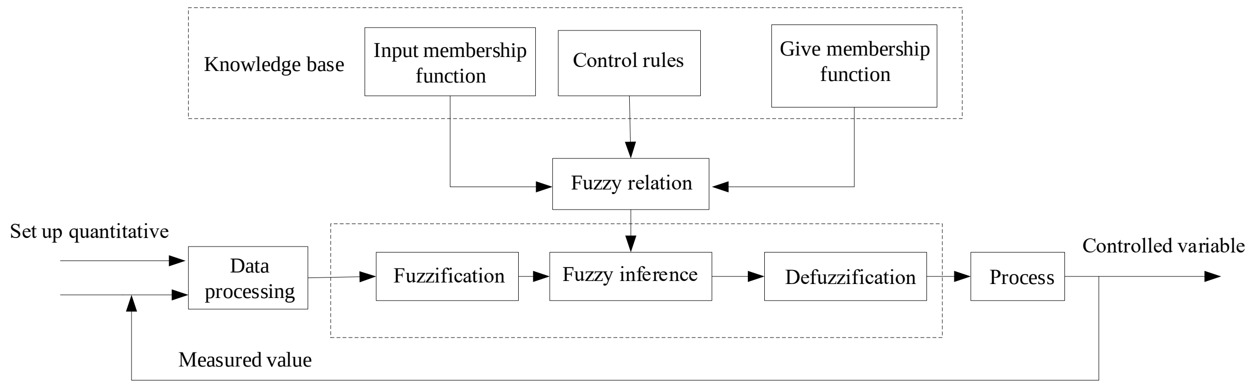


Fig.5. Fuzzy control structure diagram

and so on. Therefore, the T-S fuzzy model is adopted in this mechanism, and the following implication is adopted.

$$\text{If } e = A \text{ and } ec = B \text{ then } u = g(e). \quad (1)$$

Among them, *A* and *B* are fuzzy subset; *g (e)* is a continuous function of *e*, as shown in Table 1.

g1(e), *g2(e)*, *g3(e)* in the table are *K0e*, 0.6 *K0e* and 0.3 *K0e*, respectively. *K0* is the ratio coefficient. According to the fuzzy inference algorithm, the adaptive fuzzy query can be obtained as shown in Table 2.

The product of any element in the table and the K0e is the output *Uf* of the fuzzy adaptive mechanism of the corresponding system state. Obviously there is:

$$Uf = f(e, ec)\, K0e. \quad (2)$$

In the form, *f* represents a kind of nonlinearity, whose value can be queried in Table 2. The Matlab's Fuzzy Logic Toolbox provides a seamless connection with Simulink. After the fuzzy inference system is established in the fuzzy logic toolbox, it can be simulated and analyzed in the Simulink simulation environment immediately. In Simulink, there is a corresponding block diagram of fuzzy logic control, and the block diagram is copied to the Simulink simulation model established by the user. The name of the fuzzy reasoning matrix of the block diagram of the fuzzy logic controller is the same as the name of the fuzzy inference system which is established by the user in the Matlab workspace. The connection between the fuzzy inference system and the Simulink can be completed. The core part of the model is described as follows: the step signal issued by Step represents the set value of the standard illuminance. In this simulation, it is set as 400 lx. Considering the diversity of the light source, the controlled model uses the first order and the two order two transfer functions to verify the practicability of the algorithm. The reference model describes the dynamics of the controlled object or represents an ideal dynamic, and does not need to establish an accurate mathematical model. In this design, the

Table 1. Fuzzy Rules Table of Fuzzy Adaptive Mechanism

U		*EC*						
		PB	*PM*	*PS*	*Z*	*NS*	*NM*	*NB*
E	*PB*	*g1(e)*	*g1(e)*	*g2(e)*	*g3(e)*	*0*	*0*	*0*
	PM	*g1(e)*	*g1(e)*	*g2(e)*	*g3(e)*	*0*	*0*	*g3(e)*
	PS	*g1(e)*	*g2(e)*	*g3(e)*	*0*	*0*	*g3(e)*	*g2(e)*
	Z	*g1(e)*	*g3(e)*	*0*	*0*	*0*	*g3(e)*	*g1(e)*
	NS	*g2(e)*	*g3(e)*	*0*	*0*	*g3(e)*	*g2(e)*	*g1(e)*
	NM	*g3(e)*	*0*	*0*	*g3(e)*	*g2(e)*	*g1(e)*	*g1(e)*
	NB	*0*	*0*	*0*	*g3(e)*	*g2(e)*	*g1(e)*	*g1(e)*

Table 2. Fuzzy Self-Adaptive Mechanism Fuzzy Query Table

f		ec												
		-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6
	-6	1	1	0.93	0.82	0.66	0.46	0.38	0	0	0.3	0.3	0.3	0.3
	-5	1	1	0.9	0.81	0.65	0.45	0.37	0	0	0.3	0.3	0.3	0.3
	-4	0.97	0.95	0.87	0.77	0.62	0.44	0.36	0	0.1	0.32	0.35	0.38	0.4
e	-3	0.96	0.91	0.85	0.67	0.53	0.41	0.35	0	0.1	0.34	0.38	0.4	0.43
	-2	0.92	0.83	0.71	0.58	0.5	0.36	0.34	0	0.3	0.36	0.41	0.46	0.53
	-1	0.86	0.77	0.66	0.48	0.35	0.3	0.3	0	0.3	0.38	0.47	0.51	0.6
	0	0.8	0.67	0.5	0.4	0.3	0	0	0	0.3	0.4	0.5	0.67	0.8
	1	0.6	0.51	0.47	0.38	0.3	0	0.3	0.3	0.35	0.48	0.66	0.77	0.86
	2	0.53	0.46	0.41	0.36	0.3	0	0.34	0.36	0.5	0.58	0.71	0.83	0.92
	3	0.43	0.4	0.38	0.34	0.1	0	0.35	0.41	0.53	0.67	0.85	0.91	0.96
	4	0.4	0.38	0.35	0.32	0.1	0	0.36	0.44	0.62	0.77	0.87	0.95	0.97
	5	0.3	0.3	0.3	0.3	0	0	0.37	0.45	0.65	0.81	0.9	1	1
	6	0.3	0.3	0.3	0.3	0	0	0.38	0.46	0.66	0.82	0.93	1	1

adaptive mechanism uses the fuzzy inference method of the post – part as the function form. This method cannot be compiled directly with a Matlab fuzzy editor. The value of Table 2 needs to be filled in the two-dimensional table Look-Up Table (2-D). At the same time, the Matlab Function dialog box is changed to four to five into the round function. The feedback fuzzy controller uses the incremental signal as the output, and then outputs the output to the controlled object. This is equivalent to the introduction of integral action, which is beneficial to eliminate static deviation.

4. RESULT ANALYSIS AND DISCUSSION

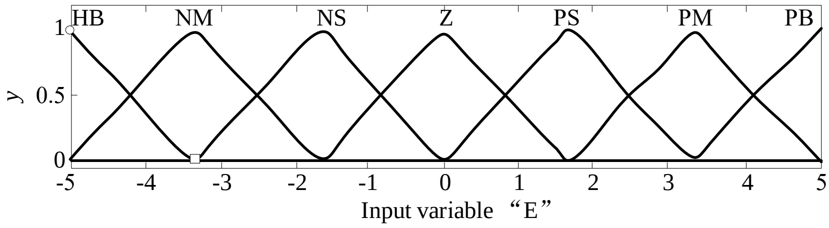
4.1. Research on Fuzzy Feedback Controller

The input / output variable of the feedback controller is determined. In this design, the feedback controller is a two dimensional fuzzy controller, which is the dual input output mode. The input variable is the illumination deviation *e* and the deviation rate e_c. This method can not only guarantee the stability of the control system, but also reduce the overshoot and concussion.

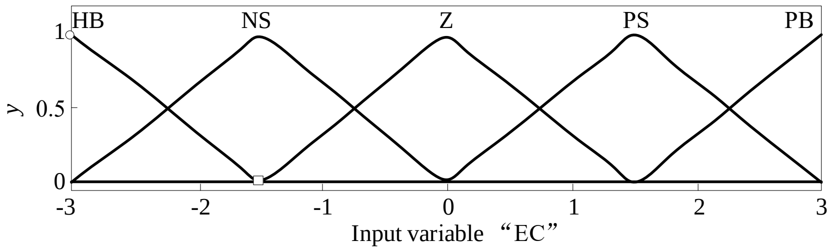
For the determination of membership function of input / output *M*, the function of *Li* is a fuzzy set, which should be applied to practical problems. In this system, the common triangle membership function is used, and the Matlab fuzzy toolbox graphic interface is used to determine the function editor. For example, Fig. 6.

The domain of the input variable is used for this fuzzy controller for the selection of the domain and factor of the input / output variable. According to the experience of the expert, if the value of the system deviation *e* is greater than 20 lx, it should be "PB" for the maximum value of the language. The value of *e* is less than equal to –20 lx, which is "NB". Therefore, the domain of the deviation *e* is [–20, 20], and the fuzzy set domain is [–5, 5]. The value of the quantizing factor *Ke* is 0.25. It is worth noting that the domain of the deviation *e* of the input variable of the fuzzy controller is not equal to the range of the deviation in the system operation. In actual control, a limiter should be added to ensure that the error value is within the allowable range.

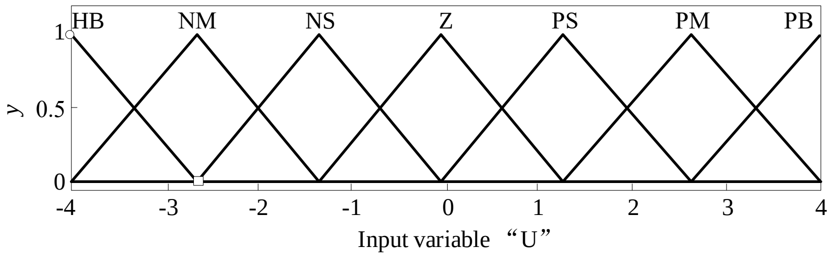
In the same way, the domain and its factors of the controller output and error change can be determined. According to the illuminance standard of China's civil building lighting design standard and international vision ergonomics indoor lighting system, 420 lx is used as the standard illumination value, and the illumination area of luminaire is set to [300, 500]. Therefore, the ratio factor *Ku* of the



(a) The membership function of illuminance deviation E



(b) The membership function of the variation rate of illuminance EC



(c) The membership function of the incremental U of the controlled system

Fig.6. The subordinate function of the fuzzy controller

controller output should be 5. And the error changes need to be set according to the actual needs, *Kec*=0.01 in this controller.

In actual control, the continuous domain needs to be discretized. For example, the fuzzy set theory domain of the error *e* is divided into 7 grades. Each level corresponds to a fuzzy subset. That is, {–5, –4, –3, –2, –1, 0, 1, 2, 3, 4, 5} respectively (NB, NM, NS, ZO, PS, PM,). Then determine the membership degree of the element in the domain on the fuzzy language variable.

The fuzzy control rule is the core of fuzzy controller for the determination of the fuzzy control rule table and the descendant table, reflecting the knowledge collection of a particular control problem, such as offset. When making fuzzy rules, the following requirements should be met: intuitively, fuzzy control models should always be able to get a proper control for every process state reasoning. This feature is called "completeness". It means you can't get out of control. For the number of fuzzy control rules, if the input of fuzzy controller is *m*, the fuzzy classification number of each input is *n1, n2,…, nm*, respectively. The maximum possible fuzzy rule number is N_{max}= *n1n2… nm*. How much the actual fuzzy control number should be determined depends on many factors. The general principle is that, under the condition of completeness, the number of rules is taken as much as possible so as to simplify the design and implementation of the fuzzy controller. For the consistency of fuzzy control rules, fuzzy control rules are mainly based on the experience of the operator, depending on the requirements for a variety of performance, and the requirements of different performance indicators are often mutually restrictive and even contradictory to each other. This requires the inconsistency of fuzzy control.

In the light control, the illuminance value of the light is mainly influenced by the external natural light. The natural light is high and the lamps in the classroom should be closed. Low natural illumination, room lamps and lanterns should be opened, and the standard value of illuminance is guaranteed. This is the work of the actual lighting control. According to the actual situation and the experience of artificial lighting control, the fuzzy control rule table can be obtained. In the results, *E, EC* and *U* are fuzzy language variables of illumination deviation *e*, deviation rate EC and output cancellation *u*.

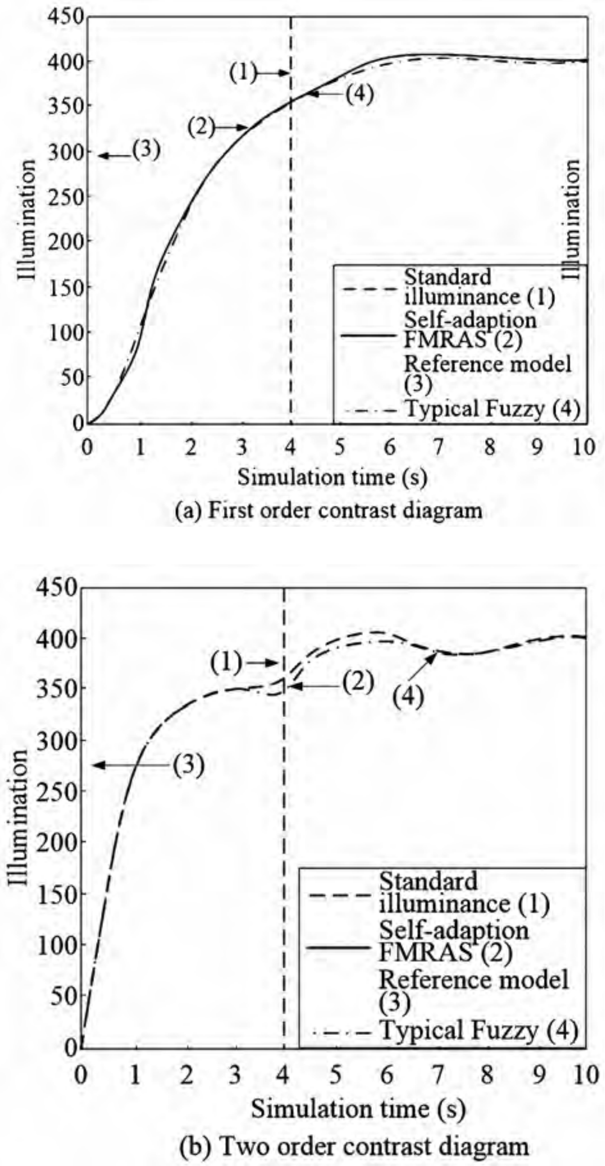


Fig.7. Improved adaptive simulation results

This table represents the control rules: if (*e* is *NB*) and (*ec is NB*) then (*U* is *PB*).

In practical use, the results are converted into a fuzzy control response table. By using fuzzy logic control method, all input languages are changed into *M* (*e*, *ec*), and the tables generated by the fuzzy controller of each state are calculated by quantized offline combinations, putting it in the form of "file" into the computer. When real-time control is carried out, the control strategy is querying from the "file" according to the input information. The fuzzy reasoning method is as follows: first, the fuzzy relation *R* is got, and then the synthetic inference method is used to get the fuzzy output, according to the input deviation and the rate of deviation change. Finally, the fuzzy quantity is transformed into the exact quantity after the anti fuzzification. In this case, the design of the fuzzy feedback controller is basically completed.

4.2. Results and Analysis of Simulation

After setting the simulation step and so on, the simulation can be carried out. To verify the progressiveness and experimentation of the improved model, the simulation is compared with the classic fuzzy control and the improved adaptive FMRAS. And the control rules of the input / output variables are guaranteed, and the quantitative factors are the same. The simulation results are shown in Fig.7. Among them, Fig. 7 (a) is the result of the performance comparison between the improved adaptive FMRAS and the classical fuzzy control under the first order system, (b) is a simulation result of the performance comparison between the improved adaptive FMRAS and the classical fuzzy control under the two order system.

From the results, we can see that adaptive FMRAS has better tracking performance, higher steady-state accuracy, smaller overshoot and higher response speed than the typical fuzzy controllers currently used, which can guarantee the requirement of classroom illumination and achieve the design goal.

5. CONCLUSION

The intelligent lighting control system of college classrooms is an important way to save energy in colleges and universities. Zigbee technology, embedded ARM technology, sensor technology and other lighting systems were combined. The intelligent lighting control system of college classrooms based on Zigbee was designed, relying on illuminance sensor, vibration sensor and human body infrared sensor to automatically collect information such as illuminance, usage state, number and location of personnel. And the modified adaptive FMRAS (Fuzzy Model Reference Learning Control) control model was used for fusion analysis, and the PWM code was automatically generated for intelligent controls lamps and lanterns. On the premise of meeting the national standard of illuminance, the purpose of saving energy was achieved. Considering the convenience of management and friendly man-machine interaction principle, LCD display and monitoring management system were attached to facilitate monitoring and viewing of managers, teachers and students. The function of making lamps and lanterns achieve standard illumination automatically was realized, quickly and stably based on indoor personnel location, natural illumination and classroom usage state. At the same time, the service life of the lamps and lanterns was prolonged, the workload of wiring was reduced, and the purpose of energy saving was achieved.

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SENCITY – EVALUATING USERS' EXPERIENCES OF INTELLIGENT LIGHTING FOR WELL-BEING IN SMART CITIES*

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ABSTRACT

This paper presents the evaluation of users' experiences in three intelligent lighting pilots in Finland. Two of the case studies are related to the use of intelligent lighting in different kinds of traffic areas, having emphasis on aspects of visibility, traffic and movement safety, and sense of security. The last case study presents a more complex view to the experience of intelligent lighting in smart city contexts. The evaluation methods, tailored to each pilot context, include questionnaires, an urban dashboard, in-situ interviews and observations, evaluation probes, and system data analyses. The applicability of the selected and tested methods is discussed reflecting the process and achieved results.

Keywords: evaluation, intelligent lighting, method, smart lighting, user experience

I. INTRODUCTION

Applications of intelligent or smart lighting will be spreading in the near future to various types of urban context. If designed wisely, smart lighting can, besides energy savings, offer added value for urban environments on various levels of experience [1]. However, as the implementations are still rather rare and recent, there is a lack of knowledge on user's experiences to support design processes. Thus, in our research and development, we aim to increase understanding of user's multifaceted experience of intelligent lighting and of the methods for evaluating it.

1.1. SenCity Project

SenCity – Intelligent Lighting as a Service Platform for Innovative Cities is a national research and development project between Finnish cities, companies and research partners [2]. The project aims at employing lighting infrastructure as a service platform – an IoT (Internet of Things) backbone – for smart lighting solutions and innovative, user-oriented services in urban environments. The project develops intelligent LED lighting pilots in the participating cities, to which the companies involved develop solutions to better respond to the cities' needs. The research partners integrate the project together through the design of pilot contents and realization, user experience evaluation and technical development and testing.

The project pilots smart lighting solutions in six Finnish cities in different kinds of urban environments. The research focus is dual: to study user needs and experiences of smart solutions, and to develop and test technology needed for such solutions. Together, separate pilots in different cities around Finland create a living lab ecosystem for developing and testing innovative solutions. Each pilot has a focus in a different theme or application con-

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text. The themes include interactive and communicative lighting and digital services; traffic safety in a residential area; smart lighting and services for kids and young people; and presence-based lighting in bicycle routes and road environments. The pilots are realized in 2016–2018. As the pilots have varying research focuses and contexts, the SenCity project provides an excellent opportunity to test different kind of evaluation methods in real world contexts.

1.2. Aims and Content

In the paper, three pilot case studies are introduced presenting objectives, contexts, smart lighting applications, and methods that are used in evaluation of users' experiences. The evaluation methods, which are tailored to each pilot context, include questionnaires, in-situ interviews and observations, evaluation probes, and system data analyses. The applicability of the selected and tested methods to each pilot and its specific context, research target, and user group is discussed reflecting the process and achieved results.

2. EVALUATION OF INTELLIGENT LIGHTING IN URBAN CONTEXTS – PREVIOUS RESEACH ON USERS' EXPERIENCES

There has not yet been wide research of the experience of intelligent lighting in real-world urban contexts, as the lighting solutions are internationally still in the process of development and piloting. However, some previous research exists and some examples can be mentioned here. The research concerning experiences of adaptive and intelligent urban lighting has covered aspects of safety [3,4], social experiences [5, 6, 7] meanings, and [6, 7] atmosphere and aesthetic experience [5, 6], participation [6], and communication [7]. Most of those aforementioned aspects have also been relevant in experiences of media architecture and described, for example, in [8] and [9]. The evaluation methods that have been used, include, for example, a psychophysical method based on questionnaires [3], and semi-structured interviews and observation [6].

Our previous research has related to understanding of the multifaceted and emplaced experiences of adaptive and intelligent urban lighting, covering all the aforementioned aspects [1, 10]. In our real-world studies in park and streetscape environments, we have applied qualitative methods inspired by ethnographic research. These include the experience gauging walking interview method, which means in situ participant observations coupled with a semi-structured walking interview [1,10]. Besides this, we have applied semi-structured interviews and questionnaires in electronic and printed form [11].

3. EXPERIENCE EVALUATION IN THE *SENCITY* PILOTS

In this section, we describe the arrangement and evaluation procedures and methods of three pilot projects, and in the next one, the methods are reflected and discussed. Two of the case studies are related to the use of intelligent lighting in different kinds of traffic areas, having emphasis on aspects of visibility, traffic and movement safety, and sense of security. The last case study presents a more complex view to the issue of intelligent lighting in smart city contexts: How lighting can serve citizens on various levels of experience and what kind of digital services can lighting infrastructure provide for the users? The *SenCity* project is still on-going and all of the evaluation processes are not yet finished. Thus, the presentation and discussion of methods is based to some extent still on evaluation plans.

3.1. Case Study 1: Intelligent Road Lighting in a Housing Area, Salo

The first case study concerns an intelligent lighting pilot in a housing area in Salo, where presence sensitive roadway lighting, adapting both to the motor vehicles using the road and to the measured traffic density along it, was tested. Users' experiences of the lighting have been collected with the help of questionnaires from the community of about 1000 households using the road in their daily traffic as well as from other interested inhabitants of the city. The evaluation was accomplished in three parts. These were connected with different phases in the development of the lighting system, the publicity of the project, and how much information was published about it.

In the first phase (23.1.–5.2.2017), the new lighting was controlled in a very basic way (*Daylight level based control*): during the bright period of the day, lights were turned off, and during the dark period, they were on at 100 % control level. The sensor detected the threshold illuminance level and turned lights on and off automatically. During the second phase (6.2.–26.2.), this basic control continued but a *presence-based dynamic control* was added. The lighting was controlled dynamically so that it was always brightened around a car to the maximum control level of 100 %, and in those parts of the road where the traffic was absent, it was dimmed down to 20 % control level. The dimming and brightening was done softly using 3 seconds ramp. The bright area around a car consisted of five streetlights: the one which detected the car with PIR (passive infrared) sensor and two forward and two backward. In the third phase (lighting control from 6.3. onward, questionnaire 19.6.–2.7.), a third control method was introduced along the two former ones, based on the *measurement of traffic density*. Now the lower control level of lighting was adapting to the amount of traffic detected along the route. When the traffic was dense, for example, during the commutation periods in the morning and in the evening, the control level of lighting was dropped to 70 % on those parts of the road were there was no traffic. With the moderate traffic, the level was 40 %, and with the lowest traffic during the night, it was 20 %.

In the first and in the second phase, the questionnaires used were almost identical. Before answering to the questions, the participants were asked to drive the road with test lighting on during the dark period of the day. There was no sidewalk on the side of the collector road, so we were not able to gain feedback from walkers and cyclists. We asked about the answerers' use of the road and conditions on it during the driving when they evaluated lighting, as the background information. Other questions concerned overall impression of lighting; colour of lighting; amount of lighting on the road surface and on the environment; evenness of lighting; and glare. The participants were also asked how well they could see the roadway and other people moving on the road or in the environment. They could also comment what good was in the lighting, and whether there was something that bothered them in it. In addition, they were asked if they had noticed any changes in the lighting during different times of the day or during driving the test route. The people answering to the second questionnaire were asked whether they had noticed any change in lighting after the first questionnaire. Most of the questions were based on rating on a scale of 0 to 5 and with a possibility to comment freely the subject in question.

During the first two phases, the participants were not given any information about the new lighting in the area except that it was realized with LEDs and that the control of lighting was developed during the winter and spring. In the first two phases, we wanted to gain feedback of the genuine experiences on site, unaffected by any previous knowledge. In the third phase, our approach was totally different: the participants were given detailed information of the three different control methods of lighting that had been tested. At this phase, we were more interested in the participants' *attitudes* towards lighting in general and especially towards intelligent lighting and the three tested control methods. The influence of the shared information on users' experiences, attitudes, and values was also interesting to us. At this phase, the participants were not specifically asked to visit and observe the lighting on site. During the third questionnaire, outdoor lights were completely turned off except for a couple of hours in the dead of night, because of the long daylit periods in northern latitudes during the summer months.

For information sharing needs we had designed and developed a test version of an urban dashboard – the City Monitor for Salo [12]. In the dashboard web page, dynamic visualization of the lighting behaviour, scalable charts illustrating the average lighting and energy consumption levels, and textual descriptions of each lighting control type were presented (http://sencity.cloudapp.net:8888/). The visualization of adaptive lighting behaviour was realized in the form of a dynamic light map, presented on the aerial photograph of the housing area with dynamically altering illustrations of light distribution along the routes. The interface was interactive so that the users could themselves change between different control methods and zoom to different time spans of the chosen date. The PIR sensor data of a single date (8.2.) was used for simulating lighting behaviour with the three different control methods, allowing comparison of the energy consumption [12]. The third questionnaire, both in a electronic version and a printed one, contained the same information but in picture and textual mode, without interactive and dynamic simulations.

3.2. Case Study 2: Presence-Based Lighting on a Light-Traffic Route, Helsinki

The second case study concerns evaluation of presence-based lighting on a light-traffic route in Siltasaari housing area in Helsinki. In this still on-going pilot, the target is to find out what kind of a detailed lighting behaviour is suitable for presence-based lighting on routes used by pedestrians and cyclists. The aim is to design and test an optimal lighting behaviour, which saves substantial amounts of energy without lessening traffic or moving safety, or the sense of security of route users during the dark. The piloted intelligent system has the ability of detecting the direction of movement of route users. Thus, the lighting control can be adapted to this information so that the lighting is brightened further ahead a walker or a cyclist than behind.

In the evaluation, two well-designed presence-based lighting behaviours will be tested and compared. The one will be designed to be perceptible by route users and the other to be imperceptible by them, changing the distance how far ahead the route users the lighting is brightened. Lighting will be dimmed to 20 % control level in those parts of the route, where no-one is moving, and brightened to 100 % control level around the route users. The brightening and dimming is done softly. Feedback of the experiences will be collected on site with the help of a questionnaire and a short, structured interview. In addition, questionnaires will be delivered to the apartments near the route, which have a view towards it, in order to find out how presence-based lighting is experienced from the interiors. For example, can dynamic changes in lighting cause disturbance to the inhabitants?

We conducted a preliminary evaluation in order to test our method, during two nights in the beginning of April 2017. We had invited participants from educational institutions for young adults around the test site. Altogether we had ten participants, two of them being primary school and high school aged children, who came with their parents. The evaluation protocol was arranged so that we had three interviewers with questionnaires, standing in the meeting point that was located in the mid-point of the route. First, we had a short introductory discussion with each participant, where we collected the background information. After that, each participant was asked first to walk to the one end of the test route and back. At this point, the first interview and filling of questionnaire was done. Then a participant walked to the other end of the route and came back for the second part of the interview and questionnaire. Each participant was walking and interviewed alone. The lighting control was designed so, that in the other half of the route, the brightened area in front of a walker was longer than in the second half of the route, and respectively, the first type of lighting behaviour intended to be imperceptible and the second type intended to be perceptible. The evaluation was conducted from 9 pm to 10 pm, when there was not many other users of the route and it was dark enough outdoors.

The questions after each lighting type concerned the general impression of lighting; amount of lighting; possible sensations of glare; visibility of the surface of the route; visibility of other people; and visibility of surrounding environment. There was also two questions regarding safety: one on the safety of movement and the other on the feeling of safety. Most of the questions were asked based on rating on a scale of 0 to 5 and with a possibility to add comments of the subject in question. The participants were also asked what was good about the lighting and whether there was something about the lighting that bothered them. Finally, they were asked if the lighting changed in any way as they were moving along the route, and if it did so in their opinion, they were asked to describe it and tell at which point they noticed something.

3.3. Case Study 3: Intelligent lighting with services in the Harbour Promenade, Lahti

In Lahti, a lake harbour promenade is being developed into an active recreational environment for citizens through introducing there intelligent lighting and new digital services. The 1.5 km long pedestrian route spans from the Sibelius music Hall in the main harbour area towards Sports and Fair Centre in the other end. The area has an interesting history with an important inland harbour, rail traffic, and industry.

The new, intelligent lighting for the area was devised with the help of a user-centric design and development process with city representatives, business partners, researchers, and users of the area. For the process and participatory methods, see [13]. The process is still on-going as the development of the area and its lighting is continuing.

TABLE I. Analysis of Evaluation Case Studies

Case Study	Analysis of Evaluation Case Studies				
	Context & Experience Aspects	**Methods**	**Successes**	**Challenges**	**Development Ideas**
1	**Roadway:** – Visual impression – Lighting quality – Visibility – Perceptibility of lighting behaviour – Traffic safety – Attitudes & values – Acceptance	- Electronic and printed questionnaire – Rating scales and open questions – Driving and observing real-world road with two lighting types – Urban dashboard for information sharing	- Good sample: Phase 1: 130 people Phase 2: 106 people Phase 3: 52 people – Motivated participants – Sharing of information was valued by the participants – Combination of rating scales and comments – Electronic and printed questionnaires	- Comparability of results weather conditions traffic density – Technology barrier with the urban dashboard and simulations	- Weather conditions more easy to control in the autumn – Observation time fixed to low traffic situation – Development of the dashboard according to the feedback
2	**Light traffic route:** – Visual impression – Lighting quality – Visibility – Movement safety – Sense of safety – Disturbance	- Interview with questionnaire on site – Comparison of two lighting types in different parts of the route – Question- naires delivered into nearby apartments	- Combination of rating scales and comments – Motivated participants – Good timing in the late evening	- Attracting enough participants for a good sample, in the test evaluation 10 participants – Influence of a different context on the experience – Real-world challenges of the sensor technology: wind and vegetation – Perceptibility of lighting behaviour	- Co-operation with local schools and senior service centre, different age groups (teachers, pupils, parents, seniors) – The same test route for all lighting types
3	**Harbour Promenade**: – Interaction and participation – Communication and information – Social experience – Atmosphere – Movement safety – Sense of safety	- Semi-structured interview and observation on site, experience gauging – Evaluation probes – System data analysis – Questionnaire for service users	**Participation process and evaluation of history augmentation:** – Motivated participants – Contextual knowledge and ideas	- Complex real-world environment and experiences – Technological challenges of the pilot	- Utilizing urban dashboard in information sharing and evaluation

In the final design, smart lighting is employed, besides for creating energy-efficient and safe environment with good visibility, for activating and engaging, artistically communicative and informative purposes. Four sub-areas of design area with different kinds of characters were recognized, and supporting lighting and service concepts for them were designed: an active event promenade by the harbour; a historical rail track promenade in between two lakes; a dangerous crossing area of a busy road; and the backyard-type of area with small-scale industry in the vicinity of the sports and fair centre. The final solution combines evenly distributed neutral white LED lighting, which is dimmed when no one is moving along the route, with an atmospheric play of dynamically controlled light dots on the path, capable of having colours, for example, for communicative purposes or seasonal themes.

The lighting infrastructure will be a combination of intelligent LED route lighting with PIR sensors, and effect lighting by RGBW LED spotlights and DMX control. Additionally, base stations for a free WiFi connection, web-cameras, loudspeakers, and assembly spaces for extra sensors will be integrated in the smart, wooden lighting poles. Thus, the ensemble will form a development platform for smart city services. The first phase of the project will be finished by the autumn 2017 and the rest during the year 2018. The participation process will continue in the autumn 2017 with a questionnaire about the needs and ideas for using the intelligent lighting system for digital services.

A history augmentation application was piloted and evaluated with users in November 2016, as the idea of presenting information about the history of the area through a service came up in the participation process. The evaluation was conducted with a testing session with a semi-structured interview and observation on site. When the lighting design will be realized and applied in services, for example in a light game application and in communicative purposes, further evaluation of experiences will be conducted. A suitable method could be, besides interviewing and observing on site, the *evaluation probes* method [14], which we have developed in our earlier research. It is inspired by *cultural probes* methodology [15], which was already applied in the user-centric design process of the lighting [13].

4. REFLECTION OF THE EVALUATION METHODS

In the Table 1, we have summarized a reflection of evaluation processes of the case studies, from the following viewpoints: 1) perspectives of experience aspects that are of specific interest, 2) evaluation methods, 3) successes we encountered, 4) challenges or problems detected, and 5) further ideas for development of methods.

The case study evaluations, the preliminary and the final ones, have been successful in many ways and provided us with interesting research material. Additionally, the challenges have aided us to develop the methods. In the case 1, *involving a community* with a close contact to the research area helped us to gain an excellent sample of answers from motivated participants. In the case 3 as well, we have already a group of participants who have been involved in user-centric design process. With case 2, we can expect challenges in attracting enough participants for a good sample, especially if we want to interview both walkers and cyclists. Community-oriented approach with co-operation with neighbouring schools and the local senior service centre will be applied.

Real-world studies are challenging due to the *complexity of environments and experiences,* which makes the research environment and situations not easily controllable. According to our experience, qualitative research methods are usually well suited to them as they are robust. Thus, with case 3, the plan is to apply a *combination of qualitative methods.* Evaluation probes [14] let the participants experience the site and give feedback in their own time without a presence of a researcher. On the other hand, interview and observation on site, in a form of experience gauging walking interview [1,10], can as a more interactive method reveal other aspects of experience. However, in the cases 1 and 2, we are also targeting to get some quantifiable data and large enough sample for analysis. For that purpose, the *free-form comments supported well the rating scales* and were essential in some parts in *interpretation of results* as the numbers only could easily have been misinterpreted. This was the situation with the case 2, where we realized from the comments that differences in the two parts of the route were influencing more the answers than the differences in lighting. This notion has led us to adjust our research protocol.

Using both *printed and electronic questionnaire* proved to be a good solution as it enabled participants of *different age and technological abilities* to take part. In the case 1, the *sharing of information* about intelligent lighting solutions was appreciated by many participants and they gave positive feedback of the interesting study and the ability to participate in the development of lighting in their city. Even though the shared information was valued, there was also some critical comments of the dashboard details and some feedback that it did not work. The *risk of technology barrier* and *usability issues* should be solved in further development. Nevertheless, this kind of *bidirectional learning process* is essential in participatory design and research and a good way to engage people in studies and in developing their communities.

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EFFECTIVE RADIANT FLUX FOR NON-IMAGE FORMING EFFECTS – IS THE ILLUMINANCE AND THE MELANOPIC IRRADIANCE AT THE EYE REALLY THE RIGHT MEASURE?*

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ABSTRACT

Research indicates that intrinsically photosensitive Retinal Ganglion Cells are not evenly distributed or evenly sensitive throughout the retina. Still, most research looking into non-image forming (NIF) effects uses an integral measured quantity, illuminance or melanopic weighted irradiance, to represent the amount of light at the participants' eye level. This paper describes a theoretical approach to define the effective radiant flux for stimulating the ipRGCs, taking into account a spatially resolved sensitivity. Research on retinal sensitivity is scares and not yet substantial, but the methodology can easily be adopted when areas of specific sensitivity are set. Preliminary results indicate that, with similar vertical illuminances and spectral power distribution, typical office lighting solutions might have a lower NIF effectiveness than settings with higher luminances in the central part of the field of view. This could explain why research on NIF effects is inconclusive, even though reported lighting conditions are similar.

Keywords: inferior light exposure, nasal light exposure, NIF effects, office lighting, retinal sensitivity

I. INTRODUCTION

Since the discovery of the intrinsically photosensitive Retinal Ganglion Cells (ipRGCs) in 2002, non-visual effects or non-image forming (NIF) effects of light have become increasingly important in lighting research, development and design of lighting solutions. In this, lighting is, for example, used to increase alertness or sleep quality, to reduce desynchronization of the circadian rhythm or to treat seasonal affective disorders. The majority of the research looks into dependencies of amount, spectral power distribution, length and temporal distribution of light stimuli. Not in focus but also of interest seems to be the dependency on directionality and position of the light source, as only a small number (less than 1 %) of the retinal Ganglion Cells are photosensitive [1], and they are not evenly distributed throughout the retina (review in [2]).

Only a few publications on the impact of spatial light distribution include the description of lighting conditions in the experimental set-up. The majority of these studies were conducted between 1992 and 2005 (review in [3]). The offered lighting conditions differed greatly from one study to another. They ranged from 5 to 1000 lx, vertical illuminance at eye level, with varying colour temperature from warm white to cool white, realized by polychromatic light sources; fluorescent lamps, halogen lamps or LEDs. Partial retinal exposure was realised by using light boxes at defined positions in the field of view, or applying modified eye shields on subjects looking into a uniformly lit half dome. All studies took place at night time, sometime between 22:00 and 3:30. The lighting conditions were offered for

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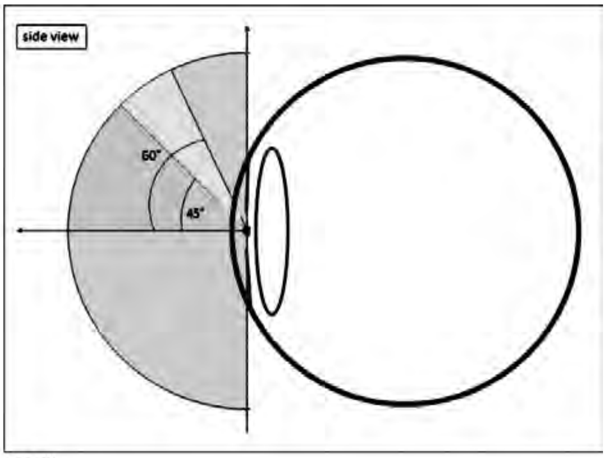


Fig.1. Approximation of spatial sensitivity due to ipRGC density or sensitivity as found in a small number of studies based on [16] with areas of “little” (yellow) and “good” (green) response to induce NIF effects

60–240 minutes and melatonin suppression was used to study the impact of light source size and / or position. The number of participants per study ranged from 6 to 32, with varying age.

The studies suggest that large sources are more effective than small sources [4]. Binocular light exposure realises a higher melatonin suppression than monocular light exposure (spatial summation in [5, 6]). Additionally to that, the studies indicate that, in human beings, nasal exposure is more effective than temporal exposure [7, 8]. Inferior retinal light exposure seems to induce a greater response than superior exposure [9, 11]. Piazena et al. partly confirmed these findings [12]. Superior warm white light exposure (800 lx, 2666 K) resulted in the reduced and delayed melatonin suppression in comparison to inferior exposure realising the same lighting level at the eye. However, similar cool white light levels (6060 K) caused comparable NIF responses for both inferior and superior light exposure.

Considering the above mentioned, it is questionable if illuminance levels or melanopic irradiance levels, currently referred to in studies with respect to NIF effects of light, are adequate parameters in terms of comparability, being integrally measured values of the full visual field. Retinal illuminance would respect human anatomic restrictions [13], and can be measured with adjusted illuminance sensors (e.g. [14, 15]). Nonetheless, a more distinct subdivision within the human field of view might be required. The number of studies is too small to define areas with different ipRGC sensitivities. Despite this, the suggestion for approximation areas of “no”, “little” and “good” effectiveness is given by FGL (Fördergemeinschaft Gutes Licht, 2014), Fig. 1, [16].

The aim of the presented study is to look into the range of the spatially resolved, effective radiant flux stimulating the ipRGCs for different distribution of the incident light under a constant (full visual field) illuminance level at the eye.

2. METHODOLOGY

The study described in this paper uses a theoretical approach to evaluate the impact of higher sensitivity for nasal and inferior light exposure. For this, a methodology to evaluate the spatially resolved illuminance contribution of defined areas in the field of view to the overall vertical illuminance at the eye was defined. Luminance images are converted into matrices containing luminance values for each pixel. Using another matrix that holds the opening angle ω_s and an additional matrix with the tilt angle ϑ of each pixel, it is possible to calculate the illuminance contributions. Generally, the following equation applies:

$$E_p = \int L(\vartheta,\varphi)\cos(\theta)d\omega_s, \quad (1)$$

where E_p is the illuminance, L is the luminance of each pixel, which position is determined by θ, φ, ω_s solid angle, ϑ is the tilt angle.

The resulting matrix comprises the illuminance contribution of each pixel to the integral vertical illuminance. Hence it is possible to define regions of interest in the field of view and to calculate the illuminance at eye-level caused by each region.

2.1. Test Room

A complete LED backlit test room with typical cell-office dimensions (5 m width, 4 m length and 2.8 m height) at the Chair of Lighting Technology of TU Berlin was used for this study. This test room is equipped with 1470 individually addressable LED panels with a size of 18 × 18 cm, covered by a diffusing material. Each panel holds 36 mid-power, cool white or warm white LEDs. The correlated colour temperature (CCT) of the LED panels behind the diffusing material was measured with a ‘Specbos 1201’ spectrometer by Jeti Technical Instruments. The cool white setting has approx-

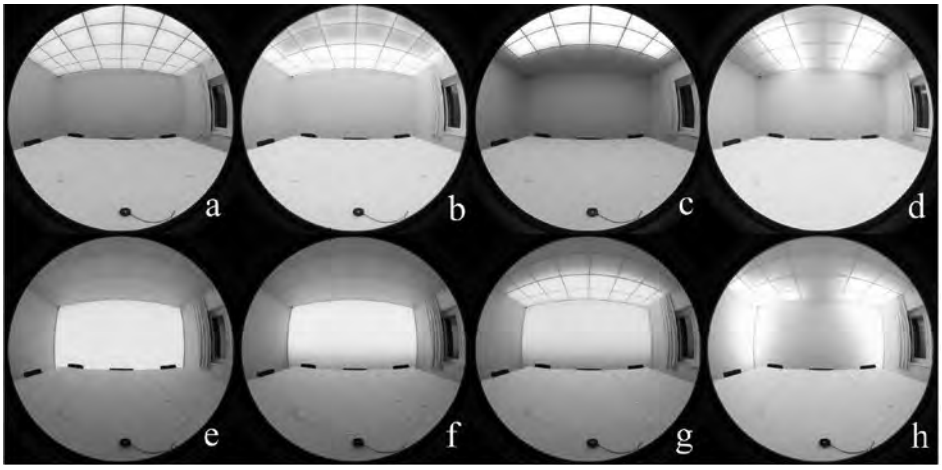


Fig.2. Lighting scenes (a – d typical office like; e – f non-typical like)

imately 5900 K, the warm white setting 2800 K. Mixed settings have 4400 to 4500 K, depending on the used lighting scenes. The cool and warm white LED panels are arranged in a checkerboard pattern to ensure good uniformity and mixing characteristics if used together as well as separately. With this installation, it is possible to set specific luminance distributions for separate fields of the walls and ceiling with different CCTs. Twelve luminaires in the middle part of the ceiling are designed to optimise NIF effects; offering a range between 2000–20000 K.

2.2. Settings

Within this study, eight different luminance distributions, some very similar to typical electric lighting solutions for offices, some very different, were set to realize a constant vertical illuminance of 500 lx (+/– 2.5 %) at eye level, Fig.2. This was measured at 1.20 m above floor level by a luxmeter MX-ELEKTRONIK Mini-Lux with a $V(\lambda)$- and cosine-corrected *Si*-photometer head. Additionally the horizontal illumination at 0.85 m, at a fixed position on the desk was measured with a cosine-corrected luxmeter LMT Pocket-Lux 2. CCT of the lighting scenes ranged from 3900 K to 4900 K.

2.3. Measurement and Processing

The variable in this study, the luminance distribution of the eight chosen scenes, was measured by a luminance camera ‘LMK mobile advanced’ based on a CANON EOS550D by TechnoTeam GmbH equipped with a 4.5 mm object lens (circular fisheye lens) with an angle of coverage of 140°. For each setting HDR luminance images were taken.

Based on the approximation of spatial sensitivity by FGL (Fördergemeinschaft Gutes Licht) (Fig. 1), and the anatomic restrictions (e.g. light shielded by

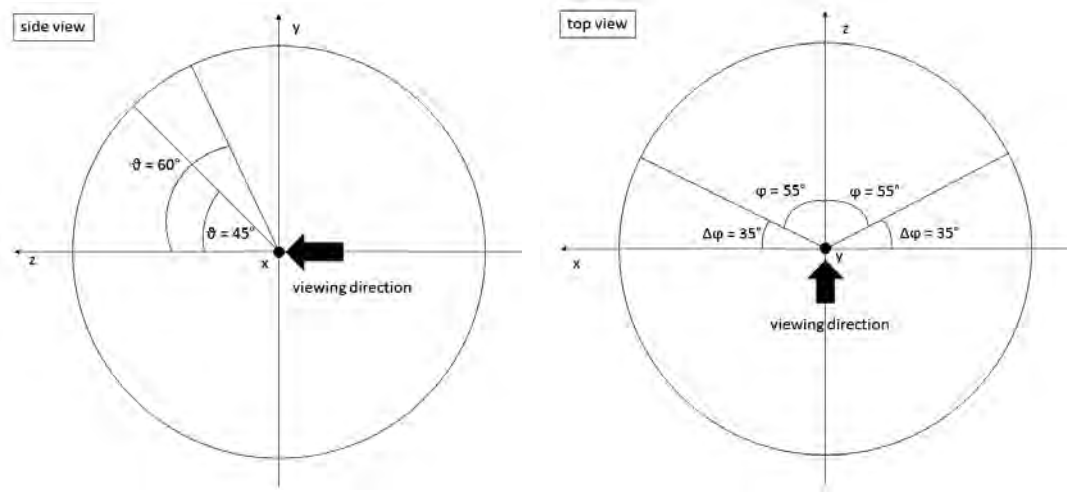


Fig. 3. Schematic of the angles in the visual field (based on [13] and [16])

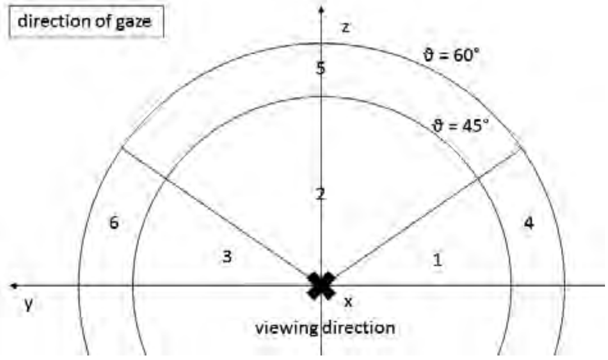


Fig.4. Overview of the region in the field of view

the nose), following areas of interest were chosen to demonstrate the potential and the consequences of a spatial differentiation (Fig. 3 and Fig. 4):

- ϑ = 0° to 45° and 45° to 60°
- φ = 0° to 55° and 0° to –55° (to both sides of the direction of gaze).

Light coming from region 1 (Fig. 4) illuminates only the nasal part of the right eye's retina. Light in region 2 causes illumination of the lower part of both retinas. Light from region 3 illuminates the nasal part of the left eye. These angles are believed to have a good impact on NIF effects, while angles between ϑ = 45° to 60° are supposed to have only weak effect and higher angles have no effect [16]. Moreover, region 2 is of special interest since the illumination of both retinas is found to cause the higher melatonin suppression [5, 6].

3. RESULTS

The methodology was applied to the eight lighting scenes shown in Fig. 2. For each region, the illuminance contribution was calculated. Table 1 holds this value represented as percentage of the measured vertical illuminance for better comparability. The lighting scenes with light mostly coming from the ceiling (a – d) show in general low values. The ϑ equal to (0–45)° region contributes only with 10 to 26 % to the integral illuminance. If ϑ=0°extended to 60° this increases up to 44 %. On the other hand, lighting scenes (e – h), with light mostly coming from the opposite wall, have relatively high values. The ϑ =0° to 45° region contributes with 35–51 %, in the extended ϑ =0° to 60° region up to 58 %. In case region 2 gets a higher weighting, taking the findings of Wang [5] and Brainard [6] into account, the differences between lighting scenes a – d and e – h become even larger.

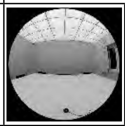
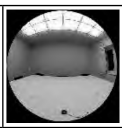
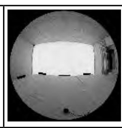
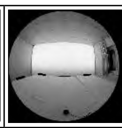
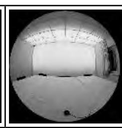
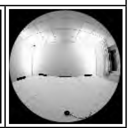
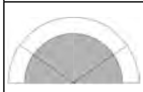
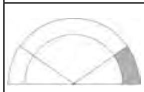
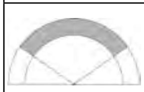
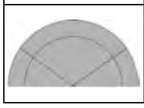
4. CONCLUSSION AND DISCUSSION

A luminance camera based evaluation method to determine the spatially resolved partial illuminance values was developed. Here regions were chosen to fit illumination of the lower left and right eye's nasal part of the retina and the illumination of the lower halves of both retinas simultaneously. Typical and non-typical office lighting scenes were investigated. Data showed that the more standard-like office lighting scenes cause only weak illumination of the defined regions. Logically, lighting of the opposite wall leads to much higher contributions from these regions. With comparable spectral power distribution and vertical illuminances, typical, electric, lighting solutions for offices will result in a lower efficiency to induce NIF effects than settings with higher vertical luminances in the central part of the field of view, such as day lit rooms or lighting solutions with wall washers.

It needs to be pointed out, that there are only few studies indicating differences in melatonin suppression if superior or inferior halves of the retina are illuminated and even fewer showing differences in nasal and temporal parts of the retina. For now, an exact determination of regions and their respective sensitivity weighting cannot be made. Furthermore, these studies were executed at night time looking into the resulting suppression of melatonin levels. Rüger et al. already showed that suppression of melatonin does not per se lead to reduced sleepiness when only parts of the retina are illuminated [17]. Additionally to that, these results are not directly applicable for daytime responses. During daytime, the mode of action for NIF effects is still not well enough understood. Cones, with their incidents mostly in the centre of the visual field, are considered to influence NIF effects as well [18]. Resulting, it could be that, at least under daytime conditions, the distribution and spectral sensitivity of more than one receptor has to be taken into account.

In this respect, this method is a theoretical approach. Nonetheless, it is an aspect of interest, as it could explain why some studies do find NIF effects, and others do not, even though vertical illuminances and spectral power distribution of the light sources applied are similar. In order to compare these studies and to allow future adjustments to areas of interests and their specific sensitivities, it is proposed to look into the representation that accounts for the

TABLE I. illuminance values

Regions		Lighting scenes							
									
		a	b	c	d	e	f	g	h
Illumi-nance	E_v [lx]	506	511	504	500	497	500	507	496
	E_h [lx] [a]	657	694	619	640	263	276	329	338
	E_v [%] [b]	2.8	3.2	2.0	2.8	9.5	10.6	7.5	8.5
	E_v [%] [b]	15.1	19.2	5.6	17.3	24.3	29.2	28.6	19.1
	E_v [%] [b]	2.8	3.1	1.9	2.6	9.9	11.1	7.7	7.3
	E_v [%] [b]	20.7	25.5	9.5	22.6	43.7	50.8	43.8	34.9
	E_v [%] [b]	1.5	1.7	1.0	1.3	1.2	1.3	1.5	2.1
	E_v [%] [b]	14.0	11.0	18.6	18.4	4.2	4.2	9.0	10.5
	E_v [%] [b]	1.5	1.7	0.8	1.2	1.6	1.6	1.8	5.4
	E_v [%] [b]	37.7	39.9	30.0	43.6	50.7	58.0	56.1	52.9

a. *horizontal Illuminance at 0.85 m*
b. *vertical Illuminance in percent of the luxmeter-measured value*

origin of light (e.g. by means of light incidence according to [19, 20].

Spectral power distribution was not considered in this study. Future research will look into spatially and spectrally resolved measurements, using a luminance camera that includes colorimetric filters and a melanopic filter, to evaluate the consequences of spatial sensitivity on NIF effects of typical lighting conditions with varying spectral power distributions in laboratory studies as well as field studies.

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RECEPTIVE FIELD MECHANISM AND PUPILLARY LIGHT REFLEX FOR THE ASSESSMENT OF VISUAL DISCOMFORT*

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ABSTRACT

Discomfort glare is defined as glare that causes discomfort without necessarily impairing the vision of objects. Traditional glare metrics fail for non-uniform luminaires. As an alternative, visual discomfort is determined by a physiological model incorporating the centre-surround receptive field mechanism and the pupillary light reflex. The pupil area, controlled by the pupillary light reflex, regulates the retinal illuminance. A centre-surround receptive field, described by a difference of Gaussians, represents the visual signal. The centre excites the signal whereas the surround controls the inhibition. A forced choice paired comparison experiment involves 7 non-uniform rear projected stimuli with different spatial frequencies. Inspired by a promising coefficient of determination of 0.90, the model is a candidate to replace current glare metrics as UGR or VCP, especially when non-uniform luminaires are to be evaluated.

Keywords: discomfort glare, luminance map, receptive fields

1. INTRODUCTION

Discomfort glare is defined by the International Commission on Illumination (CIE) in the international lighting vocabulary as: "glare that causes discomfort without necessarily impairing the vision of objects" [1]. Ever since the beginning of the previous century, researchers have been attempting to quantify the amount of visual discomfort [2]. A multitude of glare indices have been developed. The Unified Glare Rating (UGR) is proposed by the CIE for the assessment of discomfort glare for interior lighting and is included in the European standard for indoor workplace environment EN12464–1 [3, 4]. The International Engineering Society of North America (IES) proposed the VCP for the assessment of discomfort glare [5].

Traditional glare metrics often include an average luminance level calculated from the far field luminous intensity distribution [3, 5]. Any non-uniformity in luminance distribution is ignored. Since a non-uniform luminaire produces more discomfort glare than a uniform one of equal average luminance, the applicability of traditional glare metrics for non-uniform light sources is under discussion [6–12]. The non-uniformities of a luminance distribution are accurately described by a luminance map [13]. With a growing market share of highly non-uniform LED luminaires for interior and exterior lighting, a valid assessment of visual discomfort based on luminance maps becomes essential.

Although some mechanisms involved in glare perception are known, sometimes already for decades, traditional glare formula are merely phenomenological and lack any physiological or psychological justification. In the model presented in this paper, the receptive field concept is extended with the pupillary reflex for the calculation of visual discomfort.

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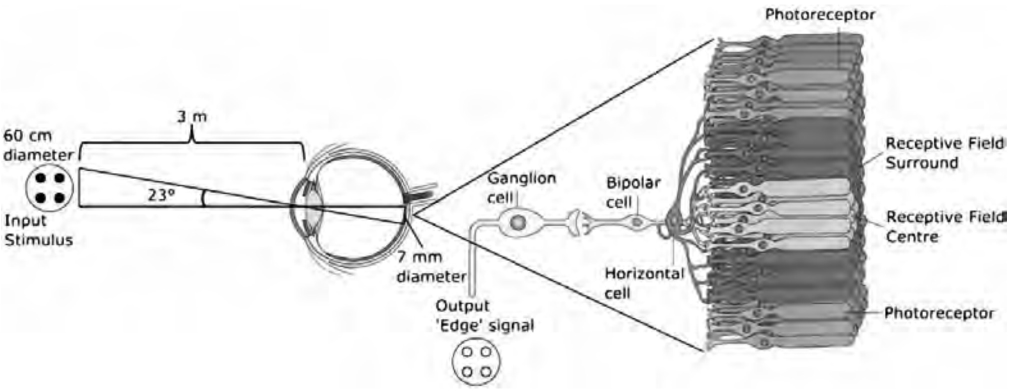

Fig.1. The human visual system includes the pupillary light reflex and receptive field mechanism

The pupillary light reflex controls the retinal illuminance as part of the adaptation process. Different formulas for the pupil size are developed [14]. Early formulas only include the luminance level of the stimulus [15–18]. Next to the luminance level, also the stimulus size is a determining factor [19, 20].

The receptive field neural pathways have been studied already from the 1930's on [21, 22]. By physically stimulating the retina of mammals and other animals, the neuron response is directly recorded [23, 24]. Patterns with different spatial frequencies invoke a neural stimulation [25, 26]. The computation of the neural stimulation forms a physiological basis for visual discomfort and is recently applied in lighting design [27].

In the present study, visual discomfort is calculated from a luminance distribution by applying a model including the receptive field mechanism and pupillary light reflex. The model is analysed with a forced choice paired comparison (PC) experiment involving 7 non-uniform rear projected stimuli with different spatial frequencies.

2. METHOD

2.1. Human Visual System

The human visual system includes several mechanisms (Fig. 1). The eye images an object plane characterized by a luminance distribution on the retina. The retinal illuminance is proportional to the pupil area, controlled by the pupillary light reflex, and the object luminance. In lit environments, a constriction of the iris reduces the pupil area and limits the incident light. In dimmed settings, an iris dilation increases the pupil aperture maximizing the retinal illuminance. The pupil size ranges approximately between 2 mm and 8 mm. In this paper, the pupil diameter is obtained from the average stimulus luminance level and the stimulus field size [19]:

$$D = 5 - 3\tanh\left(\frac{0.4\log(L_s a}{40^2}\right), \quad (1)$$

where D is the pupil diameter (mm), L_s the average stimulus luminance level (cd/m²), a is the stimulus field size (deg²).

The pupil area controls the retinal illuminance (E_{ret}) by scaling the luminance distribution (L, cd/m²). For direct view, the retinal illuminance can be approximated as:

$$E_{ret} \sim L\left(\frac{D}{2}\right)^2 \pi. \quad (2)$$

Seen from the back of the eye to the front, three retinal layers can be distinguished: the photoreceptors, the layers with the bipolar and horizontal cells and the ganglion cell layer. Under photopic conditions (Hunt, 1998), the cone photoreceptors convert the incident light into an electrical signal. Since photoreceptors are situated in the deepest retinal cell layer, nerve cells in other layers must be transparent. Centre photoreceptors link directly to a bipolar cell. The horizontal cells parallel to the retina connects several surround photoreceptors and also relay the signal to the bipolar cell in an indirect path. A bipolar cell in turn transfers the direct and indirect photoreceptor signal to a ganglion cell. The ganglion cell sends a pulsed signal train to the brain.

Combining the direct and indirect signals is resulting in centre-surround receptive fields formation. In an ON-centre OFF-surround receptive field, the ganglion signal is excited by the centre but inhibited by the surround signal and vice versa for an

OFF-centre ON-surround receptive field. Photoreceptors can be part of multiple centre and/or surround fields [22]. A receptive field is modelled by a difference of 2-dimensional Gaussian distributions. Subtracting a surround Gaussian from a centre Gaussian results in the total difference of Gaussians (DoG) receptive field pattern. When a single receptive field is uniformly illuminated, the net signal will be marginal. At a sharp dark-light edge where the surround is not entirely illuminated, the centre is not maximally supressed. A receptive field consequently acts as an edge filter (Fig. 2).

A luminaire can be represented by a luminance map. To each pixel of a high definition luminance map, a luminance value and spatial coordinate in the luminaire can be attributed. A centre-surround receptive field is modelled by a Mexican hat shaped difference of Gaussians (DoG), Fig.3. The difference between the maximum centre signal and maximum surround signal is reflected in the weighing factor (WF). The DoG kernel is scaled and discretized to correspond to the retinal illuminance map resolution. A single ganglion cell receptive field signal is calculated by overlaying the DoG kernel on one specific area of the luminance map, pointwise multiplying the overlapping matrices and adding all obtained products. The response of all ganglion receptive field signals in the eye is modelled by the convolution of the luminance map with the DoG kernel. The convoluted luminance map represents a measure for the transmitted signal to the brain for each pixel. To count both the ON- and OFF-centre receptive field contributions, the absolute signal value of the convoluted luminance map is considered. The sum of all pixel signals is a measure for the total visual signal of the luminaire. The total number of pixels is dependent on the luminance camera field of view and the luminance map resolution. To normalise for the difference in number of pixels for different resolution luminance maps, the pixel signal is weighed with the pixel visual solid angle. A natural logarithm accounts for the compression mechanisms, as can be

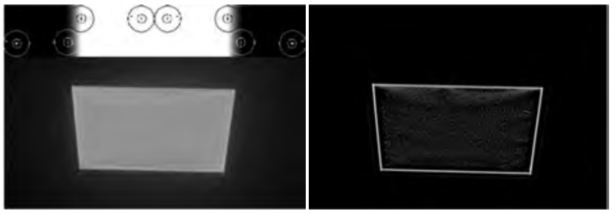

Fig.2. Left: at a dark area, there is no excitation by the centre and no suppression by the surround field; at a uniform area, the excitation of the centre is suppressed by the surround; and in both, the dark and uniform case, the net receptive field signal will be marginal; wherein at a sharp dark-light edge, the centre (or surround) is not entirely illuminated resulting in a net receptive field signal; right: the receptive field mechanism, and consequently the human vision, acts like an edge filter

found in multiple perception formulae [3, 5]. A centre and surround field width have previously been reported [11]. The natural logarithm is arbitrarily chosen in this paper. The total calculation procedure used in this paper is summarized below:

$$\textit{Visual Discomfort Model} = \\ = \ln \sum_{pix} \omega_{pix} \left| (C - WFS) * E_{ret} \right|, \quad (3)$$

where *ln* -is the natural logarithm; ω_{pix} is the pixel solid angle; C is the centre kernel; S is the surround kernel; WF is the Surround-to-Centre Weighing Factor; E_{ret} is the retinal illuminance map; * i s the convolution operator.

2.2. Paired Comparison Visual Experiment

Seven non-uniform stimuli were rear projected on a diffusor screen creating Lambertian light distributions (Fig. 4). Light patches with a luminance level of 1500 cd/m² were arranged in a 33.5 cm by 34.0 cm matrix observed from a fixed 3 m distance. While increasing the number of squares, the luminous surface per square and spatial separation between squares was decreased maintaining an average luminance level 350 cd/m² and a total light emitting surface 0.0042 m^2. The matrix consisted of 2 by 2, 6 by 6, 26 by 26, 60 by 60, 179 by 179 and 360

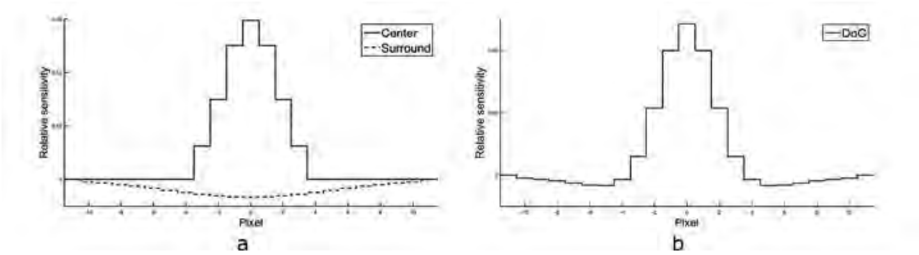

Fig. 3. Left: cross section of a discretised centre and surround kernel; right: a discretised difference of Gaussians (Centre minus Surround) kernel representing a receptive field with a WF of 1

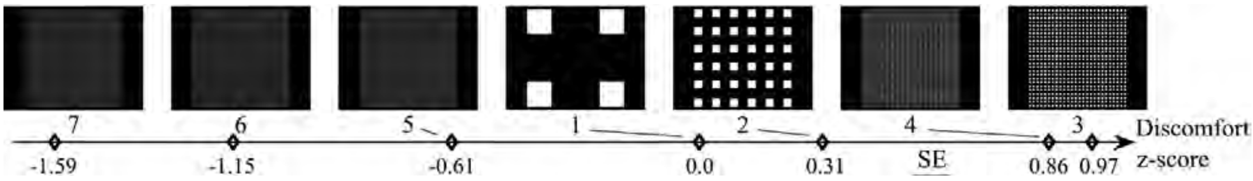

Fig. 4. The 7 rear projected stimuli and subjective PC results with standard error

by 360 light patches complemented with a uniform stimulus.

DALI controlled wall washers produced a uniform background luminance ranging (40–50) cd/m² with an average luminance level 45 cd/m². In a full forced choice PC experiment, all 20 observers were shown 42 pairs and were asked to indicate the most visual discomforting stimulus per pair. The observers were between 20 and 38 years old with an average of 26 years. The experiment took about half an hour and observers could ask for a break whenever they wanted. A generalised linear model produced a z-score on an interval scale for each stimulus and a standard error for visual discomfort (Fig. 3) [28, 29]. Luminance maps were measured with a LMK Labsoft luminance camera with a total reported uncertainty of 2.8 %.

3. RESULTS AND DISCUSSION

The subjective assessment with error bars is plotted against the modelled value in Fig. 5. The numbers in Fig. 5 correspond to the numbers in Fig. 4. A high coefficient of determination of 0.90 is found. The impact of the spatial luminance frequency on discomfort glare has been studied and recently applied in lighting design using a Fourier transformation [25, 27]. In this paper, this relation is explained by the model including the receptive field mechanism and pupillary light reflex. Visual discomfort initially increases with increasing

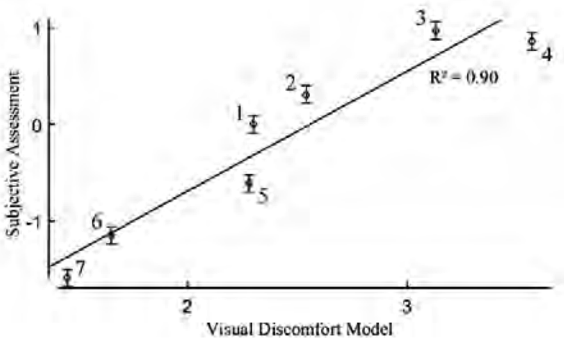

Fig.5. The paired comparison subjective assessment against the modelled value

frequency (stimuli 1 to 3). An increase in the number of light patches results in an increasing amount of edges while the spatial separation decreases. In agreement with the subjective assessment, a higher amount of edges initially results in a higher modelled value since the model acts as an edge filter. The light-dark edges become less clear when the spatial separation of the light patches reaches the spatial eye resolving power. At a certain frequency, the human eye will not clearly resolve the edges and the visual discomfort saturates at a maximum. In the model, the spatial separation of the stimuli reaches the dimensions of the centre-surround receptive field kernel. The excitation from one light patch on the centre starts to be supressed by another light patch on the surround of a receptive field. If the spatial separation of the light patches further decreases (increasing amount of patches), the edges will progressively appear less clear and the stimuli will steadily be seen as more uniform. The observed visual discomfort starts to decrease (stimuli 4 to 7). Stimulus 3 produces the maximum visual discomfort corresponding to a frequency of 4.0 cycles per degree. Conservatively, any stimulus in the range between 1.0 and 9.3 cycles per degree will produce the maximum discomfort. A quadratic fit predicts a stimulus with maximum discomfort within the range of 4.0 to 9.3 cycles per degree. From the contrast sensitivity function (CSF) [30], a maximum frequency sensitivity between 6 and 11 cycles per degree for direct view is observed. A satisfactory agreement in the range of 6 to 9.3 cycles per degree is noted.

In the formula for the pupillary light reflex (1), only the product of luminance level and stimulus field size is considered. Also age can be included in the pupil diameter calculation, but proves to be tedious [31]. In this study, the age effect is ignored. The maximum deviation in pupil diameter from age differences is 7 % relative to the pupil diameter of the average observer.

The luminance level of some projected pixels at the edge is 50 % lower than the maximum pixel luminance at the centre. None of the observers reported a drop in luminance level at the edges, even when this was explicitly mentioned. The measured luminance maps were used for the analysis. To test the robustness of the model, the light emitting patches were equalised in theoretical luminance maps. The light emitting surface was defined as all pixels with a luminance level above 50 % of the maximum luminance to include all pixels at the edge. The luminance level of all light emitting pixels was fixed at the average luminance level of the light emitting surface. The modelled value for the actual measured luminance maps was compared with the value for the theoretical maps resulting in a difference of only 4 %. In agreement with visual perception, the model is robust to gradual changes in luminance level.

Donners et al. proposed a similar receptive field model including the pupillary light reflex to assess the discomfort glare for both office and road lighting luminaires [32]. An additional local normalisation mechanism for the dark outdoor environment had to be included since luminance contrast and range is larger in a road lighting setting than in an indoor environment. The normalisation mechanism is not included in this paper.

4. CONCLUSION

A model including the receptive field mechanism and pupillary light reflex has been developed for the assessment of visual discomfort. The pupillary light reflex regulates the retinal illuminance were a centre-surround receptive field describes the visual signal. The model has been analysed with a paired comparison experiment involving 7 non-uniform rear projected stimuli with different spatial frequencies. A spatial luminance frequency in the range of 4.0 to 9.3 cycles per degree will produce the maximum visual discomfort. Inspired by a promising coefficient of determination of 0.90, the model is a candidate to replace current glare metrics as UGR or VCP, especially when non-uniform luminaires are to be evaluated.

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TM-30–15 AND CIE-CRI-RA: INVESTIGATION OF COLOUR RENDERING OF WHITE PC LEDS*

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ABSTRACT

The colour rendering properties of 21 phosphor converted LED light sources (pc LED) with different R_f and R_g values as in the Fidelity Index and Gamut Index of the TM-30–15 have been investigated. Scenarios illuminated by pc LEDs, a fluorescent lamp (FL) and a tungsten halogen lamp (THL) were presented to 34 subjects. An assortment of coloured objects was arranged identically in two adjoining booths and participants rated the test scenarios in comparison with the reference illuminant (THL). For colour quality, both indexes are reflected in the observer's ratings. The Fidelity Index strongly correlates with the colour difference and colour shift perceived; the Gamut Index with the subjects' ratings of the colour saturation. Participants found the best match with the fluorescent lamp (R_f = 80/ R_g = 100) to be the pc LEDs with R_f = 75/ R_g = 105 and R_f = 80/ R_g = 105.

Keywords: colour rendering, pc LED, TM-30–15

I. INTRODUCTION

Nowadays, light emitting diodes (LEDs) are used more and more in indoor lighting applications. In the first years, white light was produced by combining differently coloured LEDs (RGB-LEDs). Nowadays, phosphor converted LEDs (pc LEDs) are used. The light emitted by a blue LED is down-converted to light with a longer wavelength, using phosphors. This is then added to the original blue LED light, making white light. Commonly, the converter is a mixture of different types of phosphors to achieve a certain LED spectrum, which will affect the colour rendering properties. Correct description of these properties is a prerequisite to target setting in light source development. The current standard method of calculating these properties is the CIE colour rendering index (CRI) R_a, recommended in 1995 as CIE13.3 [1]. Studies have revealed inconsistency between this method and its rating by subjects especially in LED lighting [2]. Attempts to improve on it go back many years. On one hand, the method of calculation has been improved in reliance on new colorimetric discoveries; on the other, the spectral power distribution (SPD) of the light sources has been optimised, for instance by using different types of phosphors, as this is what largely defines colour quality. In 2015, the Illuminating Engineering Society (IES) published the Technical Memorandum TM-30–15, a new calculation method for colour rendering of white light sources [3]. There is international consensus that a single criterion is insufficient to describe colour quality for this includes many aspects. TM-30–15 combines colour fidelity, rated with the R_f index, and the colour gamut, rated with R_g index: this describes the area enclosed by the average chromaticity coordinates in each of 16 hue bins. THORN-

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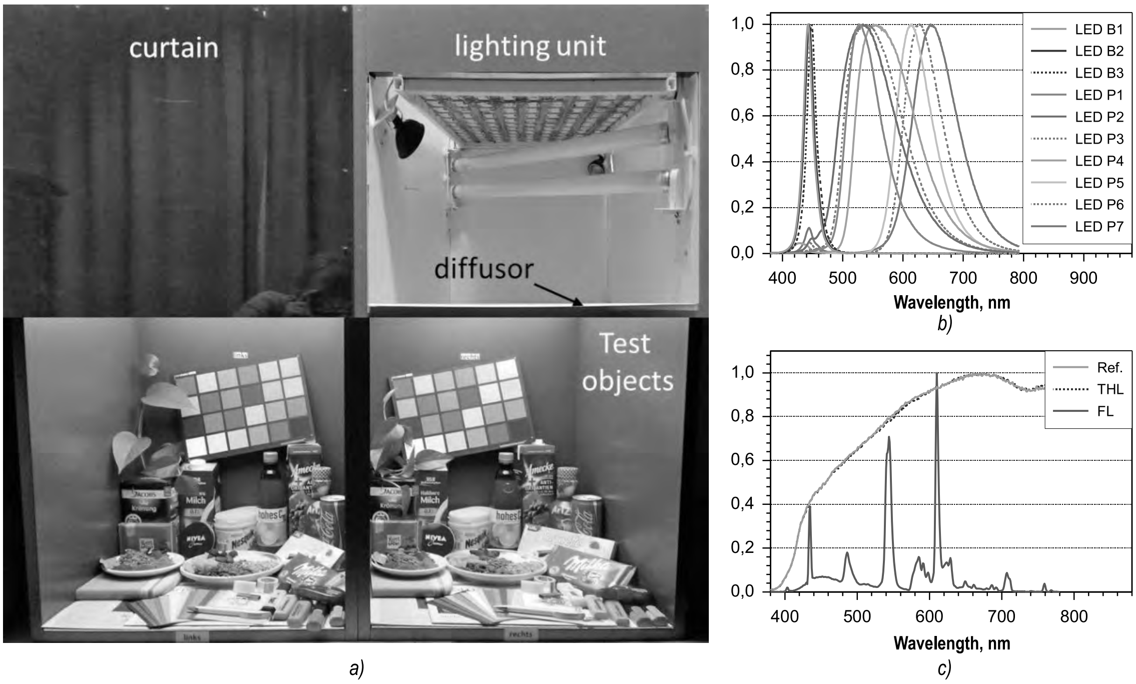

Fig. 1. a) Experimental setup with two booths (width: 46 cm, depth: 48 cm, height: 96 cm), at the top the lighting units, curtained and exposed, and below the test objects; b) relative SPDs of the light sources: B stands for blue LED, P for fully converted LED with different types of phosphors; c) Ref. for reference illuminant (SoLux THL), THL for the Solux tungsten halogen lamp, FL for the OSRAM Sylvania fluorescent lamp

Ton has shown that the larger the colour gamut, the better is the colour discrimination because the chromaticity coordinates are further apart in the colour space. There is also an assumption that light sources with larger gamut enable colours to be perceived as more saturated, more brilliant and more natural [5]. Xu assumes that the size of the area enclosed is proportional to the maximum possible number of colours that can be represented [6]. RGB-LEDs are an example of LEDs with narrow SPD. They may have a large gamut index but the rendering of certain colour may be inexact. It therefore makes sense to combine the two indices.

Royer has carried out an initial study of LED illumination in a test room with coloured objects. The illumination produces white light from seven types of tuneable, coloured LEDs with varying R_f and R_g values. The conclusion is that observers prefer LED light sources with Fidelity $R_f > 75$ and Gamut Index values $R_g \geq 100$ [7]. In the present work, this result is examined in respect of pc LEDs.

2. RESEARCH ISSUES AND HYPOTHESES

It is hypothesised that the Royer requirements are fulfilled for white pc LEDs and that the R_f and R_g values in TM-30–15 reveal high correlation with subjective evaluation of colour rendering properties on the part of observers. The present work tests whether pc LEDs with identical CIE R_a values improve on the subjective evaluation of fluorescent lamps.

3. EXPERIMENTAL SETUP AND METHODOLOGY

Two adjoining booths with two sections, one for the illumination unit with diffuser and another for test objects, were used (Fig. 1, left). In one booth, the light sources installed were a tungsten halogen lamp (SoLux) and a fluorescent lamp (OSRAM Sylvania with CIE $R_a = R_f = 80$ and $R_g = 100$), together with three types of blue LED and seven different fully converted LEDs incorporating a variety of green and red phosphors. Combining a variety of LEDs enabled various SPDs to be produced which were identical to those of white pc LEDs. 21 combinations of LED with R_f values between 66 and 94 and R_g values between 92 and 114 were investigated in comparison with a reference, as were the FL and the THL. The reference lighting in the second booth was provided by a THL (SoLux, $R_f = R_g = 100$). All lighting conditions had identical luminous colours

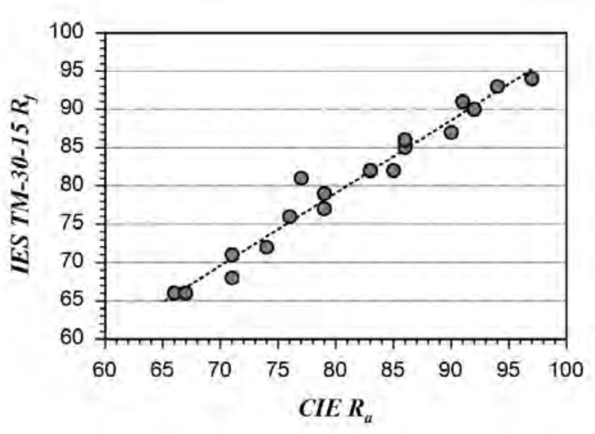

Fig. 2. Correlation between the R_a and R_f values, coefficient of determination R^2 = 0.98

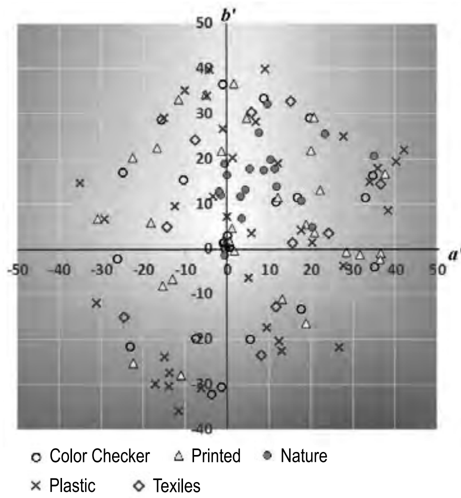

Fig. 3. Chromaticity coordinates of the test objects in the CIE CAM02-UCS when illuminated with a Planckian radiator at T = 3800 K

(CCT = 3800 K) and the same illuminance level in the centre of the floor of the booth (E = 400 lx). This experimental setup reflects the fact that both the CIE CRI R_a and the TM-30–15 are reference-based methods. Fig. 1 right shows the relative SPDs of the light sources.

The R_a values are almost identical with the R_f values, differing by an average of only one point with a maximum of four. The coefficient of determination for the lighting conditions tested is R^2 = 0.98 (Fig. 2).

An assortment of identical coloured objects was arranged equally in the two booths. The choice of objects ensured that a wide range of hue, saturation and lightness was covered. The chromaticity coordinates of the objects are shown in Fig. 3. They were objects from daily life: they included plants, food, consumer goods, office and printed materials, and colour rendition charts (Colour Checker). The SPDs of selected LED scenarios and the R_f-R_g combinations are shown in Fig. 4.

There were 34 participants between 23 and 48 years old (∅ 35 ± 7 years), 10 of them women. They filled in a questionnaire, firstly evaluating the colour rendering properties experienced simultaneously in the two booths. This evaluation was of differences in object colour perceived under the test and the reference light source according to the criteria of colour difference (CD), saturation (S), brightness (PB), temperature (T), colour shift (CS), likeability (LA) and naturalness (NN). In addition, the subjects were asked which of the object colours matched their expectation (EP) for the objects and how they rated the overall colour quality (CQ) of the objects independently of the reference. The questionnaire is shown in Fig. 5.

The differently lit scenarios were presented in random order. There was a repeat of the test for four scenarios. The mean values and intervals of confidence ($CI_{95\,\%}$) were calculated in respect of the subjects' responses and of the experimental parameters R_a, R_f and R_g. The coefficient of determination (R^2) was established for the linear regression across the mean of the ratings. Analysis of variance and post-hoc tests were carried out for the comparison between LED light sources and the FL.

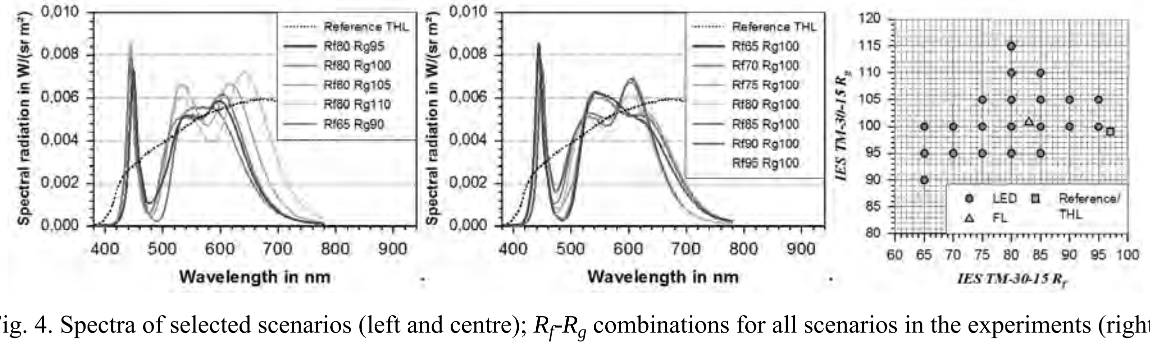

Fig. 4. Spectra of selected scenarios (left and centre); R_f-R_g combinations for all scenarios in the experiments (right)

Do you perceive a colour difference between the objects in the left booth and those in the right booth?					
Colour difference (CD)	1 = none	2 = small	3 = moderate	4 = great	5 = very great
How do you find the colours of the objects in the left booth in comparison to those on the right hand side?					
Saturation (S)	1 = very saturated	2 = somewhat saturated	3 = no diffe-rence	4 = somewhat unsaturated	5 = very unsaturated
Brightness (PB)	1 = very bright	2 = somewhat brighter	3 = no diffe-rence	4 = somewhat darker	5 = very dark
Temperature (T)	1 = very warm	2 = somewhat warmer	3 = no diffe-rence	4 = somewhat cooler	5 = very cool
Colour shift (CS)	1 = none	2 = small	3 = moderate	4 = large	5 = very large
Likeability (LA)	1 = very nice	2 = somewhat nicer	3 = no diffe-rence	4 = somewhat less nicer	5 = much less nice
Naturalness (NL)	1 = very natural	2 = somewhat more natural	3 = no diffe-rence	4 = somewhat less natural	5 = very unnatural
In which booth do the colours of the objects better match your expectation?					
Expectation (EP)	1 = left	2 = right	3 = both	4 = neither	
Ignoring the right hand side, how do you rate the colour quality of the objects in the left hand booth?					
Colour quality (CQ)	1 = very good	2 = good	3 = moderate	4 = bad	5 = very bad

Fig. 5. Items in the questionnaire (translation from the German version)

4. RESULTS

There is a diagrammatic summary of the questionnaire results in Fig. 6. The figures used are mean values and bares are intervals of confidence across all subjects (N = 34).

It can be seen in the diagrams and from the coefficients of determination for the linear regression R^2 in Fig. 6 and from Table I, that subjective colour quality rating is indeed a multi-dimensional problem and that both indices, R_f and R_g, are important aspects. While the R_f value gives a good description of colour difference, colour shift and the perception of colour as warmer or cooler in comparison with the reference light source, the R_g value is an explicit reflection of saturation rating. Whether a scenario is perceived to be likeable depends very much on how saturated the colours appear. Both indices are important in the rating of naturalness. At constant R_f value, pc LEDs have a more likeable and saturated effect the higher the R_g value up to a certain point. As the R_f value rises, so does the subjective colour rendering rating. The fidelity index R_f correlates very strongly with the CIE R_a value, so that here both indices are similarly applicable. Responses to the question on expectation of the colour of objects related to those seen under the test and reference light sources are shown on the left Fig. 6. The diagram shows the absolute frequency with which the object colours seen match those expected. Responses were given as to whether this was true for a single scenario in one of the booths (either the test or reference booth), or for both, or for neither. Represented is the "both" response has been shared in the Fig. 7 between the test and reference scenario.

As shown in the diagram, the colours of the objects are not better than the subjects' expectation when the LED light source tested has values R_f < 90 and $R_g \leq 100$. LED light sources with $R_f \geq 80$ and $R_g = 110$ are rated as better than the reference illuminant. The FL ($R_f = 80$, $R_g = 100$) investigated is

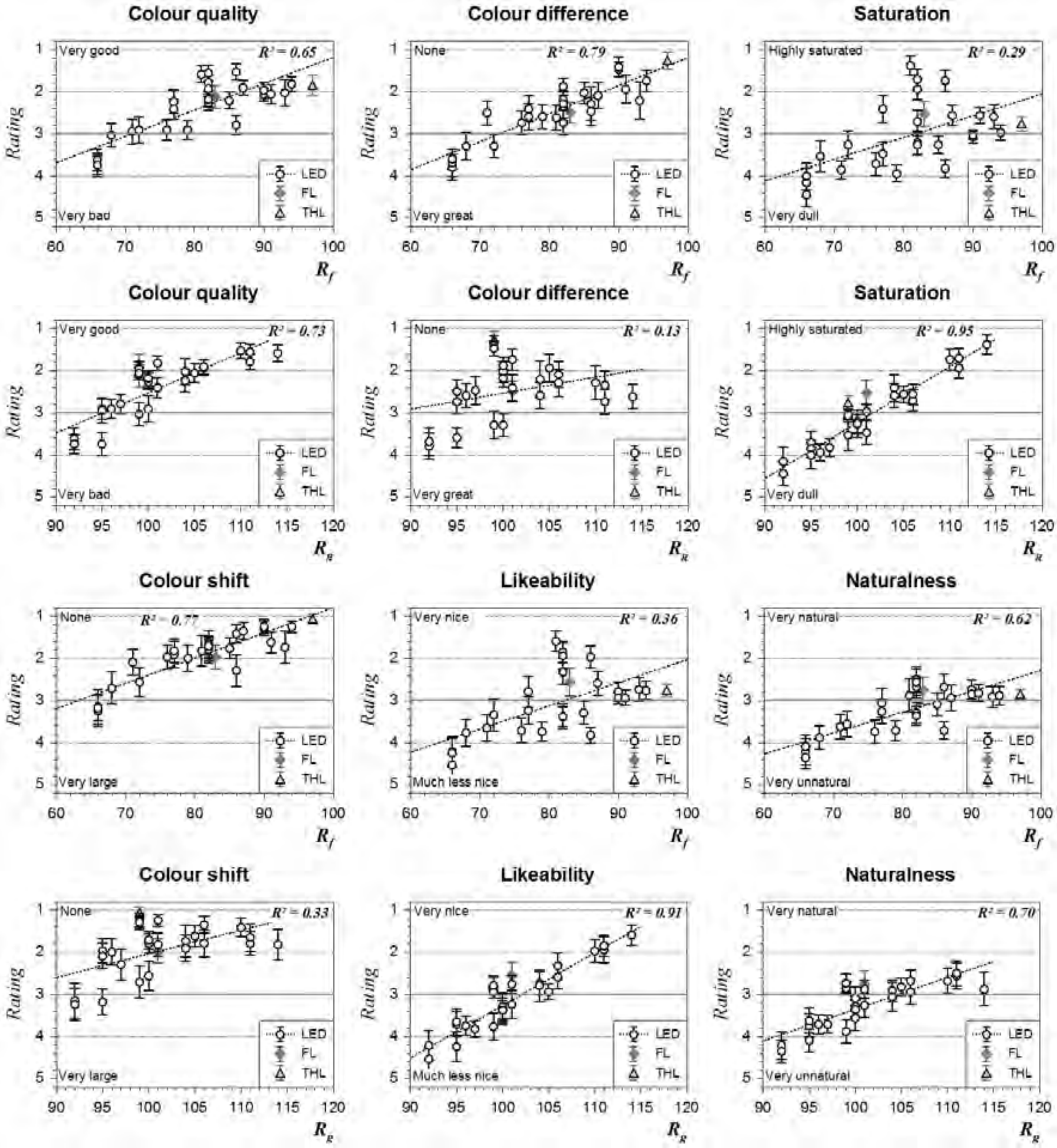

Fig 6. Subjective ratings (mean values and intervals of confidence *CI* 95 %) for R_f and R_g (the linear regression was determined for the LED scenario ratings, and the coefficient of determination R^2 for this is shown)

greatly preferred to the reference and adjudged better than the LED lighting with the same R_f and R_g values.

Table 2 gives a summary of the comparison of ratings for LED types compared with FL (R_f 80, R_g 100). The figures given are the probability p with a level of significance of $\alpha = 0.05$. At the same R_f and R_g values the general colour quality was rated identically, but the colours of the objects are perceived to be less saturated, less natural and less likeable than under the FL (Fig. 7, right). There is no significant difference in the rating of LED types R_f 75, R_g 105 and R_f 80, R_g 105 as compared with the FL. This leads to the assumption that it would be possible to compensate for slight differences in R_f value by a slight increase in saturation.

5. SUMMARY

The likeability of the colour of an object (as compared with the reference) cannot be predicted solely on the basis of the value in the Fidelity Index R_f. This index, like the CIE CRI R_a, serves to describe the difference in colour only in relation to colour appearance as compared with that under reference illuminant, which means that the refe-

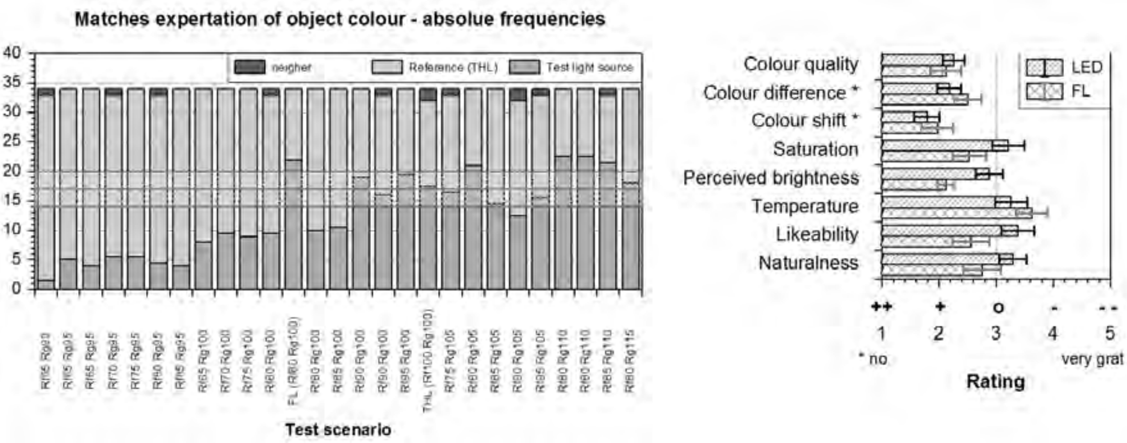

Fig. 7. Absolute frequencies of responce that object colours match expectation (left); responces for LED (R_f = 80, R_g = 100) and FL (R_f = 80, R_g = 100) – mean and intervall of confidence (CI 95 %), N = 34 (right)

Table I. Coefficient of determination R^2 of the linear regression

Item	R^2 for R_a	R^2 for R_f	R^2 for R_g	R^2 for CQ
Colour quality CQ	0.62	0.65	0.73	1.00
Colour difference CD	0.80	0.79	0.13	0.58
Saturation S	0.25	0.29	0.95	0.77
Colour shift CS	0.77	0.77	0.33	0.79
Perceived brightness PB	0.01	0.01	0.41	0.17
Temperature T	0.55	0.63	0.06	0.52
Likeability LA	0.32	0.36	0.91	0.85
Naturalness NN	0.61	0.62	0.70	0.92

Table 2. Summary of comparison between LED and FL (values given are probability p; statistical significance is denoted by italices)

R_g	95			100					105		
Item/ R_f	**75**	**80**	**85**	**75**	**80**	**85**	**90**	**95**	**75**	**80**	**85**
Colour quality CQ	*0,000*	*0,000*	*0,000*	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Colour difference CD	1,000	1,000	1,000	1,000	0,082	0,277	*0,000*	*0,000*	1,000	1,000	0,622
Colour shift CS	1,000	1,000	0,910	1,000	1,000	1,000	*0,000*	*0,002*	1,000	1,000	*0,030*
Saturation S	*0,000*	*0,000*	*0,000*	*0,000*	*0,000*	*0,002*	*0,037*	0,303	1,000	1,000	1,000
Likeability LA	*0,000*	*0,000*	*0,000*	*0,026*	*0,000*	*0,009*	1,000	1,000	1,000	1,000	1,000
Naturalness NN	*0,000*	*0,000*	*0,000*	0,185	*0,036*	1,000	1,000	1,000	1,000	1,000	1,000
Colour coding:	*FL significantly better*			*LED significantly better*				no significant difference			

rence spectrum will always be the criterion. There is no statement as to which of the colours' appearance, under test or reference light source, is better. It makes sense to incorporate the fidelity index with the gamut index into the evaluation and to set targets for the development of light sources. The present investigation indicates that $R_f \geq 80$ and $R_g \geq 100$ are useful prescriptive values. The perceived naturalness of the object colour correlates with both the R_f value and the R_g value, in that the subjects evaluated scenarios illuminated at $R_f \geq 80$ and $R_g \geq 100$ as similar to or better than the reference. This result tallies with Royer [7]. The high correlation between the R_a and R_f value, see Fig. 1, indicates the experimental results are also applicable to the R_a colour rendering index.

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ON SITE PHOTOMETRIC CHARACTERISATION OF CEMENT CONCRETE PAVEMENTS WITH COLUROUTE DEVICE*

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ABSTRACT

The standard tool for characterizing road surface photometry is the reduced luminance coefficient table (or *R*-table), as defined in the seventies by the CIE. Since these tables are no longer representative, measuring road photometry is necessary for optimizing a lighting installation and ensuring luminance level and uniformity. The objective of the study was to characterise and follow on site the photometric characteristics of different concretes with time and traffic. A first experiment was done with two concrete formulations (broomed and water jet scrubbed concrete) located around a much circulated concrete mixer plant. The photometric characterisation of these pavements was done with the portable reflectometer COLUROUTE device during three years. The selected surface treatment was applied in a tunnel and the photometric characteristics were measured during 30 months. It was shown that the concrete pavements are more diffuse and clear than classical pavements. Their use could generate significant energy saving.

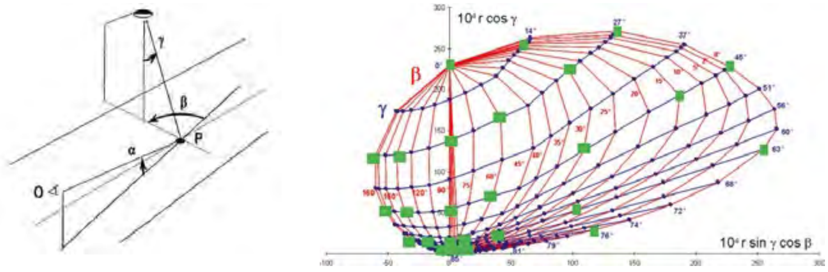
Keywords: concrete, energy saving, exterior lighting, pavement photometry, portable reflectometer

I. INTRODUCTION

Designing a lighting installation involves accounting for site-specific geometric parameters and photometric characteristics of both the light sources and the road surface. By knowing the photometric characteristics of a pavement, the design of public lighting installations can be optimized in terms of positioning and energy saving. The reflection properties of the pavement material are expressed as a table of reduced luminance coefficient (or r-table) [1,2]. To simplify the calculation, a classification based on the specularity coefficient S_1 is made and standard tables are defined by the CIE. CIE2001 [2] recommends a scaling of the chosen table according to the measured brightness coefficient Q_0. Since the photometric characteristics are generally not known, one standard *R*-table is used for the design of lighting without any rescaling [3]. This generates important errors as shown in [4,5]. Moreover, studies have shown that there is an important evolution of photometric characteristics with time and that these tables are no longer representative [6,7]. In this context, measuring road photometry is necessary for optimizing a lighting installation and ensuring luminance level and uniformity.

Concrete pavements are said to be more diffuse and clear than classical pavements [8]. The aims of the study were the followings: photometric characterisation of concrete pavements with time and traffic, comparison of laboratory and on-site measurements and calculation of the amount of possible energy saving. This work was done within a collaboration of 6 years between the French cement and concrete pavement associations CIMBETON and

* On basis of report at the European conference LUX EUROPA 2017, Ljubljana, Slovenia, 18–20 September



a) b)

Fig.1. a) The photometric characteristics of the road surface depend on the angles of observation α, sight β and incidence γ (following [2]); ***O*** represents the driver and ***P*** the point of observation; b) Representation of a pavement reflection indicatrix. The angle of sight β is in red, the angle of incidence γ is in blue and the location of COLUROUTE illuminating angles are in green

SPECBEA and the Cerema, which was in charge of the measurements and the technical evaluation. The section 2 of this paper describes the CIE methodology of photometric characterisation, the portable device COLUROUTE and the two experiments. The results obtained in the pilot study and in a highway tunnel are in the section 3.

1. MATERIAL AND METHODS

2.1. Introduction to Road Lighting

The *r*-table is a two-dimensional table with a number of standardized combinations of the incidence lighting angle γ and orientation angle β, the boundaries of which define the solid angle Ω (Fig.1a). The angle of observation α is set at 1°, which corresponds to a driver looking at about 100 m [1]. The reduced luminance coefficient *r* is defined by:

$$r\,(b, g) = ((L(b, g) / E_h)\cdot cos^3 g = \\ = q(b, g)\cdot cos^3 g, \qquad (1)$$

where *L* is the observed luminance in cd/m² and E_h is the horizontal illuminance in lx.

The characterisation of a pavement is given by its degree of specularity S_1 and its total reflectivity Q_0 (also called brightness). These two parameters are calculated from the previous matrix called *r*-table. The reflection indicatrix is a graphic representation of the r-table (Fig. 1b). Its volume informs on the brightness factor of the pavement Q_0, given as:

$$Q_0 = \int_0^{\Omega} \frac{q(\beta, \mathrm{tg}\gamma)\cdot d\Omega}{\Omega}, \qquad (2)$$

and its form is an indicator of the specularity factor S_1, given as:

$$S_1 = \frac{r(\beta = 0, \mathrm{tg}\gamma = 2)}{r(\beta = 0, \mathrm{tg}\gamma = 0)}. \qquad (3)$$

1.2. COLUROUTE Device

The portable measurement device named COLUROUTE (french acronym "COefficient de LUminance des ROUTEs"), was developed by the Cerema and complies with the CIE recommendations [9]. With this instrument (Fig. 2a), the luminance coefficients of a road surface are measured on site, in daylight and without sampling.

COLUROUTE is equipped with a sensor directed at the measurement surface with an angle of 1° and has twenty-seven sources set to illuminate successively this surface with different combinations of angles β and γ (Fig. 2b). These angles were chosen judiciously to allow the calculation of the specularity factor S_1 and to reconstruct by interpolation the complete reflection table of the road surface. Calibration is performed on site using reference plates measured with a laboratory goniophotometer [10] (Fig. 2b). The outputs comprise the reduced luminance coefficient table (*r*-table), the average luminance coefficient Q_0 and the specularity factor S_1. With this portable device it is possible to analyse a great number of areas and increase the number of interventions without damaging the road.

1.3. Experimental Setup

The aim of this pilot study was to follow the photometric characteristics of different concretes in time and traffic during 3 years and to choose

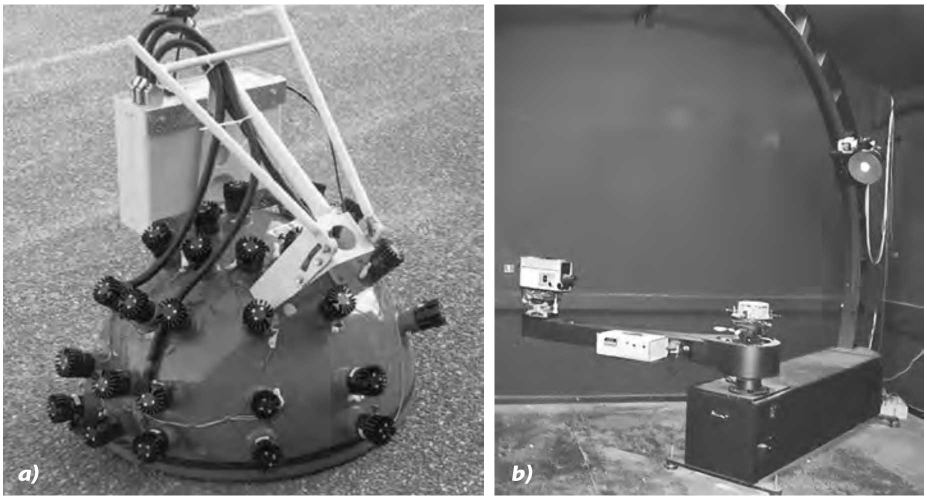


Fig.2. a) COLUROUTE device of the Cerema (Strasbourg); b) Goniophotometer of the Cerema (Clermont –Ferrand)

Fig.3. a) Localisation of the pilot study; b) View of the Sinard Tunnel; c) Picture of the broomed concrete (initial state)

a formulation for a tunnel pavement. The photometric characteristics of the two pavements were measured on site with COLUROUTE device and in laboratory on core samples with the Cerema goniophotometer. It was performed around a circulated concrete mixer plant near Lyon in France (Fig. 3a). The new concrete pavement was composed of local aggregates alluvial whose colour is a mixture of brown and beige more or less clear. Two surface treatments were used to obtain two different macrotextures: broomed and water jet scrubbed concrete. The circulation was composed of trucks carrying fresh concrete from the plant. The concretes surfaces were always watered to avoid dust. We assume that the presence of sand and water accelerates the corrosion.

The Sinard tunnel (length 980 meters), located South of Grenoble in the A51 highway, is one of the few in France to have a concrete pavement (Fig. 3b). It is an unreinforced, undowelled concrete pavement on a draining concrete subgrade. The concrete surface course was broomed across the traffic lanes using a hard brush, to provide the microroughness required for the grip of tires on the pavement (Fig. 3c). The surface concrete contains crushed materials to provide increased grip of tires after relative wear due to surface sweeping on newly laid concrete. The photometry of this pavement was measured periodically during 30 months with the COLUROUTE device.

2. RESULTS

2.2. The Pilot Study

In the pilot study, there were 3 measurements per pavement (M1, M2, M3) with COLUROUTE device every 6 months and there was one core sample taken for the laboratory measurements. All the results are shown in the Table 1 for the scrubbed concrete and in the Table 2 for the broomed concrete.

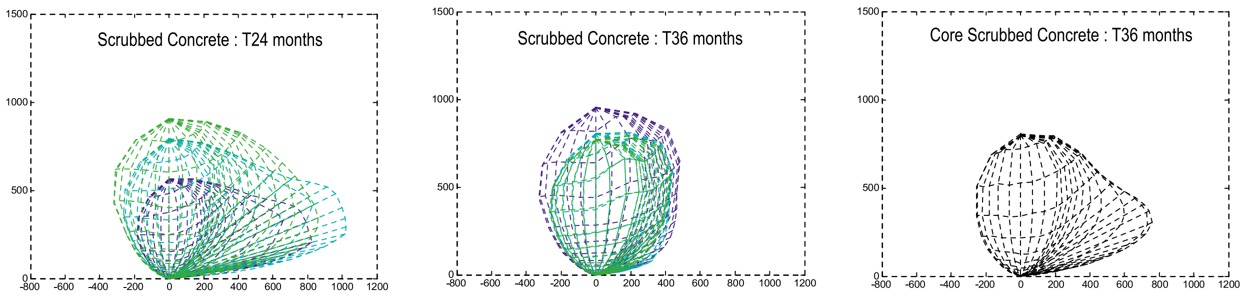
Whatever the methodology of measurements, the brightness increases with time for both pavements and reaches around 0.15. With COLUROUTE measurements, the specularity of the scrubbed concrete increases significatively (class *R3* pavement) after 2 years (Fig. 4a) but returns to a class *R2* pavement after 3 years (Fig. 4b). For the broomed

Table 1. Results for the Scrubbed Concrete, *m* is for Month

Scrubbed concrete	Brightness coefficient Q_0					Specularity coefficient S_1				
	T0	*T3m*	*T12m*	*T24m*	*T36m*	*T0*	*T3m*	*T12m*	*T24m*	*T36m*
COLUROUTE M1	0.090	0.088	0.095	0.154	0.165	0.11	0.12	0.44	1.51	0.50
COLUROUTE M2	0.084	0.094	0.095	0.199	0.152	0.12	0.10	0.86	1.36	0.54
COLUROUTE M3	0.089	0.120	0.096	0.187	0.139	0.20	0.13	0.46	1.03	0.46
GONIO on core	0.088	0.121	0.142	no core	0.157	0.23	0.72	0.86	No core	1.03

Table 2. Results for the Broomed Concrete, *m* is for Month

Broomed concrete	Brightness coefficient Q_0					Specularity coefficient S_1				
	T0	*T3m*	*T12m*	*T24m*	*T36m*	*T0*	*T3m*	*T12m*	*T24m*	*T36m*
COLUROUTE M1	0.141	0.120	0.112	0.191	0.181	0.09	0.14	0.27	0.43	0.30
COLUROUTE M2	0.120	0.149	0.140	0.176	0.136	0.08	0.16	0.28	0.36	0.25
COLUROUTE M3	0.152	0.105	0.117	0.139	0.175	0.08	0.14	0.33	0.51	0.24
GONIO on core	0.099	0.123	0.166	no core	0.138	0.09	1.10	0.80	no core	0.42



a) b) c)

Fig.4. Reflection indicatrix of the scrubbed concrete measured with COLUROUTE device on site after 24 months (a) and 36 months (b), the three measurements are represented in blue, cyan and green; measurement made on a core extracted after 36 months and measured with the laboratory goniophotometer (c), the axes are as defined in Fig. 1b

concrete, the specularity remains low (class *R1* pavement, Fig. 5). The specularity obtained in laboratory on the core samples is generally higher (Figs. 4c and 5c) than on the field. This is probably due to the presence of residual dust around the cement plant that could have an impact on the on site measurement. However, the goniophotometer and COLUROUTE measurements have shown that the specularity of the broomed concrete is lower than the scrubbed one.

The photometric measures show an important effect of erosion with time and traffic as illustrated by the pictures taken on each COLUROUTE intervention (Fig.6). The broomed surface looked like a water jet scrubbed concrete after two years (Fig. 6 b, d).

Since it is easier to obtain uniform illumination with diffuse pavements, the surface treatment chosen in the Sinard tunnel was a broomed one because of its lower specularity.

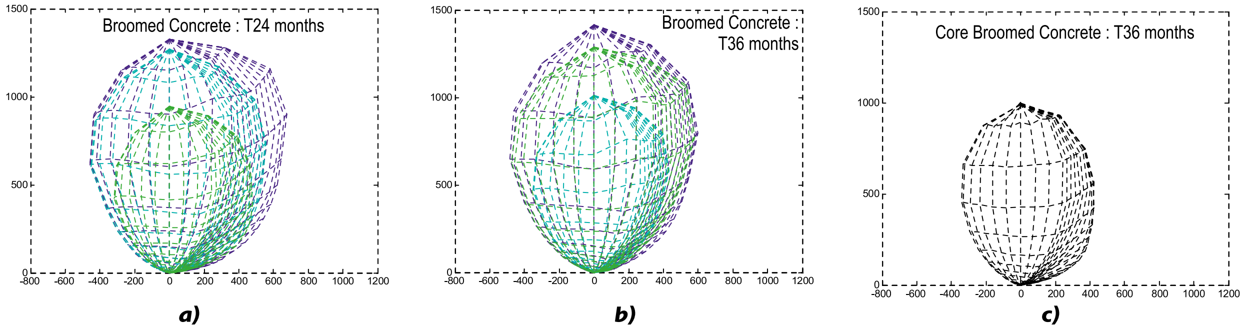


Fig.5. Reflection indicatrix of the broomed concrete measured with COLUROUTE device on site after 24 months (a) and 36 months (b), the three measurements are represented in blue, cyan and green; measurement made on a core extracted after 36 months and measured with the laboratory goniophotometer (c), the axes are as defined in Fig. 1b

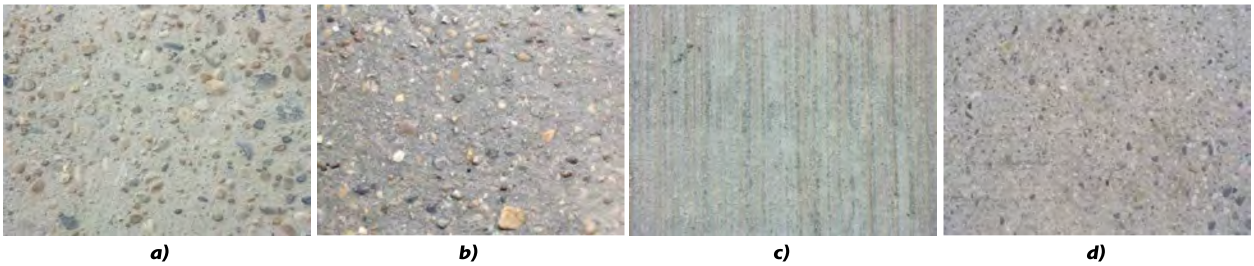


Fig.6. Pictures of the water jet scrubbed concrete (a. initial state, b. after two years); pictures of the broomed surface (c. initial state, d. after 2 years)

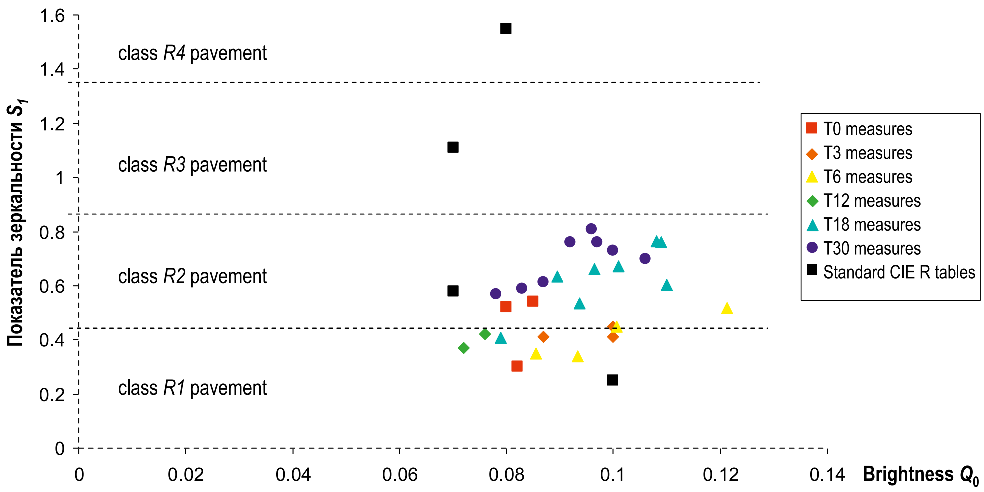


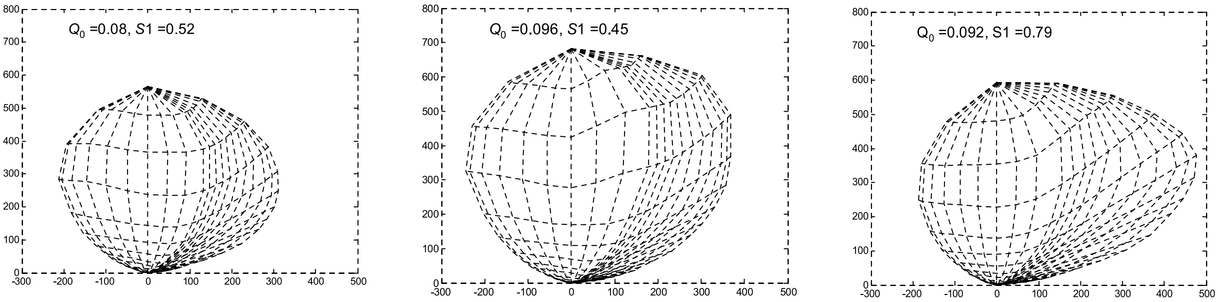
Fig.7. Representation of the photometric characteristics of the standard R tables (in black) and of all the measures done with COLUROUTE device in Sinard tunnel. In red for T0 measures, in orange for T3 measures, in yellow for T6, green for T12, light blue for T18, blue for T30

2.3. Experiments on the Sinard Tunnel

Since it was not possible to extract core sample on the A51 highway, only COLUROUTE device was used to make on site measurements on the right lane of the pavement during 30 months. They were performed on the central and on the tyre lane. At each intervention, the specularity was relatively homogenous but there were differences on the brightness factor Q_0 that could reach 30 %, as illustrated in the Fig. 7. At the initial state (Fig. 8a), the broomed concrete road surface was not very specula (class *R2*), probably because residual curing compound was still present. After 6 months of traffic, the pavement surface had an average brightness of 0.1 and was very close to *R1* pavement types (Fig. 8b). There were more specula areas, in particular on the left tyre tread and on the centre lane. After 18 and 30 months of traffic (Fig.7 and Fig. 8c), the pavement remained of class *R2* but was bright-

Table 3. Results of the DIALUX Calculation and Corresponding Electrical Consumption

Description of pavement	Q_0	Light Power in W	Consumption in kW/km	Energy saving
Standard *R2* table (reference)	0.070	54.7	1.89	0 %
R2 table rescaled with a classical bituminous pavement	0.054	70.6	2.43	-29 %
R2 table rescaled with Sinard T30 concrete pavement	0.092	38	1.31	31 %



a) *b)* *c)*

Fig.8. Photometric solids of the road surface in the Sinard tunnel, measured using COLUROUTE on new pavement (a), on a wheel track after 6 months (b) and 30 months (c) of traffic

er than typical *R2* pavements (the average brightness was 0.10 at 18 months and 0.09 at 30 months).

The energetic impact of the choice of such a concrete pavement is analysed with DIALUX software on a classical road installation with *Philips Iridium gen3 Led* and a lantern spacing of 29m (height 8m). Calculations were made in three conditions: using the standard *R2* table, using the standard *R2* table rescaled according to a 3 years old classical French black pavement from [5], and with a rescaling according to Q_0 obtained after 30 months with COLUROUTE. To achieve the class M3 requirement [11], 54.7W lantern are necessary for the standard *R2* table, 70.6W for the classical bituminous pavement and 38W for the Sinard concrete (Table 3.). The corresponding electrical consumption confirms that using a lighter pavement generates substantial energy saving.

3. CONCLUSION

The pilot study was used to choose between different surface treatments of concrete. An accordance with the results measured on core samples in laboratory and the portable device COLUROUTE was there. Differences are sometimes due to the process of sampling. In the pilot study located near a cement plant, there was residual dust that was removed during the extraction. Whatever of the type of measures, the broomed surface is always less specula than the scrubbed concrete. The results obtained in the pilot study and on the circulated tunnel were consistent. The broomed concrete pavement is and remains bright and its specularity stays moderate, despite the effect of traffic.

The energy consumption study has shown that taking into account the real characteristics of the concrete pavement used in the Sinard Tunnel, the lighting electric power could be reduced by 46 % compared to a classical French bituminous pavement. This emphasises the importance for the project owner to properly take into account the choice of pavement characteristics regarding its photometry when defining tunnel and road specifications.

With on site measurements, more measurements are done and the mean result is more representative than just one or two core sample. There is still necessity to define how many measurements shall be done and how to handle them. These aspects will be addressed during the European Empir project called SURFACE which is beginning.

ACKNOWLEDGEMENT

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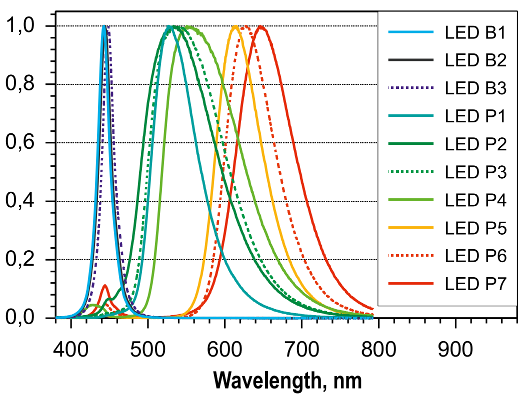
a)



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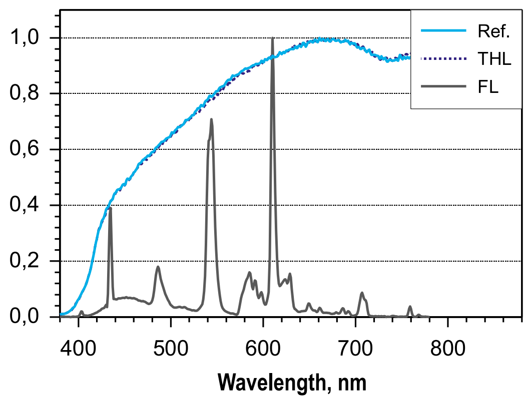

c)

Fig. 1. a) Experimental setup with two booths (width: 46 cm, depth: 48 cm, height: 96 cm), at the top the lighting units, curtained and exposed, and below the test objects; b) relative SPDs of the light sources: B stands for blue LED, P for fully converted LED with different types of phosphors; c) Ref. for reference illuminant (SoLux THL), THL for the Solux tungsten halogen lamp, FL for the OSRAM Sylvania fluorescent lamp

Fig. 1. Winter greenhouse using artificial irradiation systems (Maysky greenhouse facility, Kazan)

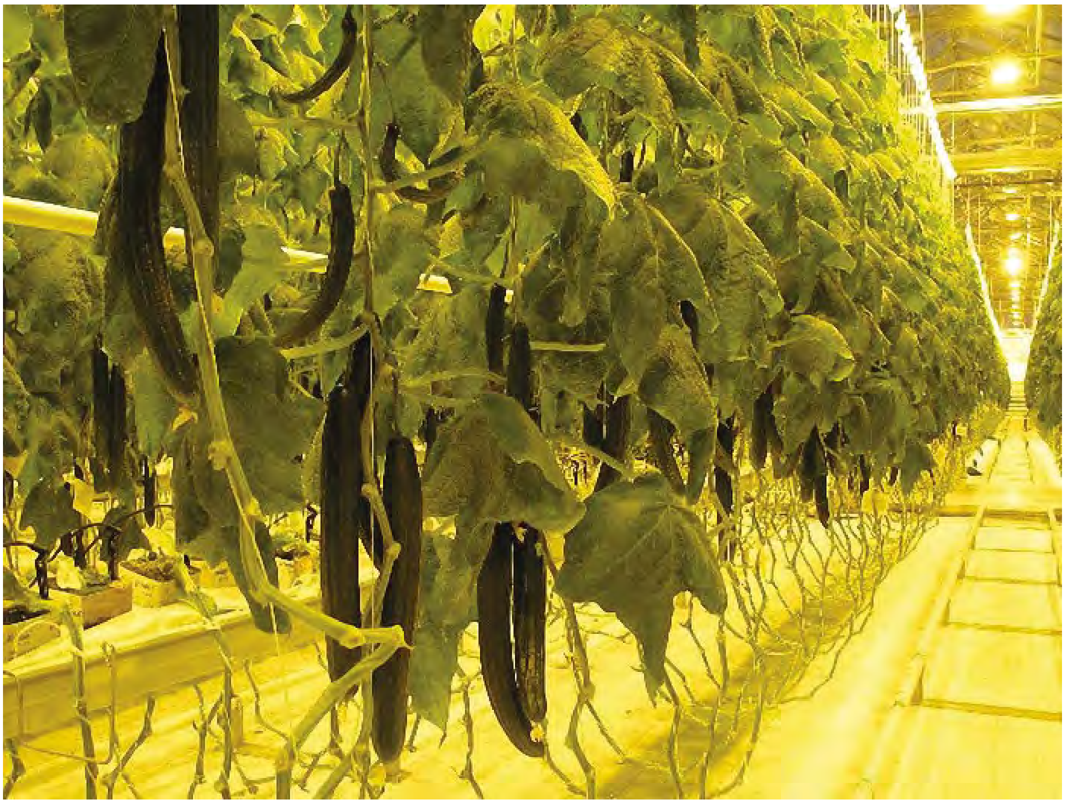

Fig. 2. Cucumber photoculture

Fig. 5. *Reflux* SSL lamps in a greenhouse

Fig. 7. LED irradiators for plant cultivation

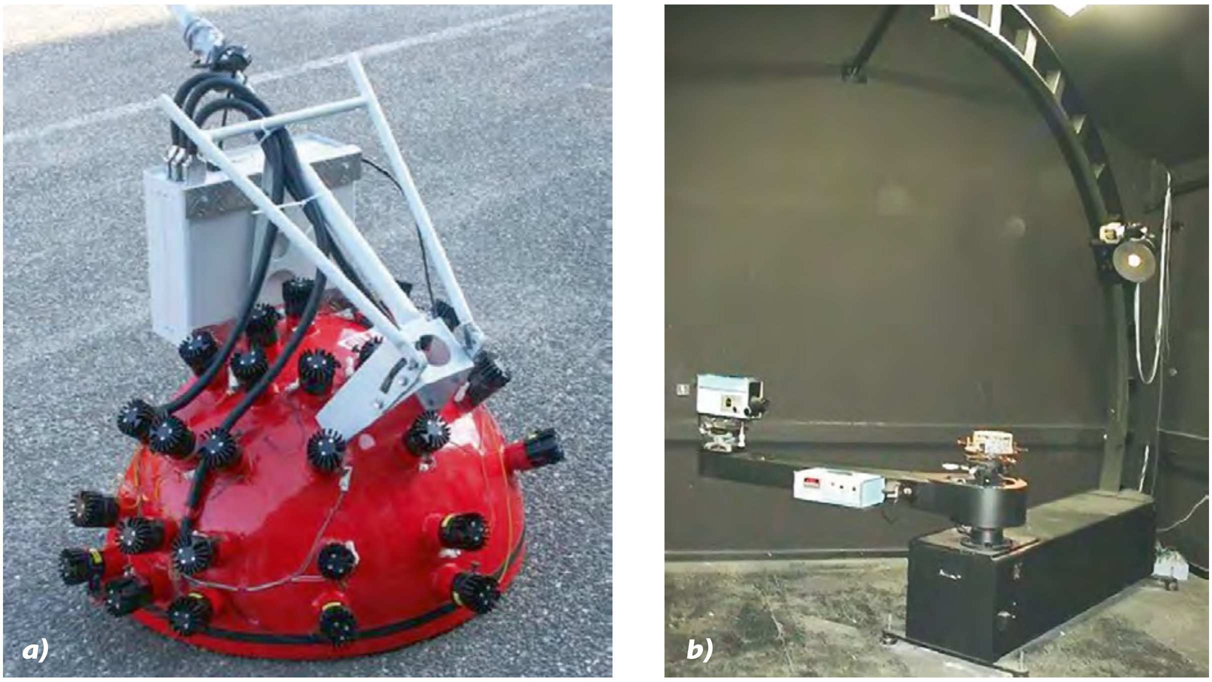

Fig.2. a) COLUROUTE device of the Cerema (Strasbourg); b) Goniophotometer of the Cerema (Clermont –Ferrand)

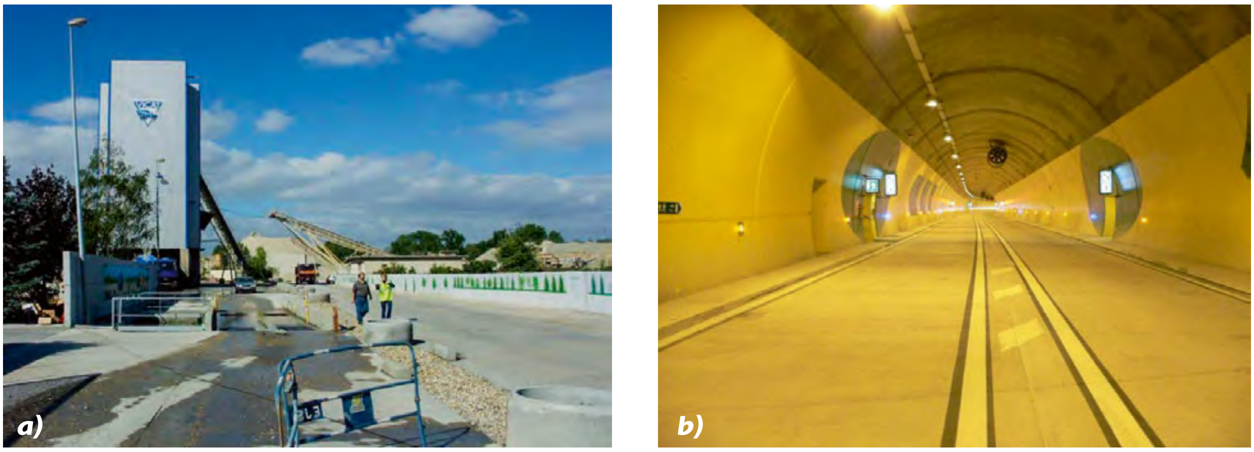

Fig.3. a) Localisation of the pilot study; b) View of the Sinard Tunnel; c) Picture of the broomed concrete (initial state)

a) b) c) d)

Fig.6. Pictures of the water jet scrubbed concrete (a. initial state, b. after two years); pictures of the broomed surface (c. initial state, d. after 2 years)

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ADVANCEMENT IN ROAD LIGHTING

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ABSTRACT

Road lighting is on the verge of one of the most attentive changes since its first introduction. The synergetic effect of the advancement of road lighting technology and usage pattern is going to change the concept of road lighting. By most estimates, light emitting diodes (LEDs) are the most energy efficient light sources that can be used in road lighting. Today, the energy saving potential when replacing HPS lamps with LED luminaires is one-third with current technology and two-thirds with improved technology in the future. This technological transformation has the potential of energy saving up to 83 % in comparison with HPS lamps. The energy saving is achievable with changing the pattern of use by intelligent road lighting control based on reducing burning hours. Intelligent road lighting can be based on such parameters as traffic density, ambient light, road condition and weather circumstances. It can also be more dynamic and consider the combined effect of road lighting and individual car headlights. The widespread adaptation of these emerging technologies is envisioned to lead towards more sustainable lighting.

Keywords: energy efficiency, LED, light source, traffic safety, road lighting, sustainability

1. INTRODUCTION

Road lighting is undeniably essential for road users to observe obstacles, decide ahead and avoid accidents. At the same time, it is becoming difficult to ignore the energy consumption and electricity costs related to the road lighting. The International Energy Agency has evaluated that in 2005, 19 % of the total global electricity consumption was used for lighting in which road lighting used 218 TWh amounting to about 8 % of lighting electricity consumption [1].

The electricity costs can be reduced by technological advancement and modification in the pattern of use via utilisation of intelligent road lighting. Lighting technologies have developed from gas lamp to incandescent, fluorescent, mercury vapour, low-pressure sodium, high-pressure sodium, and metal halide. Currently, LED technology is emerging as a new light source technology. These transitions have improved the efficiency and cost saving as well as lifespan, colour properties, dimming ability, and run-up and reignition times of road lighting [2].

It is evident that energy efficiency plays an important role in the transition of road lighting. However, there is still potential to reduce electricity consumption by dimming road lighting when and where needed based on real-time demand and by modifying the pattern of use (with intelligent road lighting systems).

Transition to new road lighting technologies and pattern of use have several benefits, such as reduction of electrical energy, costs, and maintenance, and provision of more environmentally friendly solutions. However, it is critical to acknowledge the purpose of road lighting before making any decisions to invest in new road lighting sources or making them intelligent. The primary goal of road lighting is to improve safety by increasing visibility of roadside hazards and by reducing the effects of glare from other light sources in the visual environment [3]. Many studies have shown that road lighting can mitigate nighttime accidents [4, 5, 6]. Therefore, it is essential to have an overview of advancements in road lighting.

The current paper is originated from Tetri et al. (2017) [2], where the authors' scope was broad and considered multiple aspects of road lighting such as mesopic vision, visibility and safety and 3D modelling of the lighting environment. Here the study is more focused on road lighting technology, traffic safety, and sustainability. In this article, we address the effect of road lighting on traffic safety, the benefits of using LEDs, and the effect of road lighting advancements on sustainability. By addressing the recent technological development, we describe how the road lighting technologies are changing and debate the future concept of road lighting.

2. TRAFFIC SAFETY

According to World Health Organization, over 1.2 million people were killed in road accidents in 2015, which makes it one of the 10 major causes of death in the world [7]. Generally, human (57 %), roadway (3 %) and vehicle factors (3 %) are causing traffic accidents; the rest is due to their interactions [8].

Difficulties arise, however, when an attempt is made to study the effect of one factor such as road lighting on accidents. Firstly, many interacting variables affect accidents, which make the separation of the effect of road lighting difficult [8]. Secondly, drivers' behaviour changes before and after installations of road lighting. For instance, Assum et al. [9] investigated drivers' behavioural adaptations in relation to speed and concentration before and after installation of road lighting in Norway. As a consequence of the installation of road lighting, increase in the number of older drivers, increase in speed and decrease in concentration was evident. Therefore, these interacting factors affect the accuracy of the effect of road lighting on accidents [9].

In order to measure the effect of road lighting on accidents, the comparison of accident data either on the areas where road lighting did not previously exist and is then introduced or where improvements have been made to road lighting has to be conducted. This can be done with an odd ratio, which is a metric for quantifying the effect of road lighting on accidents.

$$\text{Odd ratio} = \\ = \frac{(\text{№ accidents in darkness on lit roads})}{(\text{№ accidents in darkness on unlit roads})} + \\ + \frac{(\text{№ accidents in daylighting on lit roads}}{(\text{№ accidents in daylighting on unlit roads})}. \quad (1)$$

Road lighting has been identified as a contributing factor to the decline of traffic accidents. A number of studies have shown that road lighting can reduce nighttime accidents [4, 6, 10]. A well-known example of this is a study by International Commission on Illumination (CIE) [4]; they found that the average effect of road lighting installation on the reduction of accidents was 30 %.

The increasing trend of using intelligent road lighting [2, 9, 11] has already drawn attention to study the effect of quality of road lighting on accident [12,13,14]. A study by Gibbons et al. [15] indicated that current road lighting practices result in over-lighting and the increased lighting level does not necessarily lead to a safer road. They studied the relationship between lighting level and lighting quality and accidents based on the night-to-day crash rate ratio. The study concluded that current road lighting practices are over-lighted and there is a potential to reduce road lighting levels by as much as 50 % for the urban interstate functional class. In addition, Steinbach et al. studied the effect of reduced road lighting on traffic safety and crime prevention [16]. The results provide no evidence that switching off, part-night light, and dimming adaptations to the road lighting were associated with night-time traffic accidents. Also, there was no evidence of increasing crime in these conditions during the hours of darkness. Therefore, the relevance of dimming road lighting without adversely affecting traffic safety is supported by the findings.

3. LIGHTING TECHNOLOGY

3.1. Changes in Technology

In 2005, IEA estimated that 62 % of total outdoor light was provided by high-pressure sodium (HPS) and low-pressure sodium (LPS) lamps, 30 %

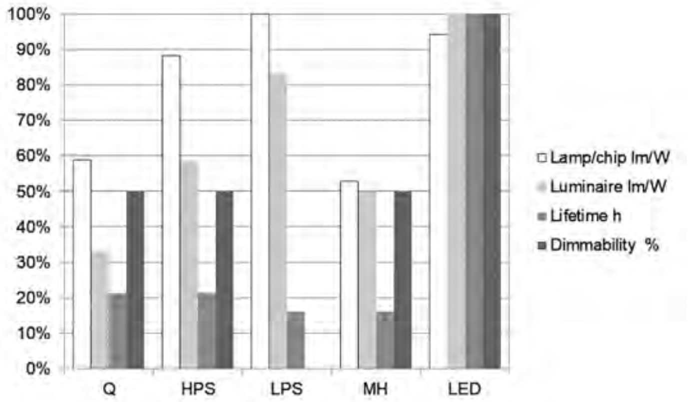

Fig.1. Characteristics of different lamp/luminaire types when compared to the 100 % reference values, which are: LPS lamp luminous efficacy 170 lm/W, LED luminaire luminous efficacy 120 lm/W, lifetime 75000 h (LED), and dimmability 100 % (LED)

by mercury vapour (Q) lamps, 6 % by metal halide (MH) lamps and the remaining 2 % mostly by halogen and incandescent lamps [1].

HPS, Q and MH lamps are also known as high-intensity discharge (HID) lamps. The light-producing element of these lamp types is an arc discharge. Each type of HID lamp produces light related to the type of metal that is contained in the arc. HID lamps have negative volt-ampere characteristics, and therefore a current-limiting device is needed, usually a ballast. They also need auxiliaries for starting. They have commonly few minutes' run-up time before the operation light output level is reached. Often, they also need few minutes to cool down, before the arc ignition can work. HPS lamps can be dimmed to roughly 50 % light level by adjusting the supply voltage. Q and HPS lamps have often 4-year group replacement period, giving them 16000 h lamp life. LPS and MH lamps have commonly 12000 hours' lamp life. Luminous efficacy is highest with LPS lamps (150–170) lm/W. HPS lamps have an efficacy of (80–150) lm/W, Q lamps (40–60) lm/W and MH lamps (60–90) lm/W. Efficacies are dependent on lamp power and colour rendering properties. For instance, with HPS lamps the increase of the pressure and temperature inside the arc tube increases the colour rendering and colour temperature, but decreases the efficacy.

Like mentioned above, the luminous efficacy of a HPS lamp can be 150 lm/W [17]. However, when a lamp is placed in a luminaire, the luminaire efficiency (lumen output ratio) decreases the total efficacy. Luminaire efficiencies are often quite low, especially with old luminaires [18]. When the luminaire efficiency and ballast losses are taken into account, the luminaire luminous efficacy is often about 40 lm/W [19]. Characteristics of different lamp and luminaire types are compared in Fig. 1.

HID lamps are based on gas discharge, whereas LEDs are semiconductors. The wavelength of the radiation depends on the semiconductor material. In road lighting, it is common to use blue radiation chips. Some of the blue radiation is then turned to longer wavelengths with a phosphor coating. There is no infrared radiation in the spectra and the excess heat of the LED junction has to be conducted to heat sink [20]. Without adequate heat sinking (or ventilation), the junction temperature will rise, resulting in lower light output and reduced lifetime. Unlike with discharge lamps, there is no few minutes run-up or re-strike time. The light output is instant after the switch-on. The rise time of LED light output is less than microseconds [21]. The rise time does not limit the use of LEDs in dimming use. The power is almost linear with luminous flux and thus the luminous efficacy remains high also in dimming use.

LED luminaires are very long-lasting, according to manufacturer data their service life can be from 50000 to 100 00 hours. The status of luminous efficacy is already higher 100 lm/W for LED luminaires [22]. However, the semiconductor material and phosphor coating can degenerate in use and thus reduce the lifetime, especially in warm environments.

3.2. Control of Light

Significant development is occurring in the area of road lighting control. The lighting control system can be adjusted in real time or according to a predefined time-schedule. The latter being called intelligent road lighting [12]. The most widely used control system is photoelectric cells that switch lights on/off based on the availability of daylight. Due to the low cost and reliability of photoelectric cells, they can be applied to individual luminaires or groups of luminaires. Currently, the most widely used photoelectric cells have the factory setting of the switch on at 70 lx as the natural lighting levels fall at dusk and off at 35 lx as the lighting levels increase at dawn. However, the operating range can be altered. A study by the Institution of Lighting Professionals [23] estimated that if the switching levels were reduced to 35 lx at dusk and 16 lx at dawn a saving of 50 hours per annum (approximately (1–2) %) could be achieved. Using this lower switch on/off lighting levels is not recommended for older lamp types such as low-pressure sodium lamps and mercury vapor lamps. Like discussed earlier, they need some time for the warm-up until their light output reach the operational value. Since mercury lamps have been phased out from the market by European Union regulation [24] and at the same time LED luminaires with new characteristics are ready to take over the market [2], photocells with switching routine of 35/16 lx are considered.

There is still potential for reducing the level or hours of operation of road lighting systems or switching off lighting whenever there is no need for lighting. For instance, during low traffic periods, every second luminaire can be turned off to save energy. However, this results in poor luminance uniformity. The dimming of luminaires may offer an acceptable alternative to switching off every second luminaire. Monitoring luminance level of road surface plays a key role in altering the road lighting outputs. Many factors can affect luminance levels of the road surface, such as road surface properties under varying weather conditions, and presence of car headlights on the road [12].

Weather conditions are also an important component in luminance of the road surface. When the road is covered with uniform snow, road surface luminance can substantially increase. Guo et al. (2007) [12] study indicated an increase of 150 % in road surface luminance in comparison with dry conditions.

Car headlights have also a significant effect on the road surface luminance. This was illustrated briefly by Guo et al. (2007) [12], in which car headlights increased the average road surface luminance value by 432 %.

The LED's capability to be frequently dimmed has made it possible to start developing control systems that react to the movements of individual road users. Such a system can fully satisfy road lighting regulation when a road user is present while providing a high level of dimming and energy saving at other times. In such cases, the maximum level of dimming is mainly dependent on acceptability to local inhabitants; for example, in rural areas, dimming down to (15–30) % of nominal light output is acceptable [13].

3.3. Car Headlights

Although considerable benefits can be gained by changing from conventional to LED road lighting, there is still another opportunity to reduce energy use and costs without affecting traffic safety. Aside from illumination by road lighting, drivers have car headlights. The combined effect of road lighting and car headlights is not complementary [25, 26, 27]. While road lighting illuminates road surface (horizontally), car headlights illuminate vertical objects on the road, and the combined effect of road lighting and car headlights reduce the contrast of objects on the road. Bozorg Chenani et al. studied this combined effect under different road lighting intensities with and without glare from an oncoming car in a stationary car [26]. The study used drivers' subjective grating of visibility performance and visibility level calculation as defined in the Adrian model [28]. The road had 100 W HPS light sources with the lighting class of M5 according to the classification system in CIE115:2010 [29]. The full road lighting had a voltage of 230 V and a luminous flux of 7252 lm. In addition to full road lighting, two other dimming levels, 71 % and 49 %, were studied with voltages of 210 and 190, respectively. They found that with only low beam headlights and in absence of glare from an oncoming car 49 % of road lighting intensity (corresponding to 4.5 lx) provided better visibility level than 100 % road lighting (corresponding to 8.3 lx) and 71 % of road lighting (corresponding to 5.9 lx) provided worst visibility level than the other two mentioned lighting levels. In addition, with low beam headlights and in presence of glare from an oncoming car there was a difference between different levels of road lighting but the effect was not significant [26].

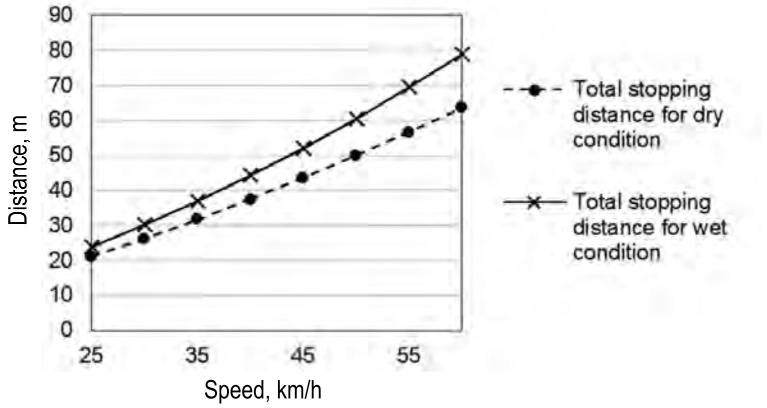

Fig. 2. Total stopping distance (TSD) for different speeds and weather conditions

Car headlights have been identified as being a potentially important parameter to dim road lighting. However, the range of car headlights are limited and driving speed can affect the effectiveness of car headlights (overdriving headlights). The assured clear distance ahead (ACDA) rule is known as maintaining speed low enough to enable the driver to stop within the range of vision and therefore, to avoid accidents with any obstacles that might appear in the car's path [30]. The main concern of ACDA rule is to find the maximum safe speed of travel, which is directly dependent on both the car and the driver as explained in Total Stopping Distance (TSD). TSD depends on the velocity of a car (m/s), perception and reaction time in sec, the coefficient of friction, and gravitational acceleration. In addition, the key human factors in TSD are perception and reaction time. These might vary due to environmental variables, drivers' experience, alertness, and physical condition of the driver [30]. American Association of State Highway and Transportation Officials [31] have appointed 2.5 seconds as the time required for most drivers to respond under most conditions and this 2.5 sec is used for perception and reaction time in road design. TSD for different speeds can indicate that car headlights can provide safe-visible distance up to 60 metres with speed up to 50 km/h (considering coefficient of 0.65 for dry condition and coefficient of 0.38 used for the wet condition for heavy truck, based on [31]). The findings of this theoretical knowledge are consistent with previous measurements studies. One criterion to examine the effectiveness of car headlights on visibility performance is detection distance with different speeds. Several studies indicate that low beam car headlights are enough while driving with low speed up to 50 km/h [32, 33, 27]. For instance, a study by Perel et al. focusing on driving with low beam car headlights alone provided enough visibility with speed up to 48 km/h [32]. In addition, it is known that on an unlit road and with only low beam car headlights, a young driver can only recognise an unexpected dark-clad pedestrian on average up to the distance of 15 to 45 meters from the headlights [33, 30].

Fig. 2 displays TSD for different speeds and weather conditions. Since car headlights have dominant effect in the area between 0 and 60 metres from car headlights [3], total stopping distances should be below 60 meters. Fig. 2 indicates that speed and road surface conditions can affect to different total stopping distance.

Also, driving with high speed can reduce the effect of car headlights (overdriving headlights) and increase the effectiveness of road lighting. Janoff et al. studied the detection distance of a small target with high speed (89 km/h) car in different road lighting intensities [34]. Their results indicated significant differences between full road lighting and other road lighting intensities. The best detection distance was achieved under full road lighting condition.

Therefore, there is a potential to reduce energy consumption by taking into account the combined effect of road lighting and car headlights in low-speed roads or when the car is approaching with low speed (lower than 50 km/h).

4. SUSTAINABILITY

4.1. Demand for Sustainable Outdoor Lighting

Due to the introduction of LEDs, the global lighting field is going through a transformation where

LEDs are replacing the conventional lighting technologies as new suppliers and organisations disrupt the industry [35]. The transition to LEDs has led the private actors to respond to the changing field and the demands regarding the environmental and technological properties of the new LED products by finding new international organisations such as Global Lighting Association [36] and Lighting Europe [37] and Zhaga [38]. This global change has also been supported by public and international organizations with the development of new international standards for testing LED products and by launching supporting programs and policies. The aim of these activities has been to further facilitate market transformation, international trade and diffusion of the new technology as LEDs' are expected to have a positive impact on sustainable development [39, 40].

However, from the different market segments especially the outdoor lighting segment is often a highly regulated domain of infrastructure of developed regions. In addition, investments in outdoor lighting are planned from a very long run perspective as investment calculations cover often even several decades [41]. In order to satisfy lighting network owners' and road users' expectations regarding functional lighting services, the outdoor lighting installations have to fulfil certain criteria as defined in international standards and recommendations of International Commission on Illumination (CIE), European Committee for Standardization (CEN) and American National Standards Institute and Illuminating Engineering Society (ANSI/IES). The standards for road lighting contain lighting requirements, including metrics for the luminance, illuminance, uniformity and disability glare produced by the luminaires.

But besides fulfilling the normative criteria, lighting installations are increasingly expected to be sustainable. This means that preference in technology selection should be put on those products, which minimize economic, environmental and social burdens and thereby determine sufficient conditions for adopting efficient lighting products. This kind of life cycle thinking entails assessing how products perform in terms of the sustainability aspects and what kind of trade-offs or dependencies, if any, exists between the different technologies and respective dimensions of sustainability [42,43]. However, sustainability assessment is still a developing framework where analysis can be conducted by combining different types of scientific assessment methods and tools [43]. For the purpose of outdoor lighting, Jägerbrand has developed a framework consisting of a set of sustainability indicators and measures for assessing especially LED luminaires' long-term sustainability from different perspectives [44]. Within the framework, the sustainability assessment is conducted by utilizing formalized indicators and methods in combination with qualitative approximations through several categories of environmental, economic and social sustainability. Moreover, the assessment of environmental and economic sustainability can be conducted with matured methods while the assessment of social impacts is still less uniform methodology [42, 45].

4.2. Assessments of Environmental and Economic Sustainability of Outdoor Lighting

The environmental and economic sustainability of different outdoor lighting technologies can be approached by comparing the performance of the alternative technologies during their different life cycle phases of environmental life cycle analysis (LCA) and life cycle costing (LCC) for financial cost accounting [46, 47, 48]. The diffusion of LEDs to road lighting has resulted in several comparative case studies with the aim to find out the environmental and economic sustainability of the products [49, 50, 51, 52, 53]. The main approach in case studies has been the comparison of the life cycle efficiencies of emerging LEDs and the dominating HPS lamps. Regarding the assessments, it has been proposed by Tetri et al. that the key parameters for comparisons are luminaire power, luminous efficacy, lamp and luminaire lifetime and pole spacing [2]. In addition, Tähkämö and Halonen suggest that assessments should use a kilometre of a lit road as the functional unit in the comparisons [49].

According to the recent results [49] and [2] the environmental impacts of HPS and LED luminaires are almost at the similar level where most of the impacts are created in the use phase of the luminaires: 96 % of HPS and 87 % in the case of LEDs. Thus, a specific feature of outdoor lighting is how different lighting products generate environmental impacts in the use phase, i.e. while the light is on. In addition to energy consumption, especially light pollution, which can be described as increased levels of artificial lighting in night-time environments [54] and lights illuminating unintended areas, is

Table 1. Comparison of Different Light Sources [2]

		Power (W)	Luminaire efficacy (lm/W)	Luminous flux (lm)	Annual burning hours (h/a)	Annual energy consumption (kWh/a)	Energy savings (%)
HPS		175	69	12000	4000	700	
LED	**Current**	120	100	12000	4000	480	31
		120	100	12000	2000[1]	240	66
	Future	60	200	12000	4000	240	66
		60	200	12000	2000[1]	120	83

[1] Burning hours reduced by 50 % with smart control

seen as a problem of different types of lighting technologies and luminaire designs [55]. Road lighting can cause light pollution described as sky glow and light trespass [56, 57] referring to the unintentionally lit areas [58] and increased brightness of the night sky [59].

Several steps have been taken to minimize these impacts. International Dark Sky Association and Illuminating Engineering Society of North America (IES) has developed tools for planning and selecting suitable lighting for outdoor purposes. The organisations have created a template for municipal lighting ordinances [60], which are aimed at combining outdoor lighting with lighting recommendations while simultaneously minimizing the negative use phase impacts [2]. Moreover, the template is supported by another tool for minimizing the negative use phase impacts of luminaires such as light pollution [61]. The rating system of IES is meant to help when selecting luminaires with adequate shielding for lighting installations.

Furthermore, the cost efficiency of HPS and LED luminaires has been assessed several times [2, 50, 53]. Often the purchase price of LED luminaires is much, even several times higher, than HPS luminaires [50, 53] creating an impression of higher total life-cycle costs. Besides the higher purchase price a major feature causing cost inefficiency for LEDs is the structure of the luminaire, which does not necessarily allow the changing of LED arrays at the end of their lifetime [50]. This increases LEDs maintenance costs during the long investment period as the whole luminaire has to be replaced during the maintenance period.

However, the studies using sensitivity and scenario analyses indicate that LED luminaires can be a cost-efficient choice over HPS luminaires [2, 50]. When acknowledging the development of the lighting industry and luminaire technology LEDs become a competitive alternative for HPS lamps [2]. The improved life cycle efficiency of LED luminaires has its roots in the global diffusion of LED science and technology [35] and the collaboration between the industry and academia. However, as the lighting technology has evolved the industry has attracted new entrants, which have adopted new operating models for building luminaires. These new ways of operating emphasize rapid prototyping and adaptation of automated manufacturing technologies such as robotics. As a consequence, enterprises have been able to quickly pilot and receive feedback from the early versions and improve products' quality for the next pilot. The increased number of competitive suppliers has lowered the purchase price of LED luminaires and is also a major explanatory factor for the products improved life cycle efficiency. On the other hand, the life cycle results are also subject to competition and local market structures indicating sensitiveness of the results.

LED luminaires have still further potential for efficiency gains and the luminaires can be optimized in respect of electricity consumption, luminous efficacy, and modularity and operation time. These advancements will make LEDs more efficient alternative than HPS technology in financial terms.

5. FUTURE OF ROAD LIGHTING

LEDs are a radical innovation and as they are evolving rapidly, they will be the dominating lighting technology. U.S. DoE has estimated that by 2020 the luminous efficacy of a LED luminaire could reach almost 200 lm/W [22]. Package luminous efficacy would be 220 lm/W and overall luminaire efficiency 89 %. Luminaire efficiency consists of thermal efficiency (93 %), driver efficiency (93 %), optical efficiency (94 %) and a correction factor for operating with reduced current (1.09). When compared to the state-of-art of discharge lamp luminaires' luminous efficacy (~60 lm/W), the luminaire luminous efficacy may be more than tripled in the future. If we use the suggested functional unit, kilometre of a lit road, we have to consider also luminaire's luminous intensity distribution, total luminous flux, pole height, pole spacing and other features as well. However, LED luminaires compete well with conventional discharge lamp luminaires. The luminous intensity distribution of a LED luminaire is enabled with external optics, usually with the lens, and thus the light can be directed to the area chosen even more effectively than with discharge lamp luminaires. Discharge lamp luminaires use reflectors to direct the light.

Benefits of LEDs over HPS luminaires can be summarized by 1) Higher luminous efficacy, 2) Higher lamp life, 3) Instant start with maximum luminous flux and no delay in re-ignition, 4) Luminous efficacy does not decrease in dimming, and 5) Dimming has no effect on lamp life [62]. In fact, reduced junction temperature in dimming use can increase LED's lifetime.

Table 1 shows that the optimized LED luminaire may result in an 83 % reduction in annual energy consumption compared to the HPS luminaire, whereas the current LED luminaire resulted in a 31 % reduction in energy consumption.

The future of road lighting systems is in intelligent lighting. Accordingly, CIE has developed a standard for intelligent road lighting that covers external parameters such as traffic density, remaining daylight level, road constructions, accidents and weather circumstances [29]. The development of the standard was supported by installing 20000 intelligent road lights across Europe (E-Street project [14]). As a result, an annual energy saving potential 38 TW·h was estimated by retrofitting old installations with intelligent road lighting. This represents approximately 64 % of the annual energy consumption of road lighting. The reason for the large-scale pilot of intelligent road lighting was based on the understanding that only low demand of light level is needed when there is very little traffic on the road. There has been a growing number of researchers in recent years that indicate that drivers do not require high lighting level when the traffic density is high because drivers' attention is on the back of the front car and in the range of car headlights [12, 25, 13]. Therefore, intelligent road lighting can be used not only in no or low traffic but also in high traffic, because of the illumination provided by car headlights. This also does not have an adverse effect on traffic safety.

LEDs and intelligent control technologies enable the change of outdoor lighting system in a way that the transition promotes sustainable development. LED luminaires improve sustainability of lighting especially due to the enhanced life cycle efficiency of the products. Moreover, the sustainability will be amplified by the emerging intelligent control technologies, which allow the supply of optimized lighting services based on the real-time demand of the users. However, we are still lacking knowledge of social impacts of road lighting, such as melatonin suppression. It is possible that in the future not only the light level is recommended, but also the correlated colour temperature (CCT). With LEDs, the CCT can be adjusted in the manufacturing process.

6. CONCLUSION

Today's energy and costs problems are accelerating the development of new technologies in road lighting systems. This paper has given an account of and the reasons for the future widespread use of LEDs and control technologies in road lighting. Some of the main benefits of using LEDs are long lamp life, high luminous efficacy and fast dimming. Therefore, the lighting control system can be adjusted in real-time based on real-time demand. Currently, several control systems are being practised which lead to saving energy. The control systems are mainly based on the ambient light, the amount of traffic and weather conditions. In periods when the traffic is low or when snow covers the road, the light output level can be reduced. Illumination of car headlights also has a great influence on the visibility of targets on the road.

The advancement of road lighting and control technology is going to change the concept of road lighting. The use of LEDs and intelligent control technology lead towards more sustainable lighting. Road lighting will be more efficient in economic and environmental terms and even in social terms. At the same time, the safety of drivers and other road users is on the same level or better than with conventional lighting solutions.

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ROAD CLASSIFICATION BASED ENERGY EFFICIENT DESIGN AND ITS VALIDATION FOR INDIAN ROADS

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ABSTRACT

Road lighting consumes a significant portion of global electricity. A good road lighting design ensures the fulfilment of visual requirements with optimized design. The initial step for a good road lighting design is to identify the exact lighting class of the concerned road. The existing Indian Road lighting Standard IS: 1944, 1970 is not so well defined with respect to the modern Indian roads. It demands a specific model for classifying any Indian road. This paper focuses towards the validation of a proposed model, which is a modified mathematical model as recommended by CIE: 115, 2010 for classifying the exact lighting category of the Indian roads. This paper also highlights the scope of energy saving by changing the design according to the changed lighting class during different traffic hours in night. Some innovative design is also proposed for a new road based on the proposed classification methodology.

1. INTRODUCTION

A road can be defined as a business connector, used by individuals to accomplish their business purpose. The lighting in the road guides the individuals through their journey to the place of affair inducing a strong influence on their mood and motivation. Thus, convenient road lighting is very necessary. Road lighting is a very special form of lighting design. The other necessities of road lighting are to allow all road users to proceed safely, to allow pedestrians to see hazards, recognize other pedestrians, and give them a sense of security, also to improve the night time appearance of the environment. To fulfil the requirements of road lighting, a proper road lighting design is required. Road lighting class is the most influencing parameter of a road lighting design. It demands the maximum attention as it defines all the photometric requirements in order to provide safety and security to road users, also to minimize the electricity consumption [1,2].

The two existing International Standards for road lighting are: CIE115, 2010 (Technical Report for Lighting of Roads for Motor and Pedestrian Traffic) and IESNA RP-8–00 (Roadway Lighting). CIE115, 2010 has proposed a model for the selection of appropriate lighting class based on luminance concept, taking into account the different parameters relevant for the given visual task [3].

In India, the road lighting standard is not well defined. It demands more specific consideration towards the optimized solution for the mixed traffic scenario in Indian roads. According to IS:1944, 1970 the roads are classified in six different groups-A, B, C, D, E, F. Group A and B are further classified into two sub-groups A1, A2 and B1, B2. In the standard, Group A1 refers to 'very important road with rapid and dense traffic' and Group A2 is for 'other type of main roads with considerable mixed traffic'. Group B is for 'secondary roads which do not require up to Group A'. Considering Group A, the term ‘important’ is a relative term which depends on users. The Indian Road Lighting Standard IS:1944, 1970 is based on illuminance but global standard says that instead of illuminance, luminance concept should be considered when selecting quality criteria for lighting roads. The normal direction of view of motorists is toward the road. The road surface forms the background to the objects present on the road. The surface is visible by virtue of light being reflected from it and entering the eye of the observer; thus the greater the amount of reflected light, the stronger will be the visual sensation which is measured by luminance. Illuminance is the amount of light falling on the surface; it is incapable of making any visual sensation; so luminance is considered as the photometric parameter for road lighting.

Hence a proper guideline is required for road lighting in Indian context. The recommendations in CIE: 115, 2010 are structured with such an intension that it is easily adaptable to the need of individual countries and it also serves for developing national standards for lighting [5]. Hence the ongoing development process of Indian road lighting standard proposed a new model following current CIE technical report on road lighting.

The aim of this paper is to validate the proposed new classification system for Indian roads and to demonstrate few case studies based on the proposed classification model [6].

2. DESCRIPTION OF THE MATHEMATICAL MODEL CONSIDERED FOR VALIDATION

The current CIE Technical Report CIE:115, 2010 for ‘Lighting of Roads for Motor and Pedestrian Traffic’ is the first step in making a new mathematical model based upon few traffic related parameters, ambiance related parameters considered with their corresponding weighting values [3]. This new mathematical model is a modification of the existing CIE: 115, 2010 model. As in India a mixed traffic scenario persists, the CIE: 115, 2010 model is modified, taking into consideration the critical aspects of Indian roads. The lighting classes for motorized road are classified into 6 different M lighting classes, from M1 to M6 and it also recommends the lighting criteria like, average luminance, overall uniformity, longitudinal uniformity, threshold increment, surrounding ratio for the corresponding class of road. The appropriate lighting class has to be selected according to traffic volume, traffic speed, traffic class, existence of medians and cross roads, surrounding brightness, existence of parked vehicles as well as visual guidance.

In the new model limits/ranges of the different parameters (traffic volume, traffic speed and ambient luminance) are set to classify the different motorized roads of India into M1, M2…M6 classes. Example the values for the three different categories of speed is provided for very high speed > (60 km/h), for high speed (40–60 km/h) and for moderate speed < (40km/h), with weights 1, 0.5 and 0 respectively. Similarly, the traffic density is categorized into very high> (60 traffic volume in number per min), high (50–60 traffic volume in number per min), moderate (30–50 traffic volume in number per min), low (10–30 traffic volume in number per min) and very low< (10 traffic volume in number per min) with weights 1, 0.5, 0, –0.5 and –1 respectively. In India a mixed traffic scenario persists in majority of the places, therefore to determine the type of traffic density or speed of vehicle by follow-

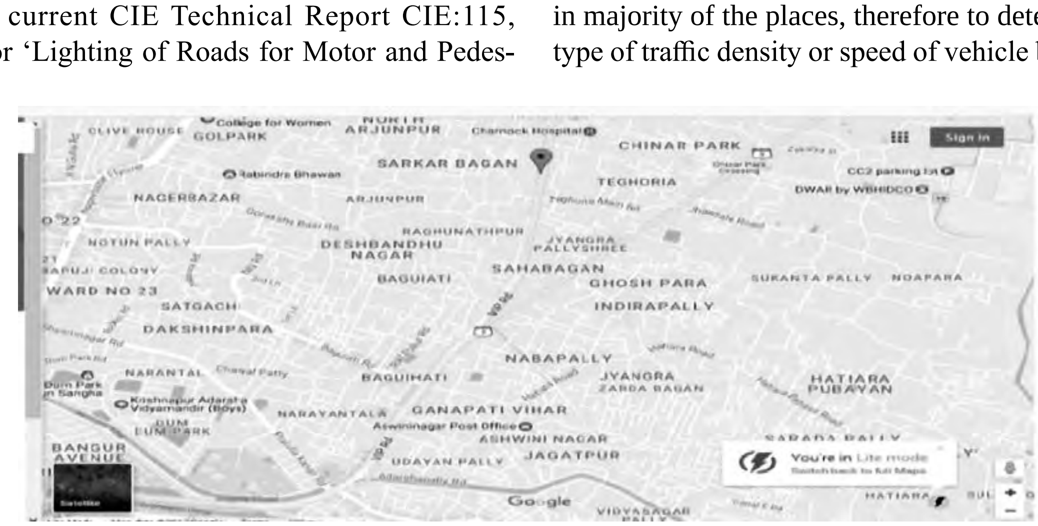


Fig. 1. Location of VIP Road

Table 1. Classification of Different Roads with Respect to New Model as per Indian Context

Sl No.	**Road name**	**Traffic volume in № / min**					**Traffic speed, km/h**			**Traffic class**			**Median**		**Cross road**		**Surrounding brightness**			**Parked vehicle**		**Visual guidance**		**Sum of weights (*Vws*)**	**Class of road (6-V_{ws})**	**Class as rounded up**
		60 and above, very high	**50–60, high**	**30–50, moderate**	**10–30, low**	**<10, very low**	**>60 Very High**	**40–60, High**	**<40, moderate**	**Mixed with High % of non-motorized**	**Mixed**	**Motorized only**	**No**	**Yes**	**High (above 3 nos. \Km)**	**Moderate (below 3 nos.\ Km)**	**High**	**Moderate**	**Low**	**Present**	**Not Present**	**Poor**	**Moderate or Good**			
		Weights					weights			weights			Weights		Weights		weights			Weights		Weights				
		1	**0.5**	0	-0.5	-1	1	0.5	0	0	1	2	1	0	1	0	**1**	**0**	**-1**	**0.5**	**0**	**0.5**	**0**			
1	G.T. ROAD	1					1			2			0		1		0			0		0.5		5.5	0.5	1
2	VIP ROAD	0					1			2			1		1		0			0		0		5	1	1
3	APC ROAD	0.5					0.5			2			1		0		0			0		0		4	2	2
4	BIDHAN SARANI	0					0			2			1		0		0			0		0		3	3	3
5	BALLYGUNGE CIRCULAR ROAD	0					0			2			1		0		0			0		0		3	3	3

6	S. C. MALLIK ROAD(BAGHA-JATIN)	0	0	1	0	1	0	0.5	0	2.5	3.5	3
7	PURNO DAS ROAD	0	0	2	1	0	0	0	0	3	3	3
8	MAYFAIR ROAD	-0.5	0	1	1	0	0	0.5	0	2	4	4
9	DOVER LANE	-1	0	0	1	0	0	0.5	0.5	1	5	5
10	NKDA 160	-1	0	1	1	0	-1	0	0.5	0.5	5.5	5
11	JATINDRA MO-HAN SARANI	-1	0	1	1	0	-1	0.5	0.5	1	5	5

ing the guideline a minute observation is very much essential. In CIE: 115, 2010, the lighting class is determined by the formula,

$$M = 6 - V_{ws}, \text{ where}$$

V_{ws} denotes the sum of all the weighing values. If M is not an integer, it is advised to adopt the first lower integer. This formula only holds for V_{ws} having values less or equal to 5. In Indian context, analysis shows that there are situations where weighing value greater than 5 may be obtained. Thus, to overcome this limitation in selection of the lighting class the existing formula is amended as per convenience. The revised formula to determine the lighting class is

$$M = 6 - V_{ws},\ V_{ws} <= 5,$$
$$M = 1,\ V_{ws} > 5,$$

where V_{ws} denotes the sum of all the weighing values. If M is not an integer, it is advised to adopt the first lower integer.

3. VALIDATION OF THE MATHEMATICAL MODEL FOR ROAD LIGHTING IN INDIAN SCENARIO

Validation is the process of ensuring that a model is sufficiently accurate for the required purpose; in other words, building the right model for a particular purpose. No model is ever fully accurate; indeed, there are justifiable reasons for not having completely accurate models. Further, the accuracy of any model is determined with reference to the purpose for which the model is to be used. In this paper the sole aim is to ensure that the model, which is a modified version of CIE: 115, 2010, is sufficiently accurate in determining the lighting class of the Indian roads, Table 1.

For validating the model, few motorized roads of Kolkata are considered. Uniqueness of Kolkata lies in the fact that it is one of the most populous metropolitan cities of India having a typical mixed traffic scenario. The motorized roads under consideration are surveyed and their distinct features are identified. Considering these distinct features of individual road, they are classified into different lighting classes. Table 1 exhibits the classification of few roads of Kolkata with respect to the modified CIE model. An extremely busy road with rapid traffic should obviously fall under a higher street lighting class than a comparatively less important road. But if a reverse situation happens, then the model used to determine the lighting class of the road is questionable.

As per Table 1, Grand Trunk Road (G.T. Road), the summation of V_{WS} is coming as 5.5. This is a very important and main road, hence, the exact class for this road is coming M1.Ballygunge Circular Road has a higher lighting class than Mayfair Road. By analyzing the practical scenario, the class of Mayfair Road should be lower than Ballygunge Circular Road as the traffic density of the latter one is much higher that the former one. Again considering Dover Lane, a very lonely road, has a lighting class lower than Mayfair Road, which is also justifiable. Thus, analysis says that the proposed classification system for Indian roads is valid, as it holds a sufficient accuracy in determining the road lighting class.

4. DEMONSTRATION OF FEW CASE STUDIES OF ROAD LIGHTING DESIGN BASED ON THE PROPOSED CLASSIFICATION MODEL

Few roads of Kolkata are classified considering the new model, and case study of these roads is done. In the case study, retrofit designing is carried out for each road.

– Vip Road lighting design condition and its existing traffic data is officially known as Kazi Nazrul Islam Sarani is a major thoroughfare connecting the city Kolkata with the Netaji Subhas Chandra Bose International Airport. It's located in the north-east outskirts of the city having an average width of 15 meters. There is also a median of 1 meter present throughout the roadway. Fig.1 shows the location of VIP Road. Fig. 2 shows the real time picture of this road.

Only motorized traffic is present with a very high average speed of more than 60 kmph. As the road leads towards the sole airport of the city, the traffic density is also very high; almost 50–60 vehicles flow per min. The visual guidance of the road is quite good because it's one of the most important roads of Kolkata.

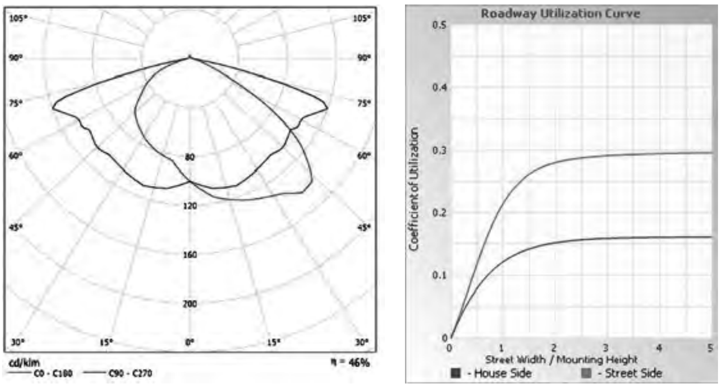
Thus analyzing the existing condition, the road class is found out to be M1. 400W High Pressure Sodium Vapor (HPS) luminaire (Fig. 3) is present with median arrangement, having mounting height 8 meter and span 18 meter.

– Redesigning of the lighting condition of the road – the controlling criteria of lighting of roads for motorized traffic are average luminance (L_{av}), overall uniformity (U_0), longitudinal uniformity (U_1), and surrounding ratio (SR). The recommended values of these parameters for different types of motorized roads are provided in CIE: 115, 2010. For every road, depending on its type of lighting class these criteria should be satisfied. But for VIP road it's seen that the criteria are not being satisfied as per its existing condition (details are provided in Table 2), thus retrofit designing is done for this road.

The luminaire used is changed and the height of the pole is also changed to fulfill the required value. Designing is done with 250W LED luminaire (Fig. 4) with median arrangement, having mounting height 10 meter and span 18 meter.

In Table 2 the comparison between the required value, the existing value and the achieved value is shown. The retrofit design does not satisfy the required value, but the achieved value by the retrofit

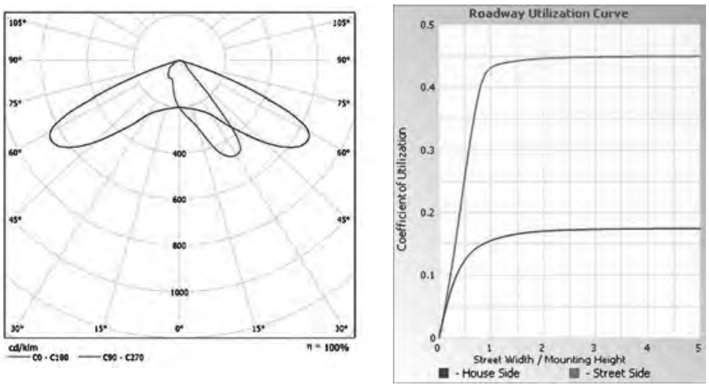
Fig. 2. Real time picture of VIP Road



Polar curve of 400W HPS luminaire

Coefficient of utilization (COU) of 400W HPS luminaire

Fig. 3 Polar Curve & COU diagram of 400W HPS luminaire



Polar curve of 250W LED luminaire

Coefficient of utilization (COU) of 250W LED luminaire

Fig. 4 Polar Curve & COU diagram of 250W LED luminaire

design is better than the value achieved by the existing design. The wattage of the luminaire used for retrofit design is much lower than the existent luminaire, which results in a huge energy saving.

– Energy saving calculation for existing design 400 W HPS is used, having an18-meter span and pole on median arrangement. Number of 400W lamp based luminaires required for the 1 km length equal to 110. Power consumption for a single 400W lamp and ballast system installed at existing pole is (400+58) W = 458 W. The total daily energy consumption of 400 W lamps for 12 h is (458×110×12) Wh = 604 kWh. For new design 250 W LED is used, having an 18-meter span and pole on median arrangement. Number of 250W LED based luminaires required for the 1 km length is equal to 110. Power consumption for a single 250W lamp and driver system installed at existing pole is equal to (250+12) W = 262 W. The total daily energy consumption of 250 W lamp for 12h is (262×110×12) Wh = 346 kWh. Hence, total daily energy saving from 400W HPS lamp to 250W LED for 1km length span of road is equal to (604–346) kWh = 258 kWh.

– When the road is classifying with respect to time, another vital issue of the time dependent lighting requirements changes is appearing. Generally, to classify any road, the weighting values of different traffic parameters are taken for evening peak hours. The recommended values of different lighting parameters are set considering the scenario of peak traffic hours. But a road that falls under a specific lighting class at evening peak hours may not fall under same lighting class at night time. The number of moving vehicles and their speed in a particular road changes with time. Changes may also occur for surrounding luminance. These changes results in the change of the lighting class of the road. For VIP Road a survey was done from 6.00pm to 12pm and from 00.01am to 6.00am. The traffic volume differs for these two separate time span. VIP Road having M1 class, changes to M2 class for the night time, i.e. off peak hours. The use of LED based luminaire not only provides the electrical energy savings, through the reduced installed power, it can also be dimmed as required. A 250 W LED luminaire is used for evening peak hours, which is dimmed to 172 W after midnight. Table 3 shows the

Table 2. Comparison of the Recommended Values of Photometric Parameters, Between the Existing Design and Retrofit Design Value

Class- M1	Recommended values of road lighting design parameter for motorized traffic mentioned in CIE115, 2010	Existing lighting design of VIP Road using 400W HPS luminaire	Retrofit design of VIP Road using 250WLEDluminaire
L_{av}	2.0	2.14	2.32
U_0	0.4	0.36	0.5
U_1	0.7	0.35	0.47
S.R	0.5	0.92	0.96

Table 3. Values of the Photometric Parameter Using a Dimmed LED Luminaire

Class- M2	Recommended values of road lighting design parameter for motorized traffic mentioned in CIE115, 2010	Retrofit design of VIP Road using 250 W LED in dimmed condition i.e. at 172W
L_{av}	1.5	1.49
U_0	0.4	0.5
U_1	0.7	0.47
SR	0.5	0.96

values of the photometric parameters achieved after dimming.

The similar studies have been carried out in few different categories roads of Kolkata. The results have been tabulated in Tables 4,5,6,7.

5. DEMONSTRATION OF A NEW ROAD DESIGN

A new road of width 15 meter is considered, which needs to be designed. The road has motorized traffic condition with vehicles moving at a very high speed and no parked vehicles present. The road lighting design of this street needs to be accomplished. The first step towards road lighting design is to find out the lighting class of the road which needs to be designed. Therefore, the lighting class of the considered road needs to be determined.

While analyzing the present scenario of the considered road it's seen that the road falls under M1 type of lighting class. Succeeding the class determination, proper designing needs to be carried out. To procure an appropriate design, the recommended values of M1 class for average luminance, overall and longitudinal uniformity, threshold increment and surrounding ratio need to be satisfied. Three types of light sources are considered:

– High pressure sodium vapour (HPS),
– Metal Halide (MH),
– LED.

Designing is done by these light sources. Table 8 shows the comparison of the obtained values by the three different luminaires. ***Therefore it is preferable to use 240W LED.***

Another vital issue is the time dependent changes of the lighting requirements. With time the number of moving vehicles in a particular road changes. Surrounding brightness may also vary with time. These changes result in the change of lighting class. For the above considered road the traffic volume is high from 6pm-11pm, almost 50–60 number of vehicles/minute are present; with the growing hours of night the traffic volume decreases gradually, it comes down to 30–50 number of vehicle/ min from 11pm to 2am, further it decreases to 10–30 vehicle number/min from 2am to 6am.There is a change noticed in the surrounding brightness also, after midnight it decreases to a lower level. Consequently, M1 type of road converts to M2 or M3 type of road. For M2 or M3 type of road the value of required luminance is less than that for M1 type of road.

Thus, when the luminance requirement is less, a lower wattage luminaire is required, but it's not possible to use two different wattage luminaire (at different time span) for the same road. LED, having a dimmable functionality, is preferred be

Table 4. Comparison of their Commended Values of Photometric Parameters, Between the Existing Design and Retrofit Design Value

Class- M2	Recommended values of road lighting design parameter for motorized traffic mentioned in CIE115, 2010	Existing lighting design of APC Road using 400W HPS luminaire	Retrofit design of APC Road using 250W MH luminaire
L_{av}	1.5	0.86	1.6
U_0	0.4	0.61	0.71
U_1	0.7	0.55	0.71
SR	0.5	0.98	0.95

Table 5. Comparison of Recommended Value of Photometric Parameters Between the Existing and Retrofit Design Value

Class- M3	Recommended values of road lighting design parameter for Motorized traffic mentioned in CIE115, 2010	Existing lighting design of Purno Das Road using 400 W HPS Luminaire	Retrofit design of Purno das Road using the under mention Luminaire 135 W LED Luminaire
L_{av}	1.0	0.9	1.4
U_0	0.4	0.71	0.67
U_1	0.6	0.53	0.57
SR	0.5	0.93	0.89

Table 6. Value of the Photometric Parameter Using Dimmed LED Luminaire

Class- M4	Recommended values of road lighting design parameter for Motorized traffic mentioned in CIE115, 2010	Retrofit design of Purno Das Road using 135W LED in dimmed condition i.e. at 90W
L_{av}	0.5	0.82
U_0	0.4	0.73
U_1	0.6	0.73
SR	0.5	0.9

used in these cases. Hence, for the considered road design with 240W LED is recommended, which can be dimmed as required. The change in the class of road with the changing hours of the day is shown in the Table 9.

With change of lighting class the requirement of luminance changes. Designing is done with dimming the 240W LED luminaire to 210W for M2 and 125W for M3 class, which is shown in Table10. It's seen that the desired level of photometric values is achieved by dimming the LED luminaire. Energy required for this condition is calculated below.

240 Watt LED is used, having a 16 meter span and double row opposing arrangement. Number of 240W LED based luminaires required for the 1 km length is 126. Power consumption for a single 240W lamp and driver system installed at existing pole is (240+10) W. The energy consumption from 6pm to 11pm of 240 W lamp for 5 h is (250×126×5) Wh= 157.5 kWh. Power consumption for a single 210W lamp and driver system installed at existing pole is (210+10) W. The energy consumption from 11pm to 2 am of 210 W lamp for 3 h is (220×126×3) Wh = 83.2 kWh. Power consumption for a single 125W lamp and driver system installed at existing pole is (125+10) W. The energy consumption from 2 am to 6am of 125 W lamp for 4h is (135×126×4) Wh = 68 kWh. The total daily energy consumption of 240 W lamp with dimming condition for 12 h is (157.5+83.2+68) Wh =308.7 kWh. Therefore, if dimming is done then energy consumed can be further reduced to 308.7 kWh from 378 kWh. Al-

Table 7. Comparison of Recommended Value of Photometric Parameters Between the Existing and Retrofit Design Value

Class-M5	Recommended values of road lighting design parameter for Motorized traffic mentioned in CIE115, 2010	Existing lighting design of Dover Lane using 135W LED luminaire	Retrofit Design of Dover Lane using 90W LED luminaire
L_{av}	0.5	1.01	0.53
U_0	0.35	0.3	0.59
U_1	0.4	0.62	0.57
SR	0.5	0.9	0.86

Table 8. Comparison of Recommended Value of Photometric Parameters Between the Existing and Retrofit Design Value

Class-M1	Recommended Values of Road Lighting Design Parameter for Motorized traffic Mentioned in CIE115, 2010	Lighting Design of New Road using 250W HPS Luminaire	Lighting Design of New Road using 250 W MH Luminaire	Lighting Design of New Road using 240W LED Luminaire
L_{av}	2	2.08	3.03	2.16
U_0	0.4	0.69	0.3	0.8
U_1	0.7	0.72	0.85	0.74
SR	0.5	0.97	0.49	0.5

most 70 kWh can be saved daily by just dimming the LED light.

Thus, for this 15-meter road designing by 240 W LED luminaire is recommended, keeping the arrangement double row opposing with a span of 16m and height of pole 9 m. For the peak hours (6–11) pm no dimming is required, from 11pm to 2am the LED luminaire should be dimmed down to 210W and further it should be dimmed down to 125W from 2am to 6 am to obtain the most optimum energy efficient design.

6. DISCUSSION

The entire paper depicts the enormous possibilities of changes to be inducted in road lighting design in Indian scenario. The example of VIP Road as has been given here clearly reveals that possibilities of up gradation of road lighting design. VIP Road is a very important road with just motorized traffic. The mathematical model as modified over existing CIE suggests that the lighting class of VIP road will be M1. The existing lighting design of VIP road is made with 400 W HPS luminaire, with 10 meter mounting height, and 18 meter spacing. The measured results are appreciably less than the recommended value. If the same is redesigned with LED maintaining the exact light level and uniformities as recommended for the specific lighting class, enormous energy will be saved as well as photometric and visual criteria are perfectly satisfying. Similarly, for Purno das Road (mixed traffic mainly motorized) the existing lighting design is made with 400 W HPS luminaire, with 9 meter mounting height and 20-meter spacing. The measured results of the existing setup are appreciably less than the recommended value. Hence, determination of exact lighting class and their energy efficient design based upon that will be the most optimized road lighting design in all the possible way.

7. CONCLUSION

A complete optimized road design encompasses all the possible aspects of photometric requirements as well as visual requirements with energy saving dimensioning. The optimization term will be justified in the context of energy saving as well

Table 9. Classification of the New Road for Different Time Span With Respect to New Model as per Indian Context

Sl No.	Road name	Traffic volume in № ./ min					Traffic speed km/h			Traffic class			Median		Cross road		Surrounding brightness			Parked vehicle		Visual guidance		Sum of weights (Vws)	Class of road (6-Vws)	Class as rounded up
		60 and above, very high	50–60, high	30–50, moderate	10–30, low	<10, very low	>60 Very High	40–60, High	<40, moderate	Mixed with High% of non-motorized	Mixed	Motorized only	No	Yes	High (above 3 nos. \Km)	Moderate (below 3 nos.\Km)	High	Moderate	Low	Present	Not Present	Poor	Moderate or Good			
		Weights					weights			weights			weights		weights		weights			Weights		weights				
		1	0.5	0	-0.5	-1	1	0.5	0	0	1	2	1	0	1	0	1	0	-1	0.5	0	0.5	0			
a)	NEW ROAD (6pm-11pm)	0.5					1			2			0		1		0			0		0		4.5	1.5	1
b)	NEW ROAD (11pm-2am)	0					1			2			0		1		0			0		0		4	2	2
c)	NEW ROAD (2am-5am)	-0.5					1			2			0		1		-1			0		0		2.5	3.5	3

Table 10. Comparison of Recommended Value of Photometric Parameters With the Achieved Values for New Road for Different Time Span

NEW ROAD	Class- M1(6pm-11pm)		Class- M2(11pm-2am)		Class- M3(2am-6am)	
	Recommended values of road lighting design parameter for Motorized traffic mentioned in CIE115, 2010	Lighting design of new road using 240W LED luminaire	Recommended values of road lighting design parameter for Motorized traffic mentioned in CIE115, 2010	Lighting design of new road using dimmed 240W LED luminaire (210W)	Recommended values of road lighting design parameter for Motorized traffic mentioned in CIE115, 2010	Lighting design of new road using dimmed 240W LED luminaire (125W)
L_{av}	2	2.16	1.5	1.66	1.0	1.12
U_0	0.4	0.8	0.4	0.8	0.4	0.8
U_1	0.7	0.74	0.7	0.74	0.6	0.74
SR	0.5	0.5	0.5	0.5	0.5	0.5

as requirements of road lighting. The different international and national standards say about the necessity of lighting classification of road. The classification methodology can help categorization of different roads from the traffic importance. This paper depicts that necessity of lighting classification of road in Indian context. Moreover, it also proposes a specific methodology to classify the Indian road from their traffic requirement. Indian road is typically mixed in nature. Hence, this specific classification methodology is suitable for lighting classification of road. The validation of the model has been executed with different roads of a metro city like Kolkata, as this city roads are more complex in nature. Moreover, the novelty of the paper is that, this paper depicts, how the requirement of lighting design parameters changed, even in the low traffic hours. This categorization method, suggests a specific shifting of the lighting class of a same road in different traffic hours at night time. Hence, lighting design of the roads should be done with luminaires having pre-programmed multi stage dimming facilities to achieve the desired lighting parameters during different traffic hours in night time. This can lead to a huge energy saving.

The other aspect, with which the paper has been dealt with, is how this classification system can be used for sake of optimized road lighting design. The evolved lighting class of the road will ensure the exact requirement of the photometric parameters for the concerned road. Hence, a step towards over designing will not at all be that frequent. The selections of luminaires as well as installation characteristics are the most vital criteria for quality road lighting design. This paper clearly reveals that aspect too. The selection of luminaire for a specific road lighting application is the most important step. The positioning of the luminaires, mounting height etc. are the installation characteristics which may change an entire design in a broader dimension. Though, the spectrum of the light sources plays a significant role in road lighting design, but that aspect has not elaborated in this paper.

This paper may finally be considered as a comprehensive guideline for optimized road lighting design. As the different countries have their different requirements based upon their nature of traffic, the proposed classification metric is also a pioneering step in Indian road lighting design.

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INFLUENCE OF GOVERNMENTAL SUBSIDIES ON GROWTH OF PHOTOVOLTAIC ENTERPRISES: EMPIRICAL EVIDENCE FROM CHINA

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ABSTRACT

As an emerging industry, photovoltaic industry has won strong support from the government. However, many problems appear in industrial development with increasing maturation of photovoltaic industrial development. The governmental effect has a critical bearing on photovoltaic industrial development as governmental policies-driven industry. In order to investigate the influence of governmental intervention on growth of photovoltaic enterprises, sample data related to photovoltaic enterprises in Chinese A-share market during 2007–2017 were selected, and the influences of fiscal subsidies and tax preferences on growth of photovoltaic enterprises were analyzed. The results show that both fiscal subsidies and tax preferences have positive promoting effects on growth of photovoltaic enterprises and influence of fiscal subsidies is more obvious. The conclusions provide decision-making support for the government to formulate intervening policies facilitating growth of photovoltaic enterprises.

Keywords: governmental subsidies, growth, photovoltaic enterprises

1. INTRODUCTION

With rapid economic development in China, excessive resource consumption and environmental damage caused by extensive-type economic development have become problems needing urgent solutions. In order to promote sustainable socio-economic development, facilitate comprehensive upgrading of industrial structure and relieve enormous pressure brought by resource environment, transforming economic development mode is a feasible measure. As a renewable energy source, solar energy has numerous advantages like cleanness, no pollution, no regional limitations, inexhaustible property, etc. Photovoltaic industry is enterprise set, which converts solar energy into electric energy through photovoltaic effect to form industrial chain of photovoltaic conversion, including production of polycrystalline silicon raw material, production of solar batteries and components, manufacturing and application of related equipment, etc. [1]. Therefore, photovoltaic industry is of environmental friendly feature and has drawn much concern of national governments.

Governments the world over have formulated numerous subsidy policies for industrial development to promote development of photovoltaic industry. Germany is the first country, which implements industrial policies to support photovoltaic industry and enacted feed-in tariff subsidy policies. The United States tends to tax incentive and preferential policies [2], and China has implemented "golden roof program", "top runner program" and all kinds of subsidy and incentive policies in order to support development of photovoltaic industry. Governmental subsidy support exerts important promoting effect on rapid development of Chinese photovoltaic industry [3]. Firstly, governmental subsidy policies facilitate continuous expansion of industrial scale.

Polycrystalline silicon output reached 194,000t in 2016 with 17.5 % year-on-year growth rate. Silicon wafer output was about 63GW with 31.2 % year-on-year growth rate. Output of photovoltaic modules was about 53GW with 20.7 % year-on-year growth rate. Added installed capacity in photovoltaic grid connection reached 34.5GW with 127 % year-on-year growth rate. Proportions of production scales in various links of photovoltaic industrial chain all exceeded 50 % in the globe, ranking the first place. Secondly, governmental subsidy policies promote good prospect of operation state of photovoltaic enterprises. In 2016, number of enterprises occupied in photovoltaic industrial production reached over 2,000, and average profit rate of enterprises increased by 3 percentages in China. Among listed photovoltaic enterprises, 9 ones enjoyed profit growth with amplitudes exceeding 100 %. Finally governmental subsidy policies accelerate industrialization of advanced technologies. Industrialization of a batch of high-efficient crystalline silicon photovoltaic cell technologies, like black silicon texturizing, back face passivation (PERC), and *n*-type double face, is accelerated. Average conversion efficiency of monocrystal and polycrystalline batteries has reached 20.5 % and 19.1 %; polycrystalline silicon production technology has been further optimized.

It can be seen that rapid development of Chinese photovoltaic industry is closely related to growth of photovoltaic enterprises. Favourable growth of photovoltaic enterprises can promote benign development of photovoltaic industry. As governmentally supported industry, rapid development of photovoltaic industry can't go without governmental policies. Governmental subsidy is a common means of the governmental supporting development of photovoltaic industry. In order to facilitate smooth and benign development of photovoltaic industry, analyzing influence of governmental policies on growth of photovoltaic enterprises helps to figure out action mechanism of governmental intervention on photovoltaic industry and provides theoretical reference and decision-making support for formulation of governmental policies.

2. THEORETICAL ANALYSIS AND HYPOTHESES

As an important constituent part of industrial policies and fiscal policies, governmental subsidy can boost economic structural adjustment. Fiscal taxation policy refers to the fact that on the one hand, a country allocates fiscal resources, perfect scientific and technological public infrastructure, increase input of R&D innovation expense and reach the goal of reducing technological innovation risks of enterprises according to enterprise demands for public finance. On the other hand, it reduces enterprise production cost through tax preferences. Policies motivating enterprises to conduct R&D innovation and governmental fiscal taxation policies implemented for enterprises can release partial governmental earnings to enterprises to realize governmental goal of supporting one industry so as to reduce enterprise production cost and operation risk, increase profit and finally promote enterprise development. The fiscal and taxation policy guides the role of social resources to the industries that the government wants to support, so as to enhance the innovation and competitiveness of enterprises. F. Bergström [4] found that government subsidies increased the economic value added of enterprises and promoted the growth of enterprises. Research conducted by K. Dongmin et al. [5] found that governmental subsidies improved enterprise operating performance and social responsibility and for state-owned enterprises governmental subsidies had more obvious improving effects on operating performance and social responsibility of private enterprises. A. Cerqua & G. Pellegrini [6] analyzed Italian fiscal subsidy policies and found that fiscal subsidies significantly enlarged employee scale of the enterprise receiving the subsidy, investment level and company growth.

The fiscal taxation policy support for photovoltaic enterprises can not only solve problems like financial difficulty encountered during enterprise development process and compensate for deficiencies of market economy but also can facilitate enterprises to improve their own R&D innovation abilities so, as to boost growth of photovoltaic enterprises. As an emerging industry, photovoltaic industry needs enormous capital input during development process due to high technical requirements, but unavoidable contradictions still exist during development process of photovoltaic industry because of problems existing in financing mechanism and governmental supportive policy mechanism mainly including national fiscal taxation policy guidance and insufficient innovative impetus of the enterprises themselves. It's generally believed in theoretical exploration that the government should give full play to supportive effect of governmental fiscal subsidy and enhance incentive and guiding effect of preferential tax policies. The government can facilitate photovoltaic enterprises to actively innovate and boost rapid and stable development of photovoltaic industry through coordination and cooperation of the two. Governmental fiscal subsidy and tax preference belong to the main part of fiscal taxation policy, so the government actively exerting effects of fiscal subsidies and tax preferences on photovoltaic industry is of critical importance to industrial development. According to the above analysis, fiscal subsidies and tax preferences can solve problems of photovoltaic enterprises like financial difficulty and insufficient innovation ability so as to promote growth of photovoltaic enterprises, based on which the following hypotheses are proposed:

Hypothesis 1: Fiscal subsidies have positive effect on growth of photovoltaic enterprises.

Hypothesis 2: Taxation preference has positive effect on growth of photovoltaic enterprises.

In addition, compared with fiscal subsidies, tax preference has some apparent defects: firstly, in terms of action objects, most preferential tax policies implemented in China are only effective for profitable enterprises in the same year, but for unprofitable enterprises and newly built enterprises without operation revenue yet, they can't enjoy these preferential policies in reality. However, for large enterprises in mature stage, these newly built enterprises and medium and small-sized enterprises have more intense demands for R&D support [7]; secondly, from the time when the policies take effect, tax preference exerts effect slower, and influence of fiscal subsidies is more direct and rapidly; thirdly, as for cost, implementation cost of preferential tax policies (like administrative cost of relevant departments, declaration cost of taxpayers, etc.) is higher than that of fiscal subsidies [8]. Based on the above analysis, the following hypothesis is proposed:

H3: Compared with tax preferences, fiscal subsidy can more obviously improve growth of photovoltaic enterprises.

3. METHODOLOGY

101 listed photovoltaic companies were searched from Pole Star Solar Photovoltaic Website (http://guangfu.bjx.com.cn/), 33 companies listed abroad like in New York and 13 companies listed after 2007 were excluded, 55 photovoltaic enterprises listed in Shenzhen Stock Exchange and Shanghai Stock Exchange were obtained, and finally data of the 55 listed photovoltaic enterprises during 2007–2017 were selected as research samples. All data used in this study were from annual reports announced by listed companies (source: Shenzhen Stock Exchange Website, Shanghai Stock Exchange Website and Cninf Website) and CSMAR database, and SPSS22.0 software was used during empirical analysis process to complete the models as follow:

$$G_{t+1}=a_0 + a_1F_t + a_2C_t + e, \quad (1)$$

$$G_{t+1}=b_0 + b_1T_t + b_2C_t + e, \quad (2)$$

where G is explained variable representing enterprise growth. According to finds of R.M. Stulz on enterprise growth evaluation [9], Tobin's Q value is selected in this study to measure growth of photovoltaic enterprises. Explaining variables F and T express fiscal subsidy and tax preference respectively. Direct fiscal subsidy and tax refund are the most common means of governmental subsidies [10], so fiscal subsidy and tax preference are selected in this paper as explaining variables to study their influences on enterprise growth. Variables in the model were fiscal subsidy and tax preference, relative indexes, which were obtained by dividing enterprise total asset by direct subsidy amount and dividing enterprise total asset by tax preference, were respectively selected, and lag one variables were selected combining lag features of governmental subsidies. C was combination of control variables, and photovoltaic enterprise scale, financial leverage, technological innovation ability, equity concentration, and capital structure were selected as control variables. Concrete variable settings are shown in Table 1.

4. RESULTS ANALYSIS AND DISCUSSION

4.1. Descriptive Statistical Analysis

Table 2 lists descriptive statistical results of explained variables, explaining variables and control variables.

As shown in Table 2, mean value of comprehensive growth scores of photovoltaic enterprises

Table 1. Descriptions of Main Variables

Variable type	Variable	Symbol	Variable explanation
Explained variable	Growth	*G*	Tobin's Q
Explaining variable	Fiscal subsidy	*F*	Direct subsidy amount/total asset
	Tax preference	*T*	Tax preference amount/total asset
Control variable	Enterprise scale	*Size*	Logarithm of enterprise total asset
	Financial leverage	*DEL*	(Net profit + income tax expense + financial expense)/ (net profit + income tax expense)
	Annual dummy variable	*Year*	It's taken as 0 when it's in the same year, or otherwise it's taken as 1
	Equity concentration	*CON*	Shareholding ratio of the first majority shareholder=-total shares held by the first majority shareholder/total number of shares
	Capital structure	*Debt*	Debt/asset ratio
	Technological innovation ability	*RDI*	R&D expenditure/main business income

Note: Both amounts of explaining variables governmental subsidy and tax preference and amount of R & D expenditure calculating technological innovation ability in control variables come from annual reports of listed companies and are obtained by the author through artificial collection; other data come from CSMAR database.

is 0.0001, maximum value is 1.76, minimum value is –2.74, difference between maximum value and minimum value is 4.5 and standard deviation is 0.46617, indicating that growth difference between sample companies is not great. Maximum value of governmental subsidy is 89.56, minimum value is 0, difference between maximum value and minimum value is 89.56 and standard deviation is 7.61276, indicating that great difference exists in governmental subsidies obtained by sample companies, possibly because some sample enterprises have not obtained national fiscal subsidies in some years within the research interval. Maximum value of tax preference is 10.14, minimum value is 0, difference between maximum value and minimum value is 10.14 and standard deviation is 1.09457, indicating great difference in tax preferences given to sample companies, possibly because many enterprises have not obtained preferential tax policies actually or tax preferences have not been given to listed photovoltaic enterprises in some years within sample research interval.

4.2. Analysis of Regression Results

Table 3 presents results of multivariate regression analysis.

From regression results in model (1), regression coefficient of fiscal subsidy (*F*) is 0.056 and passes *T* hypothesis testing at 5 % significance level [11], indicating that influence of fiscal subsidies on growth of photovoltaic enterprises is positive. According to regression results of mode (2), regression coefficient of tax preference (*T*) is 0.003 and passes *T* hypothesis testing at 10 % significance level, indicating that tax preference has positive influence on growth of photovoltaic enterprises. The greater the fiscal input, the better the growth of photovoltaic enterprises. The stronger the tax preference, the better the growth of photovoltaic enterprises, and the two verify hypotheses 1 and 2, and this is consistent with research findings of L. Xuhong, B. Charles & M. Pierre, and L. Chuanxian & L. Xiaoyu [12–14]. In addition, in terms of regression coefficients of fiscal subsidy (*F*) and tax preference (*T*), fiscal subsidy (*F*) coefficient 0.056 is greater than tax preference (*T*) coefficient 0.003, indicating that compared with tax preference, fiscal subsidy has greater influence on growth of photovoltaic enterprises, so hypothesis 3 is verified.

It can be seen from empirical results that during the process of supporting development of photovoltaic industry, the government should manage the relationship between governmental effect and

Table 2. Descriptive Statistical Results of Variables

Variable	Symbol	Maximum value	Minimum value	Mean value	Standard deviation
Growth	*G*	1.76	-2.74	0.0001	0.46617
Fiscal subsidy	*F*	89.56	0.00	4.8109	7.61276
Tax preference	*T*	10.14	0.00	0.3989	1.09457
Enterprise scale	*Size*	11.39	8.67	9.5924	0.50109
Financial leverage	*DEL*	13.59	-13.07	1.6525	1.73527
Annual dummy variable	*CON*	0.71	0.000	0.3481	0.14040
Equity concentration	*Debt*	1.20	0.06	0.5311	0.17301
Capital structure	*RDI*	0.28	0.00	0.0157	0.02795

market, respect market laws, select proper intervention mode and degree, give full play to supporting effect of governmental fiscal subsidies and incentive and guiding function of preferential tax policies and encourage photovoltaic enterprises to conduct self-innovation so as to promote their own development. The government should enlarge capital input, support development of medium and small-sized photovoltaic enterprises and perfect pathways like capital market to promote development of photovoltaic industry from the angle of fiscal subsidy. But it should further perfect fiscal subsidy mechanism, using sufficient capital to support related enterprises, which play leading roles in science and technology, while for photovoltaic enterprises with bad development prospect or those that are disqualified, the government should respect "survival of the fittest" market rule to reduce unnecessary waste of capital. Secondly, superior resources should be integrated. R&D tasks of key technologies should be carried out by building national-level photovoltaic technological development institutes and combining development status and concrete conditions of photovoltaic industry, like studying new-type solar cells [15]. Thirdly, special funds for development of photovoltaic industry should be set up to promote innovative R&D activities of photovoltaic enterprises.

From an angle of taxation, the government should stimulate innovation of photovoltaic enterprises to give full play to governmental intervention effect by means of intensifying tax preferences, formulating specialized preferential tax reduction and exemption policies and reducing cost of tax payment. Firstly, partial technological R&D expense can be used to offset certain tax to reach the goal of improving innovation ability while reducing enterprise production and operation cost, and risk allowance for R&D can be withdrawn according to certain proportion of operation revenue of photovoltaic enterprises and is allowed to be deducted before taxation by the enterprise. Secondly, scientific research cooperation between universities and enterprises can be promoted so that innovation abilities of universities and R&D abilities of enterprises can be integrated and finally universities can get better understanding of actual economic development status. Enterprises' innovation enthusiasm will surge ahead under the help of scientific research forces in universities so as to boost rapid and good development of photovoltaic industry. Thirdly, production cycle of photovoltaic enterprises is long, so fund withdrawal is slow, and then the government can delay tax payment like for 1–2 years to relieve pressure of photovoltaic enterprises in capital. Empirical analysis results indicate that supporting photovoltaic enterprises through fiscal taxation policies can not only solve problems encountered during enterprise development process like capital difficulty and compensate for deficiencies of market economy but also can facilitate enterprises to improve their own R&D innovation abilities so as to promote their growth.

CONCLUSIONS

In order to analyze influence mechanism of governmental subsidies on growth of photovoltaic enterprises, photovoltaic enterprises listed in Chinese A-share market during 2007–2017 were selected in this study as sample data. An empirical ana-

Table 3. Regression Analysis

Explaining Variable	Model (1)	Model (2)
F	0.056** (1.754)	
T		0.003* (1.543)
Size	-1.085*** (–11.056)	-1.054*** (–10.328)
DEL	-0.016 (–0.628)	-0.014 (–0.569)
Debt	-1.758*** (–6.425)	-1.853*** (–7.056)
RDI	3.530** (2.021)	3.352** (1.898)
CON	0.365 (1.126)	0.306 (0.896)
Constant	14.796*** (12.756)	14.253*** (12.355)
Year	control	control
Adjusted R^2	0.452	0.456
F-test Value	31.556***	31.895***

Notes: *, **, and *** represents significance at the 10 %, 5 %, and 1 % level, respectively, and the number in the brackets is T-test value.

lysis was carried out for effects of direct subsidies and tax preferences on growth of photovoltaic enterprises. The following research conclusions were drawn:

– Governmental fiscal subsidies have positive effect on growth of photovoltaic enterprises. As photovoltaic industry has high technical threshold, it needs input of a large quantity of capital cost. Especially for newly established enterprises, direct subsidy of governmental finance can effectively increase R&D input in photovoltaic enterprises and reduce innovation risks of enterprises through allocation of financial resources.

– Governmental tax preferences have positive influence on growth of photovoltaic enterprises. The government can transfer partial revenue to enterprises, guide and motivate photovoltaic enterprises to carry out technological innovation activities and promote enterprise self-innovation so as to reduce enterprise cost and operation risk, improve enterprise revenue and finally boost enterprise development.

– Compared with tax preference, fiscal subsidy has more obvious effect on growth of photovoltaic enterprises. As it's difficult for photovoltaic enterprises to obtain capital support from traditional channel and they can't enjoy substantial preferential tax policies in financial aspect, lack of fund is always the primary problem faced by photovoltaic enterprises during development process and it restricts enterprise growth. Therefore, fiscal subsidy can not only solve fund-lacking problem of photovoltaic enterprises and compensate for deficiencies of market economy but also can facilitate enterprises to improve their own R&D self-innovation abilities so as to boost growth of photovoltaic enterprises.

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IMPACT OF MEDIA REPORTS ON INNOVATIVE BEHAVIOURS OF PHOTOVOLTAIC ENTERPRISES: EXPERIENCE VIEW FROM CHINA

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ABSTRACT

With flourishing development of media industry, media have exerted more and more important functions in the capital market. For photovoltaic industry, which is an emerging industry, its innovative behaviours need support from the capital market. In order to investigate the influence of media reports on innovative behaviours of photovoltaic enterprises, 43 listed photovoltaic enterprises in China A-stock market were selected. 2013–2016 news reports related to photovoltaic enterprises were grabbed using Python method, and the influence mechanism of media reports on innovative behaviours of photovoltaic enterprise was explored. The results show that media reports facilitate innovative behaviours of photovoltaic enterprises. Facilitating effect of media reports on innovative behaviours of photovoltaic enterprises further strengthen with increasing business revenues of the enterprises. Policy-oriented media exert obvious effect on boosting innovative behaviours of photovoltaic enterprises, while market-oriented media have no significant influence. The conclusions contribute to further understanding of the effect exerted by media information dissemination on enterprises' innovative behaviours.

Keywords*:* photovoltaic enterprise, media reports, innovative behaviours

1. INTRODUCTION

As economic development has greater demand for electric energy, the acquisition of electric energy has become an important demand for sustainable socio-economic development. Solar power generation, as a clean energy, has become an important present means of compensating for the gap of electric energy. Solar photovoltaic power generation is a new technology using renewable resource – solar energy with advantages of cleanness, no pollution and renewable property, and it has played a significant role in energy development process. Nowadays solar photovoltaic power generation is one of the ideal alternative energy sources and exerts important effect on solving global energy shortage problem. Thus, photovoltaic industry has enjoyed rapid development.

For photovoltaic enterprises, innovation ability in related technologies like purification of silicon material, improvement of commercial silicon slice thickness, battery energy storage technology, design and installation of photovoltaic power generation system and purification of integrated silicon material has constituted the core enterprise competitiveness. Factors like background of management layer, economic system, legal environment and enterprise governance structure will affect implementation of technological innovation activities of photovoltaic enterprises [1–4]. With emergence of information economics, influence degree of media reports on enterprise innovative behaviours has been gradually deepened, especially EU conducted anti-dumping investigation on photovoltaic soda lime plate glass products with characteristics of iron content being lower than 300 ppm and solar transmittivity being over 88 % from China in 2013, which caused Sino-European photovoltaic trade dispute. Mass reports of related news media resulted in fluctuation of enterprise R&D input. Theoretical exploration shows that influence of media reports on enterprise innovative behaviours is realized mainly by three means: manager behaviours are improved through intervention of administrative and judicial departments due to news reports; corporate governance is improved by influencing reputation of enterprise management layer; management layer is influenced by market pressure mechanism [5]. Especially photovoltaic enterprises have long R&D cycle in aspects of monocrystalline silicon battery technology, polycrystalline silicon ingot casting technology, highly efficient battery technology, industrialized technology of crystalline silicon battery and special solar cell module technology, and how uncertainty of news media reports impacts innovative behaviours of photovoltaic enterprises needs further analysis.

On this basis, 2013–2016 news reports related to photovoltaic enterprises in Baidu news were grabbed using Python method as proxy variables of media reports. Proportions of total R&D expenditures of 43 photovoltaic enterprises listed in China A-stock market in business revenues were used to measure their innovative behaviours. The empirical analysis was carried out for influence mechanism of media reports on innovative behaviours of photovoltaic enterprises using a panel measurement model. The effect of media information dissemination on enterprise innovative behaviours was further revealed. The remainder of this paper is organized as follows: section 2 consists of literature review and research hypotheses, which are proposed through organizing related literatures; section 3 is data and model design; section 4 presents results analysis and discussion; section 5 draws research conclusions.

2. LITERATURE REVIEW AND RESEARCH HYPOTHESES

In terms of researches on the effect of media reports on capital market, relevant scholars have carried out discussion from corporate governance angle of media. As important external monitoring means, media generate important influence on capital market through news reports on enterprises and facilitate improvement of enterprise management behaviours by means of administrative intervention, reputation of management layer and external pressure. As for effect of media reports on enterprises, most scholars believe that media can exert external supervising effect and facilitate improvement of enterprise governance structure [6–8]. Some scholars have drawn the conclusion that media form external pressure on enterprise management layer so as to manipulate enterprise earnings management [9]. No matter that media reports exert market supervising effect of generating market pressure. The influence of media reports on enterprise behaviours is irrefutable. Because the enterprise innovations are long-term investment behaviour full of uncertainties, it is needed the enterprise should tolerate short-term risk [10]. In terms of internal management layer of the enterprise, it is keener on investing on those projects with low risk and fast benefit gain out of consideration of its own benefit [11], and this is so-called principal-agent problem. Media reports can effectively reduce agency cost through external supervising mechanism so as to strengthen supervision of management layer, eliminate enterprise short-sighted behaviours and facilitate the management layer to enhance innovation. Therefore, hypothesis 1 is proposed:

Hypothesis 1*: Media reports will promote innovative behaviours of photovoltaic enterprises.*

In terms of technology-intensive photovoltaic enterprises, technological innovation is core competitiveness. Continuous improvement of innovation ability is an important path to improve its own core competitiveness [12]. Within the enterprise, innovation is a systematic project needing its powerful financial support as backup force, and financial support is a beneficial guarantee for innovative quality [13]. In aspect of the relationship between external capital and enterprise innovative behaviours, Brown et al. [14] discussed influence of external financing environment on enterprise innovative behaviours, and found that enterprise revenue in stock market improved its risk tolerance degree so as to enhance innovative force. Leiming et al. [15] found that enterprise innovative capital came from venture investment. Relative to bank capital or stock market, venture investment could more tolerate short-term failure and risk so as to facilitate innovation. Huidong et al. [16] discussed influence of external capital on enterprise innovative behaviours from bond financing angle, and found that internal capital is of greater freedom and flexibility for enterprises. For rapidly growing photovoltaic enterprises, they can use acquired revenues to provide continuous support for enterprise innovation so as to form benign interaction between enterprise innovation and growth. Therefore, good financial status is the precondition for enterprises to conduct innovative behaviours. Hypothesis 2 is obtained:

Hypothesis 2*: Favourable business revenue growth of the enterprise exerts positive regulating effect under the precondition of media reports, namely expanding the positive influence of media reports on enterprise innovative behaviours.*

In the era of big data, diversification of information acquisition channels has become an indispensable constituent part in daily life. Content created by media information and its depth as well as transmission speed and breadth of media information play a vital role in exertion of media information effect during media "information creation – information transmission – information effect" [17]. For the print media reports, they can be divided into policy-oriented media and market-oriented media. Some scholars have carried out a large number of researches on corporate governance effects of the two-type media report. Miller [18] found that compared with policy-oriented media, market-oriented media had more significant governance effect on enterprises. Policy-oriented media served the government and its reports on enterprise behaviours would draw concern from supervision department, so it could generate supervising effect on enterprise management layer so as to improve enterprise governance effect [19]. Dongyan [20] investigated the influence on media reports on enterprise earnings management behaviours, and found that relative to policy-oriented media, market-oriented media brought about higher pressure to management layer. As for enterprise innovative behaviours, market-oriented media and policy-oriented media have different influences. For policy-oriented media, media reports on enterprises can make the enterprises obtain greater innovative capital support from governmental level so as to further facilitate enterprise innovative behaviours. For market-oriented media, its audience groups are different from those of policy-oriented media due to lack of authority, and influence of market-oriented media reports on enterprise innovative behaviours is insignificant. Therefore, hypothesis 3 is proposed:

Hypothesis 3*: Policy-oriented media will exert facilitating effect on innovative behaviours of photovoltaic enterprises while market-oriented media have insignificant influence on innovative behaviours of photovoltaic enterprises.*

3. METHODOLOGY, DATA AND VARIABLES

3.1. Data Source and Variables

As for selection of proxy indicators of network media reports, day parting searching of Chinese listed photovoltaic enterprises in 2013–2016 Baidu news (www.news.baidu.com) was conducted using Python method, and annual news quantities containing enterprise abbreviations were selected as indicators of network media reports. In order to prevent data accuracy problem generated by change of enterprise names, abbreviations of listed photovoltaic enterprises in different years were respectively searched. In terms of selection of reports made by policy-oriented media and market-oriented media, this study referred to method of Peigong et al. [21]. China Securities Journal, Securities Daily, Securities Times and Shanghai Securities News were selected as policy-oriented media and 21st Century Business Herald, The Economic Observer, CBN Daily and China Business were selected as market-oriented media. The 8 newspapers were grabbed in "Duxiu" database. Their news reports on listed photovoltaic enterprises were summarized into corresponding policy-oriented media report quantities and market-oriented media report quantities.

As for selection of enterprise innovation indicators, total R&D expenditures and R&D expenditure proportions of the above listed enterprises were taken as proxy variables of enterprise innovation. Meanwhile with a reference to precedent experience, rate of return on total assets (ROA), enterprise size (SIZE), asset-liability ratio (LEV), salary of enterprise management layer (SALARY), growth rate of business revenue (Grow), institutional shareholding ratio (ISR) and proportion of liquid asset in total assets (Liqu) were selected as control variables to verify influence of media reports on enterprise innovative behaviours. All of the above data derived from WIND database. Due to data availability, sample cycles were selected as years from 2013 to 2016.

Table 1. Definitions and Descriptions of Variables

Variable name	Definition	Descriptions
MEDIA1	Network media reports	Stock abbreviations of listed photovoltaic enterprises in Baidu news are searched to obtain network media report quantities. MEDIA1=LN (1+ number of media reports)
MEDIA2	Policy-oriented media reports	News reports by four newspapers – China Securities Journal, Securities Daily, Securities Times and Shanghai Securities News – on listed photovoltaic enterprises are searched through the “Duxiu” database to obtain policy-oriented media report quantities. MEDIA2=LN (total report quantity of 1 +4 media)
MEDIA3	Market-oriented media reports	News reports by four newspapers-21st Century Business Herald, The Economic Observer, CBN Daily and China Business – are searched through the “Duxiu” database to obtain quantities of market-oriented media reports. MEDIA3=LN(total report quantity of 1+4 media)
BILI	Proportion of enterprise expenditure in innovation	Total R&D expenditure/business revenue
HEJI	Total enterprise expenditure in innovation	Natural logarithm of total enterprise R & D expenditure
Liqu	Asset liquidity	Liquid asset/total asset
Grow	Growth rate of business revenue	Growth of business income/total business revenue in the last quarter
LEV	Asset-liability ratio	Total liabilities/total assets
ROA	Rate of return on total assets	Net profit/average total assets
ISR	Institutional shareholding ratio	Proportion of total quarterly institutional shareholdings in tradable shares of the listed enterprise
SIZE	Enterprise’s total assets	Natural logarithm of average quarterly assets of the listed enterprise
SALARY	Salary of management layer	Total annual salary of enterprise management layer

Definitions and descriptions of the variables are shown in Table 1.

3.2. Model

According to research hypotheses, panel data models were established to analysis the influence of media reports on innovative behaviours of photovoltaic enterprises, and concrete model setting was as below:

$$HEJI_{i,t} = u_i + \beta_1 MEDIA1_{i,t} + \beta_2 ROA_{i,t} + \beta_3 ISR_{i,t} + \\ + \beta_4 Liqu_{i,t} + \beta_5 LEV_{i,t} + \beta_6 SIZE_{i,t} + \beta_7 SALARY_{i,t} + \\ + Year + \varepsilon_{i,t} \quad . \tag{1}$$

$$HEJI_{i,t} = u_i + \beta_1 MEDIA1_{i,t} + \beta_2 MEDIA1_{i,t} \times \\ \times Grow_{i,t} + \beta_3 Grow_{i,t} + \beta_4 ROA_{i,t} + \beta_5 ISR_{i,t} + \\ + \beta_6 Liqu_{i,t} + \beta_7 LEV_{i,t} + \beta_8 SIZE_{i,t} + \\ + \beta_9 SALARY_{i,t} + Year + \varepsilon_{i,t} \quad . \tag{2}$$

Table 2. Statistical Description of Variables

Variable	Number of observations	Mean	Standard deviation	Minimum	Maximum	Skewness	Kurtosis
MEDIA1	172	5.947	1.006	4.454	10.127	2.196	9.467
MEDIA2	172	1.279	0.969	0	3.871	0.096	2.031
MEDIA3	172	0.595	0.785	0	3.296	1.103	3.458
BILI	172	0.033	2.840	0	0.201	2.268	12.31
HEJI	172	15.895	5.922	0	21.139	-2.183	6.157
ROA	172	0.021	0.089	-0.645	0.182	-4.227	28.32
LEV	172	0.515	0.188	0.059	0.972	-0.138	2.959
Liqu	172	0.476	0.215	0.035	0.943	-0.291	2.429
Grow	172	0.118	0.258	-0.464	1.196	1.494	7.152
SIZE	172	22.28	1.165	20.22	26.33	0.674	3.997
ISR	172	0.466	0.170	0.047	0.865	-0.2662	2.597
SALARY	172	5.163	0.542	4.193	6.973	0.737	3.991

$$HEJI_{i,t} = u_i + \beta_1 MEDIA2_{i,t} + \beta_2 Grow_{i,t} + +\beta_3 ROA_{i,t} + \beta_4 ISR_{i,t} + \beta_5 Liqu_{i,t} + \beta_6 LEV_{i,t} + +\beta_7 SIZE_{i,t} + \beta_8 SALARY_{i,t} + Year + \varepsilon_{i,t}. \quad (3)$$

$$HEJI_{i,t} = u_i + \beta_1 MEDIA3_{i,t} + \beta_2 Grow_{i,t} + +\beta_3 ROA_{i,t} + \beta_4 ISR_{i,t} + \beta_5 Liqu_{i,t} + \beta_6 LEV_{i,t} + +\beta_7 SIZE_{i,t} + \beta_8 SALARY_{i,t} + Year + \varepsilon_{i,t}. \quad (4)$$

In the above models, model 1 was used to verify the influence of media reports on innovative behaviours of photovoltaic enterprises. Interactive terms between growth rate of enterprise business revenue and media concern were added to model 2. Model 3 was used to analyze the influence of policy-oriented media on innovative behaviours of photovoltaic enterprises. Model 4 was used to verify the influence of market-oriented media on innovative behaviours of photovoltaic enterprises. *i* represents enterprise and *t* represents year.

4. RESULTS ANALYSIS AND DISCUSSION

4.1. Descriptive Statics and Correlation Testing

Table 2 shows descriptive statistical results of variables. From media report quantities, report quantity of network media was far larger than those of policy-oriented media and market-oriented media, indicating enormous influence of network media on the society. Moreover, kurtosis and skewness of all variables were small, indicating that all variables presented concentrated distribution with strong symmetry.

In order to control collinearity between variables, Pearson correlation analysis between variables was conducted. Network media report quantity represented media report and total expenditure in innovation represented innovative behaviour of photovoltaic enterprises. According to test results in Table 3, the correlation between model variables was low without multicollinearity, which guaranteed scientificity and feasibility of model setting and variable selection.

4.2. Hypothesis Testing

Table 4 describes the influence of media concern on enterprise innovation. Model 1 investigated the influence of network media reports on innovative behaviours of photovoltaic enterprises. Interactive terms between growth rate business revenue and network media reports were added to model 2 to verify regulating the effect of the receivable growth rate on innovative behaviours of photovoltaic enterprises on the precondition of media reports. Model 3 studied the influence of policy-ori-

Table 3. Correlation Test of Variables

	HEJI	MEDIA1	SALARY	ROA	ISR	Liqu	Grow	LEV	SIZE
HEJI	1.000								
MEDIA1	0.193**	1.000							
SALARY	0.239***	0.090	1.000						
ROA	0.171**	-0.026	0.282***	1.000					
ISR	0.161**	0.337***	0.135***	0.212***	1.000				
Liqu	0.396***	0.016	0.143*	-0.011**	-0.006	1.000			
Grow	0.111	0.062	0.179**	0.095	-0.002	0.184**	1.000		
LEV	-0.156**	0.109	0.060	-0.299**	0.039	-0.151**	-0.052	1.000	
SIZE	0.185**	0.287***	0.286***	0.164**	0.304***	-0.386**	-0.051	0.319***	1.000

Notes: *, ** and *** represents significance on the 10 %, 5 % and 1 % level, respectively.

ented media reports on innovative behaviours of photovoltaic enterprises. Model 4 investigated the influence of market-oriented media reports on innovative behaviours of photovoltaic enterprises. Regression results are seen in Table 4.

Model 1 verified the influence of network media reports on innovative behaviours of photovoltaic enterprises. According to results, media report coefficient was 1.635 which reached 5 % significance level, namely every time network media reports increased by 1 percentage, enterprise R & D expenditure would increase by 1.635, percentages. Results show that as network media report quantity of enterprises increases, photovoltaic enterprises will enlarge R&D input, which verifies enterprise governance effect of media, it means that media increase exposure degree of enterprises through reporting on listed photovoltaic enterprises, reduce information asymmetry of capital market and generate supervising effect on enterprise management layer. Media reports on advantages of photovoltaic power generation like cleanness, safety, universality, free maintenance, resource sufficiency and potential economic efficiency [22], which can further expand market acceptance degree of photovoltaic products. Enterprises will adopt behaviours which are more helpful for long-term enterprise development like enlarging R&D input so as to strengthen enterprise competiveness. Hypothesis 1 was verified. Therefore, media should take full advantage of enterprise governance effect of media reports, enlarge information report and information disclosure of listed enterprises and relieve information asymmetry in the market so as to form constraint over enterprise management layer. Meanwhile, long-term supervising mechanism of media should be established so as to reinforce reports on listed photovoltaic enterprises and conduct ongoing reports on enterprise behaviours. As a result, agency cost will be reduced and short-sighted behaviours of enterprise management layer will be eliminated. Moreover, enterprises will input more capital and energy into technological research and development link so as to promote long-term healthy development [23].

Interactive terms between growth rate of enterprise business revenue and network media reports were added to model 2. It could be known from model results that network media reports presented significant positive correlation with enterprise innovative behaviours. In addition, interactive term coefficients, on which the emphasis was laid, were significant positive values, indicating that growth of business revenue had positive regulating effect on enterprise innovative behaviours: with increase of media reports, growth of enterprise business revenue further boosted promoting effect of media reports on enterprise innovation. According to previous analysis in this study, favourable financial status and development trend constituted foundation for enterprise innovation. Enterprise capital strength would be stronger with its rapid development and it would put efforts into research and develop-

Table 4. Regression Analysis Results

Variable	Model 1	Model 2	Model 3	Model 4
MEDIA1	1.635** (2.20)	1.406* (1.92)		
MEDIA2			0.962*** (2.66)	
MEDIA3				0.481 (1.03)
MEDIA1*Grow		1.666* (1.70)		
Grow		-10.875 (–1.33)	-0.674 (–0.58)	-0.616 (–0.50)
LEV	2.724 (0.68)	2.216 (0.56)	1.632 (0.41)	1.706 (0.42)
ISR	0.735 (0.16)	0.546 (0.12)	0.943 (0.21)	2.402 (0.53)
SIZE	-1.908* (–1.84)	-1.835* (–1.77)	-1.749* (–1.70)	-1.662 (–1.57)
Liqu	0.028 (0.01)	-0.078 (–0.02)	-0.464 (–0.09)	-0.688 (–0.13)
ROA	-0.097 (–002)	0.133 (0.03)	-0.741 (–0.19)	-1.413 (–0.35)
SALARY	-0.478 (–0.38)	-0.327 (–0.26)	-0.567 (–0.46)	0.016 (0.01)
Constant	47.75** (2.05)	45.70** (1.98)	53.858** (2.30)	49.473** (2.07)
Year	Control	Control	Control	Control
Adj R-squared	0.19	0.20	0.20	0.16
N	172	172	172	172

Notes: *, ** and *** represents significance on the 10 %, 5 % and 1 % level, respectively. Number in the brackets is the standard error (Se).

ment. Therefore, positive influence of media reports on enterprise innovative behaviours would be further reinforced with growth of enterprise business revenue, and then hypothesis 2 was verified.

Model 3 explored the influence of policy-oriented media reports on innovative behaviours of photovoltaic enterprises, and media report coefficient was 0.962 with statistical significance. This indicated that every time policy-oriented media reports increased by 1 percentage, the enterprise R&D expenditure would increase by 0.962 percent. Thus, it could be seen that enterprise innovative behaviours would be further improved with growth of report quantity made by policy-oriented media. From the previous analysis in this study, policy-oriented media had governmental background, so their news reports were of certain authority and would generate great influence on enterprise management layer. Reports made by policy-oriented media on listed photovoltaic enterprises represented governmental voice to a considerable degree, and on the one hand, it would facilitate enterprise management layer to improve enterprise management, while on the other hand, it would enlarge governmental capital support for enterprise innovation. As a result, the enterprise would enlarge innovative R&D input.

Table 5. Robustness Test

Variable	Model 1	Model 2	Model 3	Model 4
MEDIA1	0.180** (2.47)	0.159** (2.32)		
MEDIA2			0.078** (2.35)	
MEDIA3				-0.004 (–0.08)
MEDIA1*Grow		0.232* (1.91)		
Grow		-1.909** (–2.57)	-0.497*** (–4.48)	-0.499 (–4.39)
LEV	0.234 (0.59)	0.129 (0.35)	0.048 (0.13)	0.047 (0.13)
ISR	-0.157 (–0.35)	-0.073 (–0.18)	0.069 (0.17)	0.265 (0.63)
SIZE	-0.181* (–1.78)	-0.136 (–1.45)	-0.125 (–1.31)	-0.112 (–1.15)
Liqu	-0.749 (–1.50)	-0.738 (–1.61)	-0.821* (–1.77)	-0.855* (–1.80)
ROA	0.244 (0.61)	0.373 (1.02)	0.225 (0.62)	0.146 (0.39)
SALARY	-0.027 (–0.22)	0.021 (0.19)	0.016 (0.14)	0.084 (0.72)
Constant	4.38** (1.92)	3.38 (1.61)	3.99* (1.85)	3.44 (1.56)
Year	Control	Control	Control	Control
Adj R-squared	0.17	0.32	0.29	0.26
N	172	172	172	172

Notes: *, ** and *** represents significance on the 10 %, 5 % and 1 % level, respectively. Number in the brackets is the standard error (Se).

Model 4 explored the influence of market-oriented media reports on innovative behaviours of photovoltaic enterprises. It’s found that media report coefficient was not significant. This indicated increase of report quantity made by market-oriented media on photovoltaic enterprises would not generate significant influence on enterprise innovative behaviours, possibly because market-oriented media lacked constraint effect on enterprise management layer compared with policy-oriented media. Their news reports could not receive enough attention from enterprise management layer, which would not react to market-oriented media reports, so enterprise government effect of these media could not be generated. Hypothesis 3 was verified then.

Based on analysis results, both network media reports and policy-oriented media reports have significant positive effects on enterprise innovative research and development. Therefore, media themselves will enhance their reports on photovoltaic enterprises and take full advantages of their enterprise governance effect in order to improve enterprise innovative behaviours. Market-oriented media will intensify negative reports on photovoltaic enterprises so as to form supervising effect on enterprise management layer and realize enterprise governance effect of market-oriented media.

4.3. Robustness Test

In order to verify the reliability of the above results, proportion of R&D expenditure of listed photovoltaic enterprises was taken as proxy variable of enterprise innovative behaviour while other variables were unchanged to conduct regression analysis. Results are seen in Table 5.

As seen in Table 5, network media and policy-oriented media still have positive promoting effect on enterprise innovative behaviours. But influence of market-oriented media on enterprise innovative behaviours is insignificant. As for regulating effects of enterprise business revenue on media reports and enterprise innovative behaviours, results in model 2 still show significant positive regulating effect. It means that after replacement of explained variable, model results are basically identical with previous part in this study, which verified reliability of the conclusions.

5. CONCLUSIONS

Media reports and innovative behaviours of photovoltaic enterprises were taken as research objects in this study. Network media reports, policy-oriented media reports and market-oriented media reports on photovoltaic enterprises were extracted using Python method. Panel models were established to verify the influence of media reports on enterprise innovative behaviours. The following conclusions are then obtained.

(1) Media reports exert positive promoting effect on innovative behaviours of photovoltaic enterprises.

(2) Positive promoting effect of media reports on R&D innovation of photovoltaic enterprises is further enhanced with growth of enterprise business revenue.

(3) Policy-oriented media exert obvious boosting effect on innovative behaviours of photovoltaic enterprises while influence of market-oriented media on innovative behaviours of photovoltaic enterprise is insignificant.

Besides type division, media reports can also be divided according to nature of reported contents. Total media report quantity can represent media concern, but for enterprises, influence degree of negative reports on enterprises is greater. In further research, the influence of positive and negative media reports on enterprise innovative behaviours can be discussed through division of media report contents so as to enrich researches within this field.

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EXAMINING OCCUPANCY AND ARCHITECTURAL ASPECTS AFFECTING MANUAL LIGHTING CONTROL BEHAVIOUR IN OFFICES BASED ON A USER SURVEY

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ABSTRACT

Further understanding the building occupants' needs and behaviors can reduce lighting energy consumption. This research explores how the occupancy and interior architectural aspects become effective in manual lighting control in offices. It involves a multiple sectioned questionnaire focusing on the possible architectural factors such as the desk position, the surface colours, the distance to window, the distance between desk and lighting switch, and inquiring participants' manual lighting control behaviour through the photographs of modified interior layouts, surface colours and time intervals. Statistical methods are used to determine the significant aspects, which may reduce the use of lighting control. Interior layout, distance to window, time of the day, and number of occupants in the offices are the most significant contributions to the manual lighting control behaviour. To pay attention in these contributions, it would be possible to reduce the use of electricity for lighting while user satisfaction increases.

Keywords: lighting energy consumption, manual lighting control, interior layout, user behaviour

1. INTRODUCTION

User behaviour is the action involving the presence of users and the way of performing their activities in the building [1, 2]. One possible action to decrease lighting electricity use has become the users' control over the lighting systems due to its inevitable impact on total energy consumption [3–5]. Manual lighting control, which is a sub-branch of user behaviour, is the switch on/off control by the user without any automatic control systems involvement.

Only a few of user behaviour studies have focused on manual lighting control [6]. Reinhart (2004) reviewed an extensive literature on existing user behaviour models for manual lighting control [7]. He emphasized the Hunt's and Newsham's model, generating switch on/off probabilities, assuming that users control the lights twice a day (upon arrival and on departure) and daylight illuminance has a strong role in switching on behaviour [7, 8]. Both models did not, yet, consider the switch on/off events during occupation period, i.e. for lunch or short breaks [7]. Pigg (1996) figured out that absence time proportionally determines the switching off probability [9]. Bourgeois et al. (2005) mentioned studies about "active" and "passive" users according to their stochastic functionality and dynamic responses to short-term changes in lighting conditions considering occupancy patterns [6, 10]. The active user referred to those who seek for optimal use of daylight, that controls artificial lighting and shading during the day, while the passive user referred to those who undertake no actions towards the lighting system during day [10, 11]. A recent study dealt with occupants' lighting-use patterns as a function of electricity usage of lighting and switch-on times in offices. It defined users as active and their relation to illuminance was significantly strong [5]. Daylight illuminance and absence time are two key variables; and users are categorized as active and passive due to their action type. Arrivals and leaves during the occupation period are other subject matters in this sense.

It is realized that architectural aspects have not yet been analyzed in relation to manual controls. For example, the relation of manual lighting control to occupants' desk position and distance to window (which affects the direction of daylight coming on the desk area) to manual lighting controls are not inquired yet. Similarly, although daylight illuminance has a powerful influence on lighting switch on/off actions, window area, distance to window and interior surface colours (walls, ceiling, floor), which determine the amount of illuminance, are not subjected to any correlation with the manual lighting control. Besides, triggering or inhibiting factors of lighting control (to turn on/off the lights) actions need to be explored since occupants' illuminance preferences vary significantly among each other. If the users' expectations, preferences and underlying reasons are understood in relation to architectural aspects, the manual lighting control could be modified to be more effective.

Utilizing such knowledge, architectural design can have an active role in energy savings revising/ or enhancing the users' manual control action. If complexity of user actions complementing to lighting conditions and control are figured out thoroughly, such information would be integrated in simulations to predict energy consumptions.

The purpose of this study is to examine the influence of the occupancy rate and the architectural aspects of offices on manual lighting control behaviour to generate user behaviour data on manual lighting control. The research process involves a questionnaire, which was applied to the academic staff of the university in İzmir, Turkey. The questionnaire explores the spatial, visual and contextual factors that influence user behaviour. This research design addresses two research questions:

1. Do changes of interior architectural aspects (such as desk position, distance to window, distance to switch, surface colours, and orientation) in an office affect manual lighting control behaviour?

2. How the occupancy rate (absence and occupancy time intervals) influence manual lighting control frequency?

2. SURVEY DESIGN

A multiple-sectioned questionnaire was developed to reveal the participants' current experience of her/his working environment and manual lighting control behaviour within their office. Considering that limited amount of daylight penetration may trigger the manual lighting control behaviour, the questionnaire was conducted during winter, specifically in February 2015. The participants were provided with a finite time, i.e. one month, which they had to keep in mind when answering the questions – *for instance, "how would you describe the daylight availability in your office for the last month? / the amount of light at this work area for the tasks you performed in the last one month: …".*

Participants are academic staff using offices at the university that is located in Izmir. Academic staffs enter/leave their offices frequently during the day depending on their lectures, seminars and meetings, which would provide a variation of user behaviour to examine. Invitations to this survey were sent /distributed via email to participants. A total of 125 (60.8 % females and 39.2 % males; the age of 85 % < 36) out of 398 participants (approx. 30 %) voluntarily submitted the questionnaire forms through 'Survey' (a questionnaire domain), which runs the statistical evaluations.

The questionnaire includes a variety of question formats such as multiple-choice, Likert-scale and yes-no questions. It is mainly composed of five sections that are described in detail below.

The first section of the questionnaire focuses on the architectural/physical conditions of the participants' current offices, and aimed to relate participants' visual satisfaction and manual lighting control preferences, which were gathered in subsequent sections. It involves a list of 9 multiple-choice questions, such as number of people working on the office, orientation of the room, total area of windows etc. The required information of the existing office environment was asked on the following two questions. Knowing the distance between their desk and the window (less than 1m, 1m-2m, 2m-5m, more than 5m) would be useful to interpret how they benefit from daylight penetration on their workplace. Collecting data about the interior layout (i.e, when sitting on the desk, whether the window is on the left, right, back, front or other) provides an insight into daylight penetration direction. Besides, the daylight illuminance on their desks may have distinct and varying evaluations about their visual environment depending on the direction of occupants' view (whether the occupant is facing window *-front layout-* or facing wall *-back layout-*). Participants were also asked to indicate whether they suffer from glare or not.

The second section of the questionnaire evaluates the satisfaction with daylighting availability and artificial lighting environment separately with a format of five level Likert rating designating as 1=not very satisfied, 2=unsatisfied, 3=medium, 4= satisfied, 5= very satisfied. A subsequent semantic scale is constructed to collect information on how participants assess the amount of light in the room, on the desk and at the computer screen. It ranged from –2, too dim, to +2, too much, with a neutral value of 0 corresponding to the right amount of lighting. Besides that, users were asked to define the tasks (such as working with computer, reading or writing) they accomplish, and their frequencies, using a five scaled rating. The frequency scales are composed of five categories, such as; 1=all the time, 2=most frequent, 3=sometimes, 4=rarely and 5=never.

Questions of the third section concentrate on manual lighting control habits and subjective reasons behind it. To reveal participants' manual lighting control actions, first they were asked to describe the frequency of their manual lighting control through the day. Then, four groups of questions were asked about reasons effecting their manual lighting control or inhibiting their control; aspects influencing them to turn on the lights; and the ones not to turn on (such as visual comfort needs, indicating occupancy, colleagues' request, creating an atmosphere etc.) were measured on a Likert scale from *1(always) to 5(never).* Each listed item in Figs. 1a–1d is subjected to Likert scale. Regression analysis were performed to test which reasons relate most strongly to the frequency of changing the lighting condition. Each group of listed item was significantly tested due frequency of participants' lighting control at a level of 0.05 confidence. Each item also was included separately and some aggregate per group was implemented as well.

The fourth section is composed of questions about the employee's subjective impression of how their current office layout and whether any architectural changes therein may affect their use of manual lighting control. Here, closed ended questions would be a useful and efficient way to get information about what participants have in their mind. The first question, rated on a five- point Likert scale is 'how would you rate the following interior architectural factors in terms of increasing your manual lighting control?': *'position of your desk', distance between your desk and window', 'window area', 'orientation of the window', 'surface/or objects colour in the room', 'distance between switch and your table'.* The second question aimed to learn to what extent they agree with the following statement which starts with 'my manual lighting control increases with' the subsequent factors: 'a change in my desk's position related to window', shortening the area between my desk and window', 'enlarging the window, 'a change of the orientation of the window', 'colour of the objects area'/surfaces/ room', 'shortening the distance between the switch and my table'. Responses were obtained on a scale ranging from '1' = agree to '5' = disagree.

To find out participants' response to modifications in surface colour and time of the day, photograph-response yes-no questions were used *in the fifth section.* These questions are based on a 1/5 scale model of a single occupied office (3.6 m × 5.4 m × 2.7 m) [12]. The model (Fig.2) becomes the demonstration for each photograph case. Exposure adjustments of photographs were implemented using Photoshop to avoid possible visual illusions and provide balanced brightness contrasts. Participants used the same screen all through the questionnaire, which prevented the visual perception differences.

The interior surfaces were covered with dark-coloured (surface reflectance (ρ) of walls and floor are 0.50 and 0.20) paper firstly; then with light coloured (ρ: 0.85 and 0.50) paper secondly. The reflectance was calibrated with a calibrated reflection disc with a reflection coefficient of 95.2 %. The scale model was placed in front of a North-facing window at the TU Delft Architecture and Built Environment Faculty ($52^0.00'$ N, $4^0.37'$ E). The photographs were taken with a digital camera with fish eye lenses, on Dec. 21, 2014. The model faces north to reduce high contrast differences and to avoid visual discomfort caused by direct sunlight. Diffuse daylight penetration provides relatively balanced daylight distribution during the day.

The scale model was photographed three times at the same day: respectively, at entrance in the morning (09:00–09:30), at midday after lunch (13:00–13:30) and in the afternoon after a short

2. Please, rate the following reasons on your manual lighting control over fixtures/systems?

	Never	Rarely	Sometimes	Generally	Always
To obtain visual comfort (increase/decrease illuminance level-avoid glare)	☐	☐	☐	☐	☐
For energy saving	☐	☐	☐	☐	☐
To indicate your occupancy/absence	☐	☐	☐	☐	☐
Colleagues' request	☐	☐	☐	☐	☐
For thermal comfort	☐	☐	☐	☐	☐
For computer work	☐	☐	☐	☐	☐
For reading printed text	☐	☐	☐	☐	☐
To compensate for daylight	☐	☐	☐	☐	☐
To create atmosphere for work	☐	☐	☐	☐	☐

(a) Contribution to manual lighting control

3. Which factors inhibit you from manually controlling lighting fixtures/systems?

	Never	Rarely	Sometimes	Generally	Always
My colleagues' preferences	☐	☐	☐	☐	☐
To stay focused on my work	☐	☐	☐	☐	☐
My distance to switch is far	☐	☐	☐	☐	☐
I don't care the illuminance level inside	☐	☐	☐	☐	☐
I don't notice the changes in illuminance levels	☐	☐	☐	☐	☐

(b) Inhibiting factors

4. How the following factors influence you on turning lights ON manually upon your arrival?

	Never	Rarely	Sometimes	Generally	Always
If the room is dark	☐	☐	☐	☐	☐
To indicate your occupancy	☐	☐	☐	☐	☐
Prefer to work with artificial light	☐	☐	☐	☐	☐
Generally daylight is not sufficient through the day	☐	☐	☐	☐	☐

(c) Influencing factors

5. How the following factors influence you on "NOT turning lights ON manually" upon your arrival during a regular work day?

	Never	Rarely	Sometimes	Generally	Always
To avoid excessive light and glare	☐	☐	☐	☐	☐
To indicate your absence	☐	☐	☐	☐	☐
I don't notice whether it is on or off	☐	☐	☐	☐	☐
Position of the light switch	☐	☐	☐	☐	☐

(d) Reasons for not turning on lights manually

Fig.1. Listed factors effect on manual lighting control

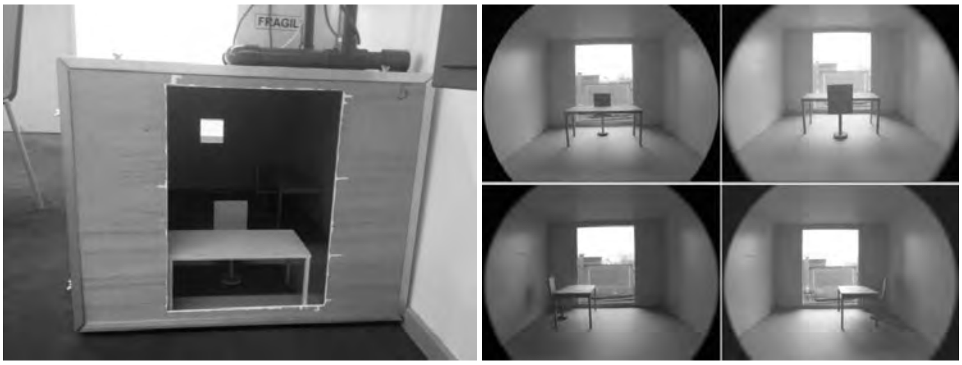

Fig. 2. Scale model and photographs for Back and Front layout (upper), Left and Right layout (lower), with light surfaces

break (15:00–15:30). Participants were asked to indicate their manual lighting control action while looking at the photographs for these three different time intervals. Based on the aspects of visual environment of the photographs, they stated their decisions as either "I would turn on the lights" or "I would not turn on the lights" upon entrance. The dependency of their decisions to control lights, on distance to window, desk position and time of the day, were analyzed through cross tabulations and chi-square tests.

3. SURVEY FINDINGS

Regarding the questions about the existing environment, 26 % of participants work single, while 17 % share the office with 1–2 people, 24 % share with 3–4 people and 32 % share the office with 5 or more people. The rates of the offices with 15m^2–30m^2 window area is 51.2 %, while 16 % of offices have smaller than 15m^2 window area and 32,8 % of offices have more than 30m^2 window area. The major room orientation is North with a 20.8 % rate, while the percentage of other orientations ranged from 1.6 % to 16.8 %. The distance to window varied from 1m to 2m for 40.8 % of respondents while 31.2 % of them declared that the distance is less than 1m. The majority participants do not suffer from glare in their offices (92 %).

When the respondents were asked to rate their satisfaction of the artificial lighting condition in their office, the highest "satisfactory" responses were obtained from participants who work in single and 3–4 people-occupied offices, both with a similar rate of 80 %. The participants who work in the 5–6 people sharing offices gave the highest "unsatisfied" responses. Type of artificial lighting system was not questioned considering the wide variety of lamp and luminaire types, and respondents may not be capable of describing the existing system. In the latter, users are more likely to find the illuminance higher than what they would wish (80 %). This output can be interpreted as, if they would have the chance to control the lights individually, they would prefer lower illuminance, which leads to less energy consumption. This outcome corresponds with Gu's study (2011) [13] that there will be energy savings with individual lighting control, since there are always some occupants who prefer illuminance lower than the fixed lighting levels. Such a finding can provide feedback to architects, in terms of promoting them to design single occupied or up to 3–4 people occupied working spaces, to contribute in electricity savings. Another possibility, for crowded offices, can be the design of desks with personal visual comfort, with personal lighting.

Almost 50 % of respondents whose offices face North were satisfied with the daylighting condition in their working environment, due to their choice of indicating *"4-very satisfied"* in the questionnaire form. A similar rate of satisfaction was observed among respondents in North-East facing offices. Among the responses about various desk positions, left positioned desks have the highest value of satisfaction (with almost 50 %), while the back position has gathered the lowest (approx.30 %). As the window area was the matter to find out its relation to daylight fulfillment, highest satisfaction responses (approx. 42 %) were given by the respondents with window areas of 2m^2–5m^2. Participants' responses verified that the ones, who have a distance of more than 5m between their desks and window, consider the daylight penetration as too dim. Participants, whose desks are (1–2) m away from the window, were in majority in declaring the daylight penetration "sufficient".

To figure out whether daylight satisfaction was independent of orientation, desk position, window area, distance to window or not, chi-square test of independence tests and cross-tabulations

Table 1. Chi-Square Results

	Pearson chi-square (χ^2-crit)	p-value	
Orientation	33.267	0.405	independence
Desk position	10.588	0.834	independence
Window area	18.407	0.018	dependence
Distance to window	24.024	0.020	dependence

were applied at a 5 % level of confidence (α=0.05). Daylight satisfaction was dependent of only two aspects: window area and distance to window. Results, indicated independency of orientation and desk position on participants' daylight satisfaction, are in Table 1.

Respondents were asked to indicate their ideas to the each given statements which proposes a modification increase their manual lighting control. Orientation of the window (81 %) and enlarging the window area (79 %) are the most commonly chosen factors to increase manual lighting control. Shortening the distance between the desk and the window (Always 31 %, Generally 43 %), changing colours of the surfaces (Always 22 %, Generally 29 %), and changing the desk's position (Always 37 %, Generally 32 %) are the other significant modifications on lighting control behaviour; while the distance between the switch and table (Always 11 %, Generally 14 %) has the least effect. However, users' opinions on how the above listed modifications can influence their control behaviour were conflicting with their responses on daylight satisfaction in their actual work environment.

Almost 57 % of the participants control the lighting system manually several times a day depending on either their absences or daylight penetration. They do not operate the lighting system only during entrance and departure; so they can be categorized as active users. 21 % of the participants claim that they control it twice a day (only when they enter in the beginning of the day and when they leave at the end of the day); while 9 % of them state that, they control it before/after lunch and breaks, additional to their control in their morning entrance and evening departure. Yet, 13 % of them indicated that generally they do not control lighting systems manually. So, 34 % of the participants can be grouped as *passive users*. The above data show that the assumption in studies and models, which identifies all users as passive, is not realistic. This study shows the importance of taking the user behaviour realistically.

The majority of the participants (39 % and 40 % respectively) declare that the main reason for manual lighting control is to provide visual comfort and to create atmosphere for work; in other words, to fulfil their tasks. To save energy (by 21 %) has become the second meaningful personal motivation to control the lighting system. Indicating their occupancy/or absence has no or a very slight impact on control decisions of 52 % and 20 % of participants. Response rates for the two factors; 'computer work' and 'reading printed text' are quite similar, meaning that, one type of task does not have a stronger effect on users' control behaviour than the other one has. Almost 27 % of the participants never take into consideration their colleagues' demand of lighting control; 32 % of participants turn on/or off the lights because of colleagues' demands, even they do not prefer it themselves. Thus, individual lighting control for each workstation can be a good solution for obtaining visual comfort.

Regarding associations of each listed reasons to affect manual lighting control (as explained in Section 2.2.3, when aggregate per group was tested, a low value of R^2 is calculated as 0.12 (group in Fig. 1a), 0.04 (group in Fig.1b), 0.04 (group in Fig. 1c) and Significance F and *p* values are greater than 0.05. Results are not reliable so, listed items are decreased, only two individual items, obtaining visual comfort (Significance F=0.002, *p*=0.002) and creating atmosphere for work (Significance=0.002, *p*=0.001), are found to be significantly related to manual control with almost 0.10 R^2. That means, we can explain/predict the 10 % of the variation among data. For example, visual comfort, alone, might affect manual lighting control without a major contribution. This makes sense and is reasonable; since, manual control decision is a human action and many other factors might be influential and some cannot be predictable. Not noticing the changes in illuminance is the only significant factor (Significance F=0.042, p=0.04), which inhibits the users to control light.

Almost 72 % of respondents consider that modifications on interior layout can be effective on their control behaviour. Accordingly, the window area (39 %-Always, 40 %- Generally), its orientation (37 %-Always, 44 %-Generally), position of the desk (37 %-Always, 32 %-Generally) and distance to window (31 %-Always, 43 %-Generally) were defined to have a strong effect while distance between switch and table (18 %-Rarely, 40 %-Never) was found to be the least effective factor. Colour of the surfaces has shown no strong effect among the response rates.

To understand participants' reactions according to the desk layout, distance to window, surface colours of the walls, and time of the day, they were asked to give feedback by looking to photographs of given indoor scenes of the scale model. Those feedbacks could be derived from two choices; "I would turn on the lights" or "I would not turn on the lights". Chi-square test of independence was applied to reach a deep and notable understanding whether manual lighting control was independent of the above mentioned interior factors or not.

First, participants' manual lighting responses to two different distances to window (A and B) were compared significantly. When the desk was in Back position and the surfaces were light, control responses showed very slight or no variation if the desk was moved away from the window. After the 'afternoon break', the control action displayed variation. The rate which corresponds to 32,8 % of respondents turning on the lights was raised up to 40.8 % when the desk moves to away from the window in B position. After lunch arrival, the reverse was happened. The responses of 36 % for turning the lights on decrease to 32,8 % when the desk was in B position. When the desk was in Front position, the approx. 88–96 % of respondents prefers not to turn on the lights during the day. In the morning, a strong drop was observed in rates of responses "I would not turn on the lights" (11 % to 2.41 %) when the desk is moved near the back wall in B position.

Cross-tabulations and chi-square tests are applied to figure out statistically whether there is any significant relation between distance and turn on/off behaviour. The implication for each case of layout and surface colour according to time (morning, lunch and afternoon) was iterated extensively. Results on a total of 24 cross tabulations for each time interval – morning, lunch, afternoon break – separately indicate that the turning on/off behaviour is dependent to distance to window since p-values are below α=0.05 in all cases (p=0.000) except only Left A-B in the afternoon (χ^2= 2.65, df=1, p= 0.104).

When manual lighting control responses of Back are compared to Front, significant differences are achieved in all time intervals (morning, lunch and afternoon break). For example, during morning entrance "turn on the lights" response is 57,6 % for Back B Light, while it falls to 2,41 % in Front B Light under same conditions. Similar results are valid for Back A Dark and Front A Dark during morning entrance. For Back A position, the response of "not turn on the lights" is 8 %, while it increases to 84 % for Front A desk position. However, the response percentages of Right and Left desk positions do not vary significantly with each other compared to Back-Front. For instance, "not turn on the lights" response Left A Dark (after lunch) is 87,2 %, while under same conditions Right A Dark positioned desk responses reduces to 45,6 %. Chi-square tests and cross-tabulations reveal the dependency of manual control behaviour on desk position according to very low p-values (p<0.001) except the positions of Front-Back B in the morning entrance and lunch (χ^2= 2.30, df= 1, p=0.129 and χ^2 = 3.34, df= 1, p= 0.067), Front-Back A(dark) in the morning (χ^2 = 0.29, df= 1, p=0.589).

Such an outcome is noteworthy not only in developing architectural design merits but also in enhancing technical ways to evaluate daylight performance and energy efficiency in working spaces. Users' desk layout can be involved as a certain affecting variable/or constant in performance and energy calculating tools. Additionally, personal issues can be integrated to get a deep understanding and insight. A further study can analyze in detail how a left-hand writer receiving daylight from the left side satisfies differently than a right-hand writer in the same layout; and how the lighting electricity is consumed or saved in both cases.

To understand whether the time of the day reflect to respondents' manual lighting control or not, photographs were taken at three different time moments (morning entrance, lunch and afternoon break). Users most likely attempt to turn on the lights for all desk positions and surface colours during morning entrance. For example, the percentage of "turn on the lights" response for Left A Light condition is 65.85 % during morning entrance, while it reduces to 4,8 % and 4 % for after lunch and break entrances respectively. After Lunch and after Break manual lighting control responses are closer to each other when compared to after morning responses. Chi-square tests of independence applied to 48 cross tabulations supported the significant relation among manual lighting response to time of the day. Significantly low p-values ranged from 0.000 to 0.003. However, a few observations such as relations between morning and lunch in Left A-Light position (χ^2 =3.27, *df*=1, *p*=0.070) and between morning and afternoon in Left A-Light position (χ^2= 0.46, df= 1, *p*=0.496) constitute the independency with higher *p* values.

4. DISCUSSIONS AND CONCLUSIONS

This research aimed to statistically determine the contribution of certain factors (such as architectural and occupancy) to manual lighting control behaviour and user comfort within the university offices. Testing the relation between the physical environment and satisfaction of daylight conditions among the given parameters, window area and distance to window are found to be the two most significant and dependent aspects on users' daylight satisfaction. On the other hand, neither orientation nor position of the desk was found to have a statistically significant effect on daylight satisfaction.

Some factors are found to be remarkable on how they affect manual lighting control. In detail, North/North East orientation, the window area of 2–5 m^2 and distance to window of 1–2 m are specifically identified as sufficient for successful daylight conditions. Such conditions would increase the number of people not turning on the lighting when entering the office. Responses show that most of the participants can be classified as "active" users, since they don't only turn on the lights during their entrance in the morning, and turn off them in their departure at the end of their working period, as defined by Love (1998) [10], but frequently do control during the working period. These results are in contrast with the European Standards, where the value of manual control factor (occupancy dependency factor) is implemented as 1 (which means the lights are switched on during the working hours and users are passive) indicating that users do not control the lighting system during the day [14]. This active user behaviour can contribute to energy savings significantly, yet it is impossible to determine the saving with the data obtained in this study. A further study that analyzes the energy savings according to different user profile can be suggested. Obtaining visual comfort and creating atmosphere have significant impact on switching the lights, while energy saving has not such a strong impact when compared to them. That is interesting to realize that energy consciousness is less of a motivation than the wish for comfort. The reason may be the unawareness of users about the amount of energy they are consuming, so energy use takes place without any conscious considerations as mentioned in Toth et.al. 2013 [15].

Interior layout modification (change of location of desks) has been the strongest deriving force in the manual lighting control as supported significantly through analyses. For instance, locating desk close to window (in A position) and/or positioning desk facing window result as lower rates of switch on behaviour. These two factors were significantly affecting for all time moments. Such findings are similar to Thorndike et al.'s outputs [16], where interior layout affects user behaviour. Lighting control behaviour differs due to changes in daylight penetration. When the daylight penetration is not sufficient (especially in the morning), it triggers users to switch on the lights upon entrance. Thus, daylight illuminance should be taken into consideration when predicting lighting energy consumption.

Users' contribution on improving energy savings should not be underestimated. This study intends to enrich the knowledge on user behaviour in lighting energy consumption by analyzing possible effective factors and interpret how they influence the manual lighting control. The listed findings of manual lighting control frequency, with triggering and inhibiting factors, can be used as inputs during eco-friendly office design without using any automatic lighting control systems, but only the users. Furthermore, this study revealed to give best insight to user preferences, raise awareness on their manual lighting control actions, and point on how users should be realistically included in user behaviour models. To deliver energy efficient buildings, a more sophisticated understanding of user behaviour is needed, and interior design parameters should be taken into consideration for that purpose.

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COST-BENEFIT ANALYSIS UNDER THE DSM MODEL OF GREEN LIGHTING

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ABSTRACT

Based on the concept of DSM and the requirements of the demonstration project, the DSM model of green lighting was studied, carrying out the cost-benefit analysis. Combining the characteristics of the demonstration area, first of all, the cost-benefit of different interest subjects was analyzed. Secondly, the association rules algorithm was analyzed in detail, and the cost-benefit was analyzed by the association rules algorithm. Finally, the sensitivity analysis of the key factors, affecting the cost and benefit of each interest subject, was done by using the algorithm. And it is concluded that the user subsidy rate and consumer electricity price are the key factors that affect the user's willingness to use green lighting technology and power grid enterprises to implement DSM measures.

Keywords: DSM model, green lighting, electricity saving technology, cost benefit analysis

1. INTRODUCTION

Green lighting is the concept proposed by the national environmental protection agency in the early 90s of the last century. The complete green lighting contains 4 indexes, which are efficient, energy saving, environmental protection, safety and comfort. The implementation of demand side management (DSM) in the electricity side mining terminal electricity saving potential to a large extent, can effectively improve energy utilization efficiency, energy saving and emission reduction [1]. Green lighting energy saving technology as a means of DSM technique, can effectively reduce the peak load and improve the characteristics of power grid, improve power supply reliability. However, the application of the technology in the electric side will increase the purchase cost of energy saving lighting products [2]. The Power Grid Corp will decline due to the sale of electricity and reduce electricity generation enterprise income, also as a result of the implementation of DSM measures and affect the benefits and costs [3]. Therefore, in the current social background of energy saving and emission reduction, it is necessary to analyze the cost benefit of the relevant stakeholders from the economic perspective. In view of this, this paper was based on the cost efficiency method [4]. From the four aspects of the user, the power grid enterprises, power generation enterprises and the whole society on the energy saving technology of green lighting in the electricity are terminating by cost benefit analysis. Moreover, this paper conducted a sensitivity analysis of the key factors that affect the interests of the main costs and benefits, so as to reduce the risk of decision-making departments [5].

2. STATE OF THE ART

The feasibility of evaluating a DSM technology requires cost-benefit analysis. We assume that B is the full benefit of the implementation of a DSM technology, C is the total cost of implementing a DSM technology, ΔB is net income, and p is the cost and return ratio [6]. Obviously, only when the $\Delta B=B-C\geq 0$ *or* $=B/C = 1$, the implementation of a DSM technology is feasible. Whether or not the income is greater than or equal to the cost is the basic judgment basis for evaluating the feasibility of a DSM technology or energy conservation project and the possibility of large-scale popularization and use of the green lighting technology in the electric terminal [7]. Based on the basic principle of cost-benefit analysis in respective to the four aspects of the user, the power grid enterprises, power generation enterprises, and the whole society analyzing the cost and benefit of energy saving technology in the green lighting electricity terminal [8]. And the sensitivity analysis is made to the key factors that affect the cost and benefit of each interest subject [9].

The example analysis results show that it is feasible to carry out the green lighting power saving technology at the power consumption terminal, and the user subsidy rate and the resident consumption price are the key factors to decide the feasibility of the green end lighting technology [10].

3. METHODOLOGY

3.1. User Cost-benefit Analysis

The cost and benefit of the user were analyzed. In user cost analysis, users' participation in green lighting projects needs to pay additional costs for changing incandescent lamps into energy-efficient lighting products. That is, direct cost or increased purchase cost of equipment can be expressed as:

$$Cc = \sum_{j\in J,k\in K} (C_{c(j,k)} n_{(j,k)} N_{(j,k)}). \quad (1)$$

Among them:

$$C_{c(j,k)} = (P_j - Q_j / Q_b P_b) / (p_b - p_j), \quad (2)$$

$$N_{(j,k)} = \sum_{j\in J,k\in K} N_0 i_{(j,k)}. \quad (3)$$

In the formula, *Cc* is the total direct cost of users, yuan /W, *K* is the user category collection that participates in green lighting power saving projects, mainly including residents, shopping malls, hotels and restaurants. *J* is a collection of green lighting products. Currently, more mature and simple measures for lighting and electricity saving are mainly using compact fluorescent lamps (commonly known as energy saving lamps) instead of incandescent lamps or instead of common inductance ballasts for fluorescent lighting. $C_{c\,(j,\,k)}$ is the direct cost of saving 1 W electricity using seventh types of green lighting products for class *k* users, yuan /W; $n_{(j,\,k)}$ uses seventh types of green lighting products to replace the number of original lighting products for class *k* users. $N_{(j\ k)}$ has the intention to replace the original lighting products with seventh types of green lighting products for class *k* users. Respectively, Q_b, Q_j are the average life of the original lighting products and seventh kinds of green lighting products, *h; p_b, p_j*, respectively, the power of the original lighting products and seventh kinds of green lighting products, W; N_0 is the total number of users in a certain area, $i_{(j,\,k)}$ is willing to replace the original lighting products with the *j* class green lighting products for class *k* users. The analysis of the benefit of the user is done. The benefit of users using energy saving lighting products is the energy saving income in the life period of the product. It is accumulated by all kinds of users involved in the project of green lighting saving. The energy saving benefits obtained by users during the life period of green energy saving lighting products are as follows:

$$B_{c(j,k)} = \Delta W_{c(j,k)} P_k. \quad (4)$$

Among them:

$$\Delta W_{c(j,k)} = (p_b - p_j) Q_j n_{(j,k)} N_{(i,k)} \times 10^{-3}. \quad (5)$$

In the formula, $B_{c(j,k)}$ is the power saving benefit of class k users using seventh kinds of green lighting products, yuan; $\Delta W_{c(j,k)}$ is used for class k users to use class J green lighting products for energy saving, kW/h; P_k is class *k* user lighting consumption price, yuan / kW/h. In the period of static investment recovery, the static investment recovery period of users using all kinds of energy-saving technology is one of the key factors that affect the willingness of users to participate in this DSM measure. The static investment recovery period for users using green lighting products is as follows:

$$T_j = \frac{P_j - Q_j / Q_b P_b}{P_k h_j (p_b - p_j) \times 10^{-3}} = \frac{C_{c(k,j)}}{P_k h_j \times 10^{-3}}. \quad (6)$$

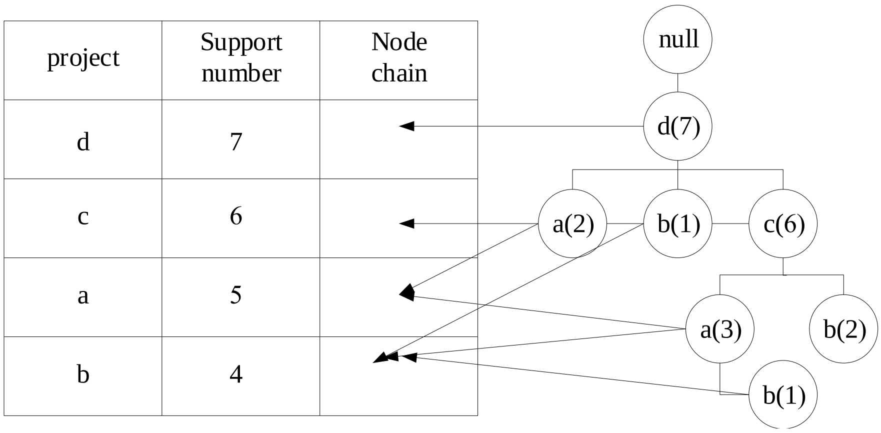

Fig.1. Head table and FP-tree

In the formula, h_j is the lighting time in hours for seventh types of green lighting products per day.

3.2. Cost-benefit Analysis of Power Grid Enterprises

For user subsidies, whether residents, shopping malls or hotels, or restaurants, the basic premise for users to adopt green lighting power saving technology is to recover more cost from electricity saving than to conventional technology. Even a shorter period of static investment recovery is required. Otherwise, users generally do not use this technology unless the power company grants users until the user feels profitable. The amount of the power company's subsidy to the user is related to the user's ideal static investment recovery period (T_{id}). If the user's ideal static investment recovery period only needs to meet the lifespan days of lighting technology (Q_j/h_j), then the power grid enterprises do not need to subsidize users, that is, the subsidy amount is Cs=0. If the user hopes that the ideal static investment recovery period is shorter than the T_j, the power grid enterprises need to subsidize the users. The number of subsidies per 1W is:

$$C_s = \begin{cases} 0 \quad T_j \le T_{id} \le Q_j / h_j \\ \dfrac{P_j - Q_j / Q_b P_b}{p_b - p_j} - P_k h_j T_{id} \times 10^{-3} \quad T_{id} \le T_j \end{cases}. \tag{7}$$

In addition, the rate of user subsidy can be defined as

$$\eta = C_s / C_{c(j,k)} \quad \eta \in [0,1]. \tag{8}$$

For management costs, the power company takes on the cost of each phase of the feasibility study, design, implementation and supervision of the DSM measures, which mainly has administrative management, design, evaluation, technical support and other costs, collectively known as the cost of management, expressed in C_m, usually accounting for 10 %~20 % of the cost of compensation. For the loss of electricity sales, the reduction of electricity consumption due to the use of energy-efficient lighting products is equal to the loss of electricity sold by the power company due to the implementation of the DSM measures. The corresponding losses of the sale of electricity are as follows:

$$\Delta I_{loss} = \sum_{k \in K} [(\sum_{k,j} \Delta W_{c(j,k)}) P_k]. \tag{9}$$

For the benefit analysis of power grid enterprises, the first is to avoid the cost of electricity purchase. The cost of avoiding electricity purchase is mainly reflected by the reduction of the power supply of the peak load on the power supply side, which is caused by the use of energy saving lighting products. Then the cost of power purchase is reduced, so the cost of electricity purchase can be avoided.

$$\Delta M_b = (\sum_{k \in K, j \in J} \Delta W_{c(j,k)}) P_B / [(1-l)(1-m)] \tag{10}$$

In the formula, P_B is the unit purchase cost of power grid enterprises, yuan / (kW h); l is the terminal distribution loss coefficient, and l is the transmission loss coefficient of the power grid. The cost of electricity can be avoided. As the terminal load of power supply line is reduced, the loss of supply and distribution power supply will be reduced. The economic benefit caused by the loss of transmission and distribution loss can be seen as the avoidable electricity cost of the power grid enterprise, that is:

$$\Delta M_l = P_k f \sum_{k,j} \Delta W_{c(j,k)}. \quad (11)$$

Among them:

$$f = 1/[(1-l)(1-m)] - 1. \quad (12)$$

In the formula, *f* is the loss coefficient of the transmission and distribution.

3.3. Association Rule Algorithm

Apriority algorithm is based on continuously constructed set, screening item sets mining the frequent item sets, and each screening needs to scan all the original data. So, the original data needs to be repeatedly scanned, when the original data quantity is large, efficiency is relatively low. So, ways should be proposed to reduce the number of scanning the original data, simplify the frequent item sets mining strategy, simplify the calculation, and shorten the time. In order to avoid the defects of the Apriority algorithm, J. Han et al. proposed the FP-Growth algorithm. This algorithm does not produce candidate frequent item sets, which only needs to scan the original data two times and compress the original data through the FP-tree data structure, having high efficiency. Therefore, for a large amount of data under the condition of mining frequent item sets, FP-Growth algorithm is a more efficient algorithm.

The so-called FP-Growth is the frequent pattern of growth. The idea of this algorithm is to construct a frequent pattern tree (FP-tree) with frequent item sets on the premise of preserving the information of the item set by the first scan. Then the frequent pattern tree is differentiating into several conditions of library, these conditions database mining. FP-Growth algorithm is divided into two steps: construct and recursive FP-tree mining FP-tree construction. By two data scanning, will compress the original data in the transaction to a FP-tree. The FP-tree is similar to the path prefix tree, and the same prefix can be shared, so as to achieve the purpose of compressing data. Then, through the FP-tree, to find the conditional pattern base and conditions of each project FP-tree, FP-tree mining conditions recursively get all frequent item sets. Similarly, the main steps of FP-Growth algorithm are introduced for example given earlier.

First, the construction of FP-tree, scanning the entire database of a single item of frequent item sets and their support are $\{a\}:5, \{b\}:4, \{c\}:6, \{d\}:7, \{e\}:1$, respectively. The minimum support number is 1 and the result set in descending order is A= $\{\{d\}, \{c\}, \{a\}, \{b\}\}$. Then we can construct FP-tree. First, build an empty root node, and then scan the database second times, creating branches for each order according to the previous degree of support. For example, there are a, b, d, e in order 1. The support ranking is three branches, d (7) – a (5), empty nodes connect to *d, d* is connected to *a*; the branch node of order 2 is *d* (7) -b (4). At the same time and so on, create a header table, and the recording project support and node, convenient behind mining convenient traversal. The frequent pattern tree and the head table are shown in Fig.1.

Then the FP-tree is excavated recursively. Starting from the last item of the item table (the lowest support), the condition pattern base for each project is built. Calculate all the paths that project contain, and the prefix path of the project is the conditional pattern base. For example, the paths that include the b project are d-b, c-a-b, c-b, d-c-b. Among them, the prefix path of b is d, d-c-a, c, d-c, which is the conditional pattern base of the *b* project. Then, under the constraint of minimum support, the condition tree of the project is constructed by the set of conditional pattern base of the project. The condition tree of b is presented in Fig.2.

The minimum support number is 1 for all the combinations of frequent item sets generated on the basis of a conditional tree. For *b*, the frequent item sets are {*b, d*} {*b, c*}, these frequent item sets support are respectively 2 and 3. The results obtained with the Apriority algorithm is the same. But the FP-Growth algorithm also has its fatal flaw. Because the algorithm is recursive condition database and conditional frequent pattern tree, so the lar-

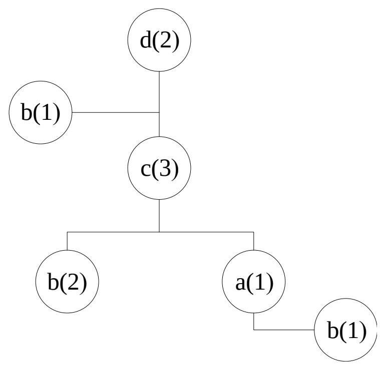

Fig.2. *b* – conditional mode

Table 1. Values of Relevant Parameters

Parameter	Company	Value (using experience value)	Parameter	Company	Value (using experience value)
Tid	a	1.0	l		0.04
k	%	15.0	m		0.07
θ		0.7	δ		0.05
γ		1.2			

Note: k is the cost ratio of the management cost.

ger memory, this is the main problem of this algorithm lies. The recommendation based on association rules is that it is simple and intuitive to mimic real shopping scenes and do not need knowledge about goods. At the same time, it can also discover the potential interest points of the user and stimulate the purchase. However, computational complexity is a significant disadvantage of association rule mining. With the increase of the size of frequent item sets, especially in the case of large data sets, the cost of mining will be higher and higher. However, for the same set of data, in the same degree of a given minimum support, confidence limit conditions, association rules by Apriori algorithm and FP-Growth algorithm are the same. The only difference is that whether the candidate frequent item sets mining process of association rules, mining efficiency is different, different memory operations.

4. RESULT ANALYSIS AND DISCUSSION

4.1. Basic Data and Parameter Hypothesis

The use of energy saving lamps instead of incandescent lamps for residents is taken as an example. Suppose that there are 1 million families in a city, and 30 % of families are willing to take part in the green lighting energy-saving measures under the call of DSM for electricity saving and environmental protection. The incandescent lamps used by users have 15, 25, 40, 60, and 75,100 W. The power of the weighted average incandescent lamp is based on 40 W. The 40 W incandescent lamp can be changed by the 9W energy saving lamp, the energy of the energy-saving lamp is based on the 9W. It is assumed that the cost of the incandescent lamp is 1 yuan per only, the life span is 1000 h, the price of the energy-saving lamp is 30 yuan, and the life of the lamp is at 3000 h. The number of incandescent lamps in each household is 2. The electricity price of the residents in this area is 0.50 yuan / (kW. h), and the lighting time is 4 h/d. The cost of unit capacity is 0.25 yuan / (kW. h), and the unit capacity cost is 7000 yuan /kW. The electricity price of the power generation enterprise is 045 yuan / (kW h), the peak electricity price is 0.2 yuan / (kW h), and the standard coal consumption of power generation is 320 gce/ (kW h). Among them, the relevant parameters involved in the calculation are assumed to be shown in Table 1.

4.2. Calculation Results

According to the above formula, it can be calculated separately. The costs and benefits of green lighting projects are implemented by users, power grid enterprises and the different interests of the whole society. As a result, see Table 2. It can be seen from the table that the cost efficiency is more than 1 as compared with ρ . Therefore, it has good economic benefits for users, power grid enterprises, power generation enterprises and the whole society to implement green electricity saving lighting technology on the electric side.

It is feasible to implement green electricity saving lighting technology on the electric side. Among them, the cost benefit ratio of the power generation enterprises and the whole society is relatively large. The reason is that the power generation side is saved by the electricity side, which avoids the capacity investment cost of the new generating units. Thus, better economic benefits have been produced.

4.3. Sensitivity Analysis

The user subsidy rate η and the consumer electricity price P are two important factors that affect the net income of each stakeholder, ΔB, especially

Table 2 Cost-benefit Analysis Results of Different Beneficial Bodies

Different interests subject	Benefit project	Benefit/10000 yuan	Cost project	Cost/million yuan	Cost benefit ratio/%
User	Electricity saving benefit	2790.0	Direct cost	1620.0	
Total	User subsidy	262.2		1620.0	1.88
Power grid enterprise		3052.2		262.2	
	Avoid electricity purchase cost	2812.3	User subsidy	39.3	
	Avoidable elec-tricity cost	334.8	Management cost	2790.0	
			Loss of electricity	3091.5	1.02
Total		3147.1		2963.0	
Power genera-tion enterprise	Avoid capacity cost	1644.7	Loss of sale of electricity		
	Avoid peak load capacity cost	15363.3			
	Avoidable elec-tricity cost	1106.2		2963.0	6.11
Total		18114.2		1620.0	
	Avoidable elec-tricity cost	1644.7	Direct cost	39.3	
	Avoid capacity cost	15363.3	Management cost		
	Avoid peak load capacity cost	1106.2			
	Carbon emission reduction benefit	397.1			
Total		18511.3		1659.3	11.15

Note: the direct cost is the increase of the purchase cost of the product.

for the power grid enterprises as the main body of DSM implementation. The relationship between the net benefit ΔB of different stakeholders, the rate of user subsidy and the consumption price of residents is analyzed as follows.

The rate of user subsidy is η and the fixed resident consumption price P is calculated. According to equation (5) and combined with the cost benefit formula, users and grid enterprise net income ΔB at subsidy rate η were identified with the user. The relationship is shown in Fig. 3. It is shown that: in the case of P value under the ΔB users and power grid enterprises respectively, into positive and negative correlation. Because the user subsidy cost occurs between the user and the power grid enterprise, it does not affect the ΔB of the power generation enterprise and the whole society is also negatively related to ΔB. For the power grid enterprises, when $\eta \geqq 0.18$, power grid enterprises will increase subsidies for the cost of the loss, so the grid enterprises should implement DSM measures to obtain certain economic benefits, requiring the user to formulate reasonable subsidy policy.

For the level of consumer electricity price, the fixed user subsidy rate is η, and the effect of P changes on net benefit ΔB is analyzed, as shown in Fig. 2. It is shown that: the value of certain circumstances, the user's ΔB and were associated with the power grid enterprises positively and negatively correlated. Among them, the ΔB of the whole so-

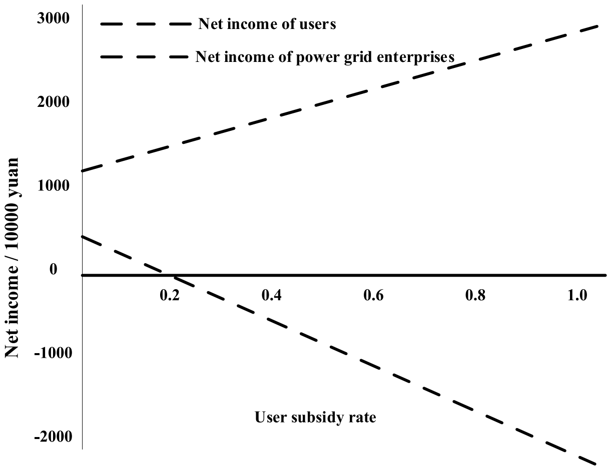

Fig.3. Relationship of net benefit and user subsidy rate under fixed price

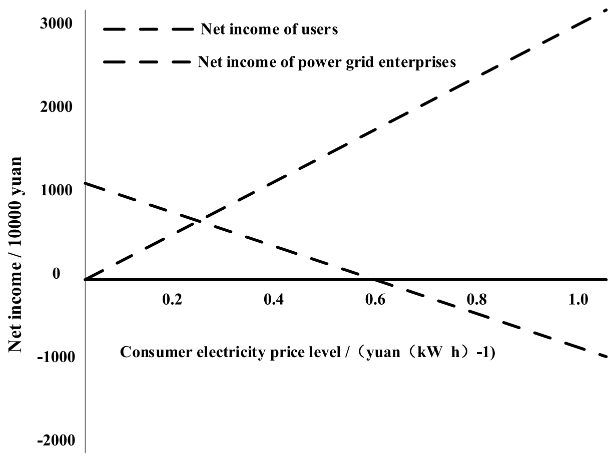

Fig.4. Relationship of net benefit and tariff under fixed subsidy rate consumer

ciety is also positively related to the corpse. If the consumer electricity price level is higher than 0.53 yuan / (kW h) according to the subsidy level of this article η=0.16, the power grid enterprises will lose because of less electricity. When electricity prices are below that level, power grid companies will gain revenue.

If the power grid companies do not want to subsidize the users, the consumer electricity price should be reduced to 0.43 yuan / (kW h). In this way, it can make up for the loss caused by the sale of electricity and not make a loss. That is, under the premise of no loss, the lower the willingness of the power grid enterprises to subsidize the users, the level of consumer electricity price must be reduced accordingly (Fig. 3). However, because the change of consumer electricity price is affected by many factors, the power grid enterprises must determine the rate of user subsidy according to the actual situation.

5. CONCLUSION

As a technical means of power demand side management (DSM), efficient lighting power saving technology can reduce peak load, improve load characteristics and improve power supply reliability. Based on this, the cost efficiency of implementing green lighting was analyzed, saving technology from the user, the power grid enterprise and the society. At the same time, the theoretical basis and technical guidance were provided for the implementation of green lighting project in the region. The result of the case analysis shows that the cost-benefit analysis is one of the effective methods to evaluate the DSM technology. It is also found that user subsidy rate and resident consumption price were two key factors that affected users' willingness to adopt green lighting power saving technology and grid enterprises to implement this DSM measure. At the same time, the feasibility of popularizing green lighting saving technology with electric side was also determined to a great extent. The cost benefit analysis method can also be applied to other DSM measures. It is worth a large-scale application to evaluate the feasibility of a DSM measure by quantitative study of cost benefit.

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DAYLIGHT IN UNDERGROUND SPACES

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ABSTRACT

Underground spaces in town centres present a big attraction for investors. However, they put special requirements to the internal environment. Those requirements can be fulfilled by means of daylighting. Examples of lighting of underground spaces are discussed. It is shown that the common systems of natural lighting are not always possible to use and cause big heat losses. Hollow light guide pipes allow avoid the shortcomings of common daylight systems. Method of calculation of daylight factors from hollow light guide pipes is shown. The results of calculation of daylight factors under the light guide pipes of different diameters in the different depths are presented.

Keywords: underground space, daylighting, hollow light guide pipes, daylight factor

INTRODUCTION

Subsoil surfaces of cities attach growing importance in the architecture. In the Central districts of cities territories are fully developed. Any open areas are an invaluable urban element that attracts people's attention, allows them safely explore the adjacent buildings go for a walk in centre. At the same time, the underground space in such areas is attractive for investors allowing them to use it as a shopping and leisure area, restaurants, shops, services, etc. However, urban underground space is put special requirements to the internal environment. People under the ground should feel comfortable and safe and, if possible, not to lose touch with the external environment.

EXAMPLES OF UNDERGROUND SPACES

The most known in Russia example of such underground spaces is the subsoil shopping Mall on Manezh square "Okhotny Ryad" in Moscow. A three-level underground complex has input knots in the form of atriums, covered with large translucent domes. One of these domes has a diameter of about 20 m (Fig.1). The dome illuminates with natural light the central hall having three levels of underground space. At the same time, restaurants and cafes under balconies of the atrium are lit by permanent lighting systems of artificial light. The changing levels of natural illumination create the natural dynamics of light. All the underground shops flank-

Fig.1. The dome of the central hall of the trading complex "Okhotny Ryad"

Fig.2. Ground planning of the Manezh square

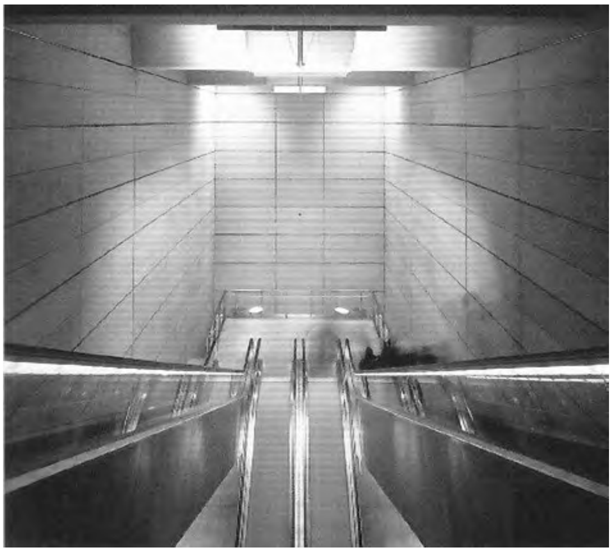

Fig.3. Entrance zone in tube, Kopenhagen (Photo of Peter Bartenbach)

ing a Central atrium and corridors connecting the input nodes are lit by artificial light. Lighting dynamics, inherent to natural light, there is absent.

The corridors, at least at the first underground level, could be lit with natural light using a band roof lights. Stores could have natural light through a hollow tubular light guides (HLTG) [1,2,3]. The light guides could serve the natural light to illuminate the second and third underground levels of shops. This, of course, require necessity to reorganize the ground planning the Manezh square (Fig.2) to make room for the upper parts of skylights and the light receiving devices of tubular light guides which can be obstacle considering the main recreational purpose of the ground area of the Manezh square. Such reconstruction in the future would be possible. The conduct of natural light into the underground space would enhance the comfort and sense of safety in the underground space. The monotony and continuous spectrum of artificial light will be broken by the dynamics of levels and spectrum of natural light. Visitors will feel minimal necessary connection with the outside environment, feel the time of day and weather condition.

Another example of using natural light to illuminate the underground space is the hub of Flint Holm in Copenhagen (Denmark), bringing together metro, ring railway, and the railway station leading to Frederikssund. Six platforms are located under a glass roof with a size of 180 to 60m. As a result, all station is lit by natural light. Two stations are located at bridges. Station on lines passing in the transverse direction, are arranged on the lower bridge level. Even lower is the bus station [4].

On the structure that is above a glass roof, artificial light systems are mounted. Therefore, they can be easily serviced without disturbing the movement of trains. To provide a warm light with a colour temperature of 3000 K halogen light sources are applied. The main artificial lighting is provided by using the LEDs strip with a length of 2.5 km, illuminating in the dark and in cloudy weather the subsurface and steel structures of the hub.

The project of natural and artificial lighting of this major interchange hub and all the new metro in Copenhagen are created by the engineering bureau of Bartenbach (Switzerland) – light laboratory “Light underground”. In the new metro stations, the designers have tried to avoid twilight corners, turning a dark and dirty metro station in the bright rooms partly lit with natural light. If the passengers earlier felt the strain, approaching the dark entrance to the tube escalators, now in the input zones is created a pleasant atmosphere of natural light (Fig.3). At the same time, people feel the changing weather situation outside. In the morning there is cool natural light with a colour temperature of about 6500K, and warmer light with a colour temperature of 4500K in the evening. All this has provided communication with the external environment and increased feeling of safety underground. People, located at the metro station, can immediately feel the outside, whether outside shines the sun or the sky is covered with clouds.

Natural light in the station is served, usually, through skylights. To increase their effectiveness, the sidewalls of the skylights shafts are lined with pure aluminium and allow to deliver natural light at the depth of metro stations without big losses like

Fig. 4. Sunlight spectral components on the wall of the tube escalator, Kopenhagen (Photo of Peter Bartenbach)

light pipes. However, it should be noted, that in case of a large section of the shafts, which are characteristic to the roof skylights, to create a mirror surface of the shaft, like this takes place in the tubes of the light guides, is a very difficult and a very expensive task. Therefore, it is impossible to compare the effectiveness of these devices.

The movement of the sun is transmitted into the room using glass prisms, mounted in skylights. Prisms are decomposing sunlight into spectral components. This creates pictures on the walls like rainbows that move around the surface of the input knots and escalators (Fig.4).

LIGHTING OF UNDERGROUND SPACES BY USING HOLLOW TUBULAR LIGHT GUIDES

The examples show that for not deep underground spaces of the city it is possible and useful to illuminate the space using different systems of natural light. The conventional systems in the form of skylights and translucent coverings provide a lot of light, but have disadvantages.

First of all, roof lights and translucent coverings require the use of large urban areas, which can no longer be used as recreational zones.

Secondary, skylights and other translucent structures create a large heat loss in winter and in summer they create heat gains in the underground spaces of the city that need to be neutralized with significant expenditures of energy.

The use of hollow tubular light guides reduces these disadvantages [1,2,3]. The area, occupied by the receiving elements of the tubular light guides is considerably less. The heat gains through the light guide are also many times smaller [5]. At the same time, the light guides retain such advantages of natural lighting as the natural light spectrum and its dynamics depending on time of day and weather.

The evaluation of natural light through light guides as well as from the usual light openings can be made with the help of Daylight Coefficient (DK). Thus, in the calculation of duration of natural lighting it can be used not the diffuse illumination from the sky, but the total illuminance from sky and sun.

Coefficient of performance (η) of the light guide system is determined by the formula:

$$\eta = \tau_c \times \tau_d \times K_m \times \xi, \quad (1)$$

where τ_d – light transmission of the diffuser: for example, by the Italian system SOLARSPOT $\tau_d = 0.8$; τ_c – light transmittance of the outer dome of the light guide, its rim and the intermediate lenses. By the SOLARSPOT system τ_c = 0, 92; K_m – the safety factor (takes into account the pollution of the dome during operation, J. Bracale K_m = 0, 92) [1]; ξ – is the efficiency of the pipe of a hollow straight light guide. It depends on the reflection coefficient of the mirror coatings of the pipe of the light guide ρ, the ratio length of the light guide to diameter of the tube (L/D), i.e. the number of reflections of light rays inside the tube and the angle θ of the rays falling on the dome of the light guide, to its axis. θ is most easily defined for the direct component of solar light. In vertical position the axis of the light guide, it is equal to the Zenith distance of the sun in a given time. I.e. efficiency varies depending on the height of the sun. The average efficiency of the fibre is well represented by the CIE cloudy sky. In this case $\theta = 30^o$. This value is proposed to calculate ξ. The efficiency of the light guide ξ can be determined according to the simplified formula of multiple reflections [1]:

$$\xi = (e^{L/D}\ tg\theta\ ln\rho)\ /[1\text{-}L/D\ tg\theta\ ln\rho]^{1/2}. \quad (2)$$

This value may also be determined according to the table given in [1 and 7], calculated by the formula (2).

The luminous flux emitted by the diffuser:

$$\Phi_d = \eta \cdot \Phi_{outer}, \quad (3)$$

where Φ_{outer} – luminous flux included in the light guide outside:

$$\Phi_{outer} = [(180-\theta)/180] \cdot E_h \cdot A, \quad (4)$$

where $(180-\theta)/180$ – input coefficient of the HLTG; A is the cross – sectional area of light guide pipe, $A = \pi \cdot D^2/4$; E_h – illuminance outside on a horizontal platform. If you want to determine the daylight factor (DF) under the HLTG, E_h =100 %.

The DF-value under the light guide in point M is determined by the formula:

$$\xi_m = L_d \cdot A/r^2, \quad (5)$$

where L_d is the luminance of the diffuser; $L_d = \Phi_d/(\pi \cdot A)$.

Substituting in the formula (5) the values of L_d and Φ_d (3) we shall receive a calculation formula for calculation DF-value under the light guide.

$$\xi_m = [\eta \cdot D^2 \cdot 0,83)/(4 \cdot r^2)] \cdot 100\ \%, \quad (6)$$

where 0, 83 = (180–30)/180; 30° – the average height of the sun, corresponding to the conditions of a cloudy sky; *cosβ=cosy=1* for our calculation case where the reference point is located directly beneath the light guide; *r* is the distance between centre of diffuser and the reference point. For our design case this is the height of the diffuser above the work plane. According to Fig.5 for our calculations *r* = 4m.

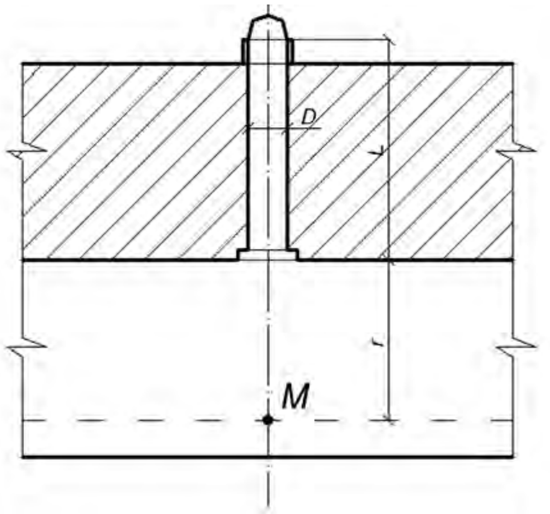

Fig.5. Diagram to the calculation of DF-value under the light guide in point M

The result of the DC-value calculation direct under the right tube of light guide for underground spaces at various depths for different diameters of the light guide and different values of the reflectance of mirror-like inner surface of the pipe are presented in Table 1. All the symbols in Table 1 see formulae (1) and (2), as well as Fig.5. Light transmittance coefficients of the dome and diffuser are taken according to J. Brakale [1].

Dependences of DC-values on the diameter of light guide tube (D) by different length of the tube (L) are represented in the Fig.6. As it is seen in the Fig.5, the DF-value is grooving practically according to the parabola law, depending on the D-value. The dependence of decrease of D on the rising of length of the tube (*L*) is smoother (Fig.7). This is

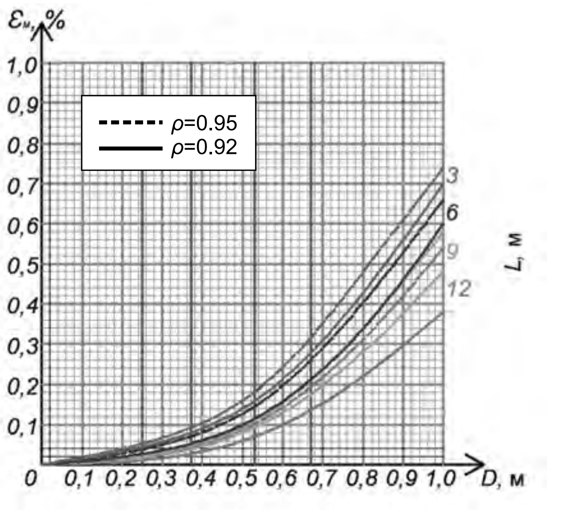

Fig.6. Dependence of DF-value under the light guide in the point M from the diameter of the tube of the light guide

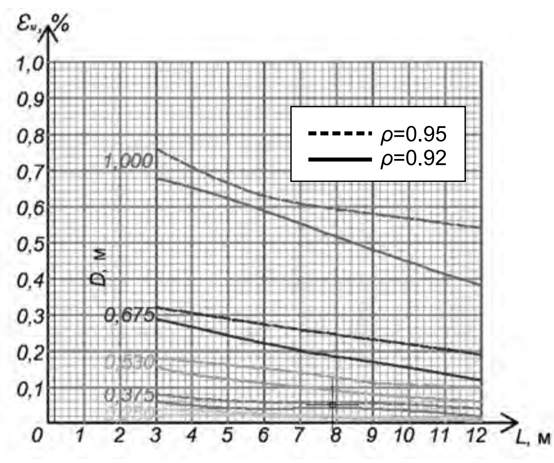

Fig.7. Dependence of DF-value under the light guide in the point M from the depth of the underground space

Table 1. Calculation of DC Under the Direct Waveguide for the SOLARSPOT System

ρ = 0,92																	
D	D^2	L = 3				L = 6				L = 9				L = 12			
		$\frac{L}{D}$	ξ	η_d	$\varepsilon_м$	$\frac{L}{D}$	ξ	η_d	$\varepsilon_м$	$\frac{L}{D}$	ξ	η_d	$\varepsilon_м$	$\frac{L}{D}$	ξ	η_d	$\varepsilon_м$
0,25	0,0625	12	0,45	0,31	0,025	24	0,24	0,16	0,013	36	0,15	0,1	0,008	48	0,06	0,04	0,003
0,375	0,1406	8	0,58	0,39	0,072	16	0,35	0,24	0,043	24	0,17	0,11	0,02	32	0,18	0,12	0,02
0,53	0,2809	5,66	0,68	0,46	0,168	11,32	0,46	0,31	0,113	16,98	0,33	0,22	0,08	22,64	0,25	0,17	0,06
0,675	0,4556	4,44	0,73	0,49	0,292	8,88	0,55	0,37	0,22	13,33	0,44	0,3	0,17	17,76	0,31	0,21	0,12
1,0	1,0	3	0,78	0,53	0,684	6	0,67	0,45	0,59	9	0,55	0,37	0,48	12	0,44	0,29	0,38
ρ = 0,95																	
D	D^2	L = 3				L = 6				L = 9				L = 12			
		$\frac{L}{D}$	ξ	η_d	$\varepsilon_м$	$\frac{L}{D}$	ξ	η_d	$\varepsilon_м$	$\frac{L}{D}$	ξ	η_d	$\varepsilon_м$	$\frac{L}{D}$	ξ	η_d	$\varepsilon_м$
0,25	0,0625	12	0,61	0,41	0,033	24	0,39	0,26	0,021	36	0,27	0,18	0,015	48	0,16	0,11	0,009
0,375	0,1406	8	0,69	0,47	0,085	16	0,50	0,34	0,062	24	0,39	0,26	0,048	32	0,31	0,21	0,038
0,53	0,2809	5,66	0,76	0,51	0,19	11,32	0,63	0,42	0,155	16,98	0,48	0,32	0,12	22,64	0,40	0,27	0,10
0,675	0,4556	4,44	0,81	0,55	0,32	8,88	0,67	0,46	0,27	13,33	0,58	0,39	0,23	17,76	0,47	0,32	0,19
1,0	1,0	3	0,86	0,58	0,76	6	0,72	0,49	0,63	9	0,67	0,45	0,59	12	0,60	0,41	0,53

explained by the fact that from the diameter of tube and input set of the light guide the light flux value coming into the tube depends. At the same time, only the amount of reflections in it is depending from the length of the tube. The bigger diameter of the tube, the less the amount of reflections will be in it by the same length.

Having obtained the DF-value direct under the light guide it is possible to calculate DF-value in each point of the room either according to Lambert law or by the method given in the Russian norm СП 23–102–2003 as from round light source [6].

It must be noted, that DC-values given in Table 1 and in the Figs.6,7 calculated by means of formulae (1–6) are taken without internal reflection, which can be calculated according to СП 23–102–2003, as for convenient systems of roof lighting. The average DF-values for the whole lit area of the underground space can be calculated as a sum of DF-values in all calculation points of the room from all light guides divided by the amount of calculation points.

CONCLUSIONS

Subsoil space of a city, there, where it is possible, must be good lit with daylight. It gives to the people confidence, ensuring connection with external environment. But the convenient systems of upper daylight can be applied in not deep underground spaces. What depth is maximal for the effective use of different daylight systems is to be still investigated. Besides it the convenient systems of daylighting require big areas on the surface of the ground, which decrease possibilities of planning free areas and their recreational value. Applications of the light guides for illumination of underground spaces do not have this shortcoming. Additionally, using of light guides do not have such restrictions to the depth, as the convenient daylighting systems.

As by convenient systems of daylighting, therefore by light guides, the maximal economy of electric energy can be gained only in combination with automatic control of supplementary artificial lighting. For all that from the point of view of daylighting, the light guides of big diameter are more preferable, but it comes in to contradiction with their costs and with increasing of heat gains and heat loses through their constructions.

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ACCOUNTING OF CLIMATIC FEATURES IN DESIGNING SOLAR SHADING DEVICES

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ABSTRACT

Zoning maps of the territory of the Russian Federation on solar radiation and outdoor temperature are given. It should provide for shading of fenestration during the cooling period of buildings, depending on the total amount of solar radiation and the temperature of the outside air. Depending on the amount of solar radiation, five zones are proposed in the territory of the Russian Federation. For each of the five zones, the cooling period of the building is proposed, on which the choice of the parameters of the solar ray daily cone depends on the shape of a solar shading device. A map of isolines of solar radiation for July in the North Caucasus and Southern Federal Districts of the Russian Federation is proposed, which can be used to calculate heat input through fenestration.

Keywords: solar shading device, map of isolines of solar radiation, parameters of insolation, zoning of the territory

INTRODUCTION

In 2016, by assignment of the Federal Autonomous Institution "Federal Centre for Standardization in Construction" (FAI "FCS"), NIISF RAASN together with the Crimean Federal University named after V.I. Vernadsky developed a draft code of rules "Solar shading devices of buildings: Rules for Design", [1].

The effectiveness of the use of solar shading devices in buildings for various purposes has been repeatedly proven by domestic and foreign research [2–6]. It is also obvious that the economic efficiency of their use depends largely on the climatic conditions of the construction site.

Unlike the most European countries, where the climatic conditions are fairly homogeneous, in such states as Russia, the United States, China, Ukraine they differ radically in different regions. So, for example, in construction guide of Ukraine [7, 8] the territory of the country is divided into 5 main zones.

Prior to the development of the above mentioned draft Building Regulations [1], there were no documents in the Russian Federation that would regulate the use of various modern solar shading devices depending on the site of building construction and their destination, as well as actual climatic conditions.

Design of solar shading devices should be carried out taking into account the climatic conditions of the construction region in accordance with Building Regulation (BR) СП 131.13330.2012 [9].

In accordance with BR СП 50.13330 [10] in areas with an average monthly temperature of July 21 °C and above for windows of residential buildings, hospital facilities (clinics and hospitals), dispensaries, outpatient clinics, maternity homes, children's homes, houses-individuals for the elderly and disabled, kindergartens, day nurseries, and orphanages, as well as industrial buildings, in which the

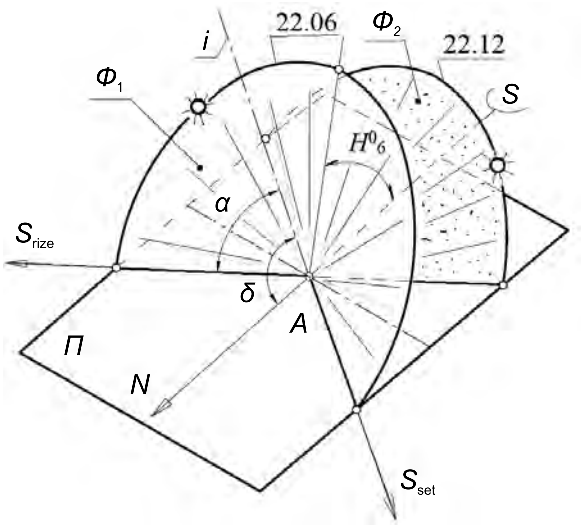

Fig. 1. Geometrical model of the solar ray daily cone: *A* – insolated point; *Φ* – solar ray daily cone; *α* – angle between the generator of the cone and its axis; *П* – horizontal plane; *δ* – latitude; *i* – axis of the Earth rotation; *S*, *N* – directions to the South and North; S_{rise} – sunrise direction; S_{set} – sunset direction; $H°_6$ – the angular height of the Sun at noon in June

optimum standards of temperature and relative humidity in the work area, or in which constant temperature or temperature and the relative humidity of the air must be maintained, should include solar shading devices.

Solar shading devices should be provided in the premises of public and industrial buildings, where in accordance with BR СП 52.13330 [11] it is supposed to perform visual works of high, very high and the highest accuracy.

In accordance with Sanitary Requirements (SR) 2.2.1 / 2.1.1.1076–01 [12] in the arrangement of windows of the western and south-western orientation in the buildings under construction and reconstruction in residential premises of apartments, dormitories, the main functional premises of children's educational organizations, educational organizations, general education organizations, having boarding schools and other specialized secondary educational institutions, medical and preventive, sanatorium and health institutions, social security institutions solar shading means should be provided.

GEOMETRICAL MODEL OF INSOLATION PROCESS

When designing solar shading devices to account for both: passive cooling in the warm period of the year and passive heating in the cold period of the year, it is necessary to take into account the total solar radiation with actual cloudiness in the construction site and the orientation of the building facades.

Differences in the positions of the Sun for different orientations and time of year are determined by the solar ray daily cone (SRDC) (Fig. 1).

The basis of all methods of forming stationary solar shading devices is the geometry of the apparent movement of the Sun across the sky, namely the geometric model of the insolation process in a point on the Earth during the day. This model is a one-parameter set of solar rays coming in one point on the Earth's surface during the day and is a solar ray daily cone (SRDC) [5]. Using the solar ray daily cone is the basis of all methods of forming solar shading devices (SSD), as well as the majority of methods of determining the duration of insolation.

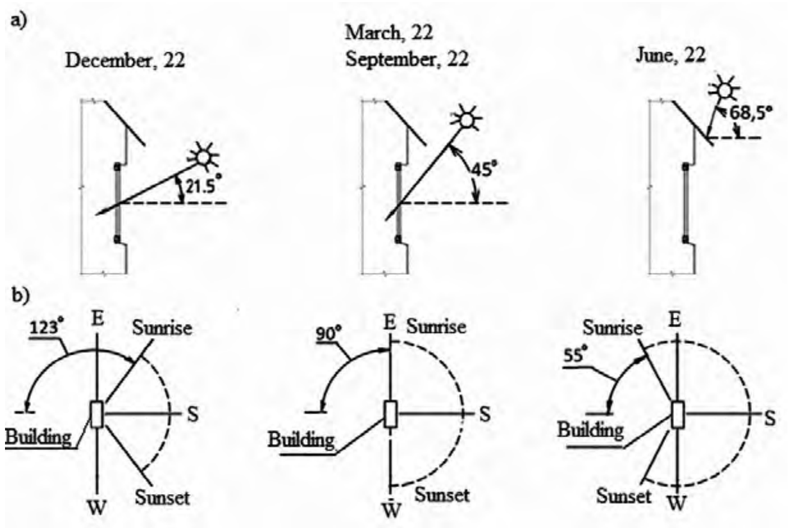

Fig. 2. Solar angles for the facade of southern orientation in the city of Krasnodar (45^{0}N) a) angular heights of the Sun; b) azimuths of sunrise and sunset

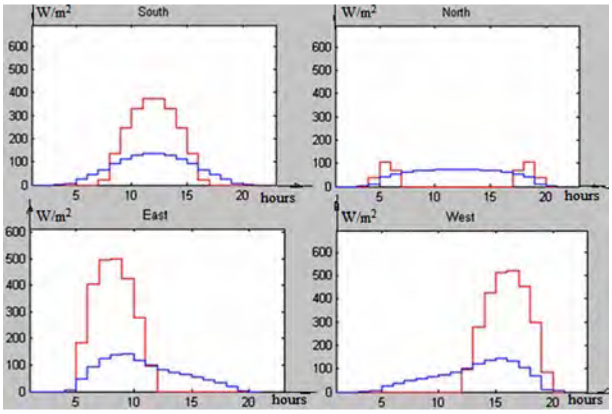

Fig. 3. Average monthly solar radiation (direct and scattered, W/m^2) for four orientations of the facade in July in Belgorod depending on the time of a day (50^0 N): red line – direct solar radiation, blue line – scattered solar radiation

The methodology for designing a SSD with the use of a solar ray daily cone is described in [5].

With the solar ray daily cone (SRDC):

- The angular height of the Sun at noon $H°_{12}$ for the selected day of the year – is used in calculating the parameters of the position of solar collectors and photovoltaic panels;
- Azimuths of the sunrise S_{rise} and sunset S_{set} for the selected date – used when determining the duration of insolation;
- Time of sunrise τ_{rise} and sunset τ_{set} of the Sun.

The horizontal plane *П* cuts the cone on two generators, which indicates the directions of the sunrise and sunset in horizontal projection. S_{rise} is the azimuth of sunrise. S_{set} is the azimuth of sunset. The values of the azimuths of the sunrise and sunset for the city of Krasnodar are shown in Fig. 2.

When designing the solar shading device (SSD), it is necessary to take into account the differences in the amount of solar radiation on the building facades of different orientations during the winter and summer periods of the year. Average monthly solar radiation (direct and scattered) for four orientations of the facade in July [7] in Belgorod is shown in Fig. 3.

ZONING OF THE TERRITORY OF THE RUSSIAN FEDERATION ON SOLAR RADIATION AND OUTDOOR TEMPERATURE

Fig. 4 shows a map of the territory zoning of the Russian Federation on total solar radiation on a horizontal surface under real cloud conditions, constructed in accordance with the procedure [13] and data [14].

Five main zones were identified according to the conditions of total annual solar radiation on a horizontal surface under the actual cloud conditions:

- The first zone – 900 kWh / m^2 or less;
- The second zone – over 900 to 1000 kWh / m^2;
- The third zone – over 1000 to 1100 kWh / m^2;
- The fourth zone – over 1100 to 1200 kWh / m^2;
- The fifth zone – over 1200 kWh / m^2.

It is necessary to provide shading of fenestration during the overheating period (cooling period of buildings) depending on the total amount of solar radiation:

- In the first zone – it is not regulated;
- In the second zone – from May 22 to July 22;

Fig. 4. Schematic map of total annual solar radiation on a horizontal surface in conditions of actual cloudiness, kWh / m^2

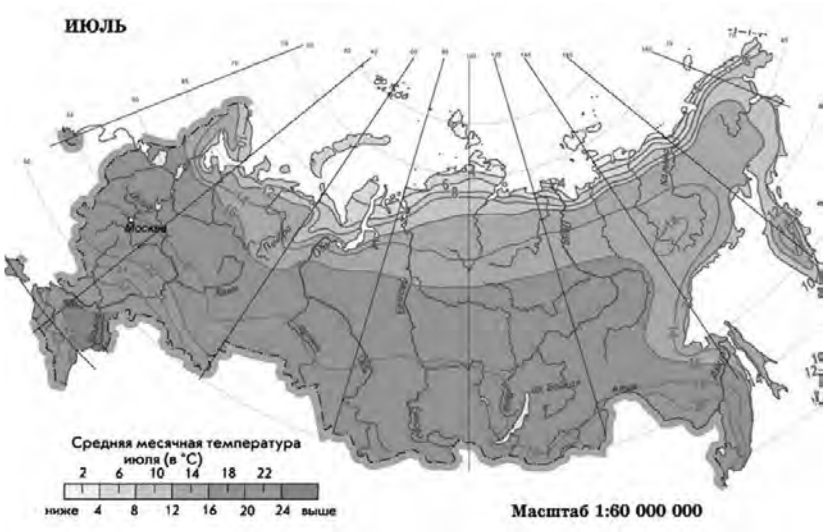

Fig. 5. Schematic map of the average temperature in July

– In the third and fourth zones – from April 22 to August 22;

– In the fifth zone – from March 22 to September 22.

For each of the five zones, periods of cooling and overheating affect the choice of the parameters of the solar ray daily cone [5].

To ensure visual comfort in the premises and privacy at night, solar shading devices should be provided for all orientations of the facades of buildings, including northern, in climatic regions where the polar day is observed in the summer.

In climatic regions with a predominance of sunny weather in the cold period of the year, it is necessary to ensure the possibility of providing passive solar heating of premises to reduce the energy costs for the operation of the heating systems of buildings.

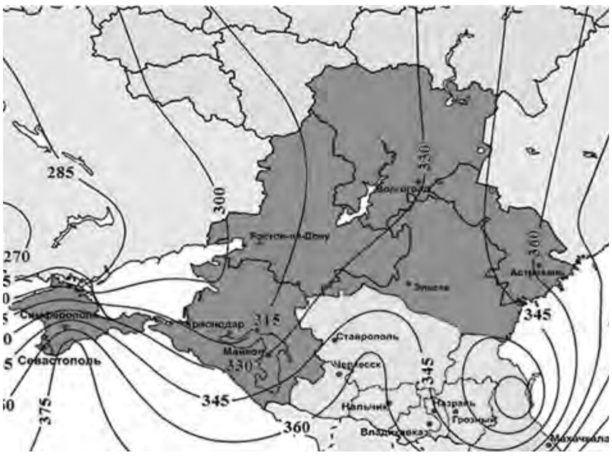

Fig. 6. Total solar radiation on a horizontal surface in July, W/m²

Fig. 5 shows the zoning of the Russian Federation territory by the average monthly temperature of July, which should be used to determine the location of the SSD relatively to fenestration.

In the Crimean Federal University named after V.I. Vernadsky monthly maps of solar radiation isolines on a horizontal surface under conditions of actual cloudiness in W h/m^2 are developed, which is necessary for the calculation of heat input through fenestration. As an example, this article presents the results for the North Caucasus and Southern Federal Districts (Fig. 6).

CONCLUSIONS

To reduce the impact of harmful factors of direct solar radiation on the microclimate of premises, including overheating, during the cooling period of buildings it is necessary to use the solar protection of buildings. As a solar protection various measures can be considered:

– The rational orientation of the facades;

– The rational planning of the premises (loggias, visors on the facades, blinds, roller blinds, etc.);

– Planting green plantations near the facades of buildings;

– The equipment of fenestration with solar shading devices.

In all cases it is necessary to use solar geometry, the values of solar radiation and the temperature of the outside air.

In more detail, the basic principles of designing modern solar shading devices will be considered in subsequent publications.

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LED INDUSTRIAL SPATIAL STRUCTURE AND ITS EVOLUTION TREND IN HANGZHOU BAY AREA, CHINA

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ABSTRACT

The numbers of spatial scale structural dimensions and associated structural dimensions in the light emitting diode (LED) industry in Hangzhou Bay Area, China since 2002 were estimated through the fractal method for the prediction of the future evolution trend of the industry. We found that the spatial structure of the LED industry in that area is of strong monopoly but tends to be generally optimal and stable. The morphology in which the main enterprises concentrate in a linear space contributes to the interactions among the enterprises; future spatial structure of LED industry in Hangzhou Bay Area will be a stable state. Changes in external environments and the interaction between internal industrial factors constitute the basic dynamic mechanism for the formation and evolution of LED industrial spatial structure in the Hangzhou Bay Area.

Keywords: Hangzhou Bay Area, LED industry, fractal, R/S analysis, spatial structure

1. INTRODUCTION

Owing to the increasing popularity of semiconductor lighting, semiconductor light sources, especially light emitting diodes (LEDs), has attracted interest worldwide [1]. The LED industry is considered as one of the high-tech industries with the greatest development prospect in the 21st century [2]. Faced with this enormous market space, several countries have correspondingly promoted LED industrial development plans and started to occupy the global market [3]. The Hangzhou Bay Area is one of the areas with the most developed economy in China. After years of development, the LED industry in this area has gradually developed self-innovative abilities. In addition, a complete industrial chain has been formed. To date, there are more than 2000 LED enterprises engaged in epitaxial wafer, chip, encapsulation, and application in Hangzhou Bay Area. Thus, Hangzhou Bay Area has become one of the largest LED production and supply bases worldwide.

The spatial evolution of the LED industry is a complicated dynamic process with large time span. Clearly revealing this evolution process is a problem needing urgent solution in the current industrial development. However, discussing about problems, such as spatial structure and evolution trend of LED industry, may party improve the competitiveness of LED industry and eventually drive the development of related industrial clusters and realize industrial transformation and upgrade. Therefore, in this study, we attempt to introduce fractal idea into LED industry research, expecting to completely present the spatial structure of the LED industry in the Hangzhou Bay Area and its evolution features since 2002. This work is also a significant supplementation for the research contents and methods of the LED industry.

2. LITERATURE REVIEW

The LED industrial field has always been a great concern among academic circles [4]. With continuous development of LED technology, related studies have drawn increasing attention [5]. However, not a few scholars have explored the main factors influencing the spatial evolution of LED industry. Taking Taiwan as an example, Ma et al., used the fuzzy analytical hierarchy process method to evaluate the paths for the effective acquisition of core technologies in the LED industry. Their results showed that Taiwan enterprises acquire new technologies by licensing or realize technological independence by building R&D alliance and attracting relevant enterprises with commercial potential and potential market shares [6]. Yushan Chen et al. discussed the competitive and cooperative behaviour among LED enterprises through patent analysis. Their study contributed to spatial agglomeration in the industry [7]. Meanwhile, Kaa et al. verified that national institutional environment negatively affects the development of regional LED industries by restricting the progress of industrial standardization [8].

In general, existing literature on the spatial structure of LED industry is quite limited, lacking empirical works based on quantitative method. On this basis, a measurement model for spatial structure and evolution trend was established in this research by using fractal methods, such as the measurement of scale structural dimensions and associated structural dimensions and R/S trend analysis method. We conducted an empirical study of the LED industry in an area in Hangzhou Bay, China.

The rest of this study is organized as follows. Section 3 expounds the application of the fractal method in LED industry studies. Section 4 conducts empirical analysis of the spatial structure and evolution trend of the LED industry in Hangzhou Bay Area. Section 5 analyzes the dynamic mechanism of spatial evolution of LED industry in Hangzhou Bay Area. The final section summarizes the entire study and draws related conclusions.

3. RESEARCH METHOD

3.1. Measurement of Scale Structural Dimensions

The LED output values in the main cities of Hangzhou Bay, China are selected as representative indicators of industrial scale. The LED industrial scales are sorted by size, and the logarithms of the ranks and numerical values of the LED industrial scales are used for drawing a scatter diagram. Its fitting trend is also observed. When a linear regression functional relationship is observed between the two, the rank-size distribution of the LED industrial scales is regarded conforming to Zip's law. The concrete computational formula is as follows:

$$T(r) = T_1 \times r^{-q}, \quad (1)$$

where r is the scale ran of LED industry (r =1,2,…,10), $T(r)$ is the urban LED industrial scale with rank as r, T_1 is the LED industrial scale of the first-rank city, and q is the Zip f parameter. Logarithms at two sides of formula (1) are taken to obtain the following:

$$lnT(r) = lnT_1 - qlnr \, . \quad (2)$$

A series of data pairs [lnr, $\ln T(r)$] are solved using formula (2). These data pairs are fitted, and if they present linear regression relationship, then the number D_f of scale structural dimensions of urban LED industry is

$$D_f = R^2 / q \, , \quad (3)$$

where R^2 is the coefficient of determination of the fitted equation. Fractal dimension D_f has effective geographic significance and reflects the spatial distribution pattern of LED industrial scale structures. If D_f <1, then the LED industries present a Pareto unbalanced distribution. The monopoly of the first-rank city is strong, and the overall development of the LED industry is not mature enough. If D_f =1, the ratio of the first-rank city and the smallest scale city is rightly equal to the number of cities. If D_f >1, LED industrial distribution is under relative balance, the number of cities in intermediate rank is large, and the overall development of LED industry is relatively mature.

3.2. Measurement of Associated Structural Dimensions

Associated structural dimensions in LED industrial space can be explained as spatial interaction laws between LED industries, which depict relative distribution state of LED industries in various cities within the area. Considering that the spatial distribution of LED industry is generally two-dimensional, its spatial correlation function can be defined as

$$C(k) = \frac{1}{N^2}\sum_{i,j=1}^{N} H(k - d_{ij}), \qquad (4)$$

where $C(k)$ is the spatial correlation function; N is the number of cities meeting certain conditions; k is the step length; d_{ij} is the Euclidean distance from city i to city j; H is the step *Heaviside* function.

$$H(k - d_{ij}) = \begin{cases} 1 & k > d_{ij} \\ 0 & k \le d_{ij} \end{cases}. \qquad (5)$$

If the spatial distribution of the LED industry is fractal, then $C(k) \propto k^{D_g}$ should be met. Here, D_g is mainly the associated structural dimensions, and its actual calculation is similar to the measurement method of scale structural dimensions on the map. Euclidean distances between cities are first calculated for obtaining the Euclidean distance matrix. Then, the $C(k)$ value is calculated, and k value is changed. The scatter diagram concerning a series of [k, $C(k)$] data pairs is obtained, and the value of associated structural dimensions D_g can be obtained through linear fitting of data pairs. Under general circumstances, $0 \le D_g \le 2$. When $D_g \to 0$, the LED industries inside the system concentrate into one point. When $D_g \to 2$, the LED industries inside the system concentrate on a smooth curve. A large D_g value means several balanced LED industries are distributed in various cities within the area and in a geographic space. Meanwhile, a small D_g value indicates that small space industries are concentrated in the areas.

3.3. Rescaled Range (R/S) Trend Analysis Method

Proposed by Hurst in 1951, the R/S method in fractal theory is an analysis method for time sequence [9]. R/S analysis method can be used for studying fractal features and long-term memory process of time sequences and determining the evolution laws and predicting their future development trend. An analysis process using the R/S analysis method is as follows: for time sequence $\{B(t)\}$, t =1, 2,…, n, and for any positive integer $\tau \ge 1$, then:

1) The mean sequence is calculated as

$$\langle \xi \rangle \tau = 1/\tau \sum_{t}^{\tau} B(t);$$

2) The cumulative deviation is computed as

$$X(t,\tau) = \sum_{\mu=1}^{t} \{\xi(\mu) - \langle \xi \rangle \tau\};$$

3) The range is calculated as

$$R(\tau) = \max_{1\le t\le \tau} X(t,\tau) - \min_{1\le t\le \tau} X(t,\tau);$$

4) The standard deviation is calculated as

$$S(\tau) = \left[1/\tau \sum_{t=1}^{\tau} \left(\xi(t) - \langle \xi \rangle \tau\right)^2\right]^{1/2};$$

5) $R/S \equiv R(\tau)/S(\tau)$.

If $R/S \propto \tau^H$ is satisfied, then *Hurst* phenomenon exists in time sequence $\{B(t)\}$ and H is the *Hurst* index. We determine a whether time sequence trend is persistent or anti-persistent according to the H values. If H =0.5, then time sequence is a random walk sequence, and if $0.5 < H \le 1$, then the time sequence evolution is persistent. A large H value means strong persistence. If $0 \le H < 0.5$, then the time sequence evolution is anti-persistent, whereas a small H value indicates strong anti-persistence.

3.4. Data Source

We select the LED industries in the 10 main cities in the Hangzhou Bay Area, including not only central cities with high concentration of LED enterprises, such as Shanghai, but also medium and small supporting cities, such as Jiaxing and Shaoxing. These industries cover epitaxial wafer, chip, encapsulation, and application. Sample selection was of certain cover degree and representativeness. Indicator data came from investigations on related guilds, official websites of enterprises, and competent departments.

4. EMPIRICAL ANALYSIS OF SPATIAL STRUCTURE OF LED INDUSTRY IN HANGZHOU BAY AREA

4.1. Analysis of Hierarchical Structure

The 2017 LED output values of the sample cities were selected as the basic data and sorted according to LED industry size in descending order.

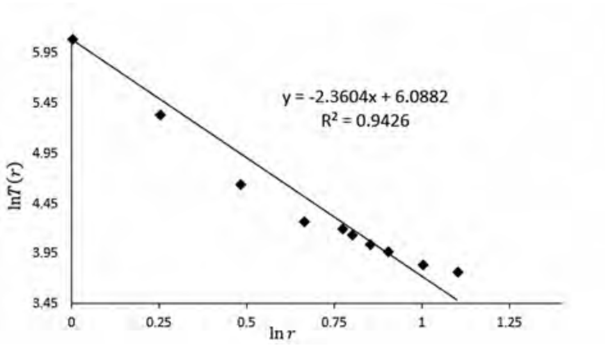

Fig.1. Dial-logarithm diagram of LED industrial rank-size distribution in Hangzhou Bay Area

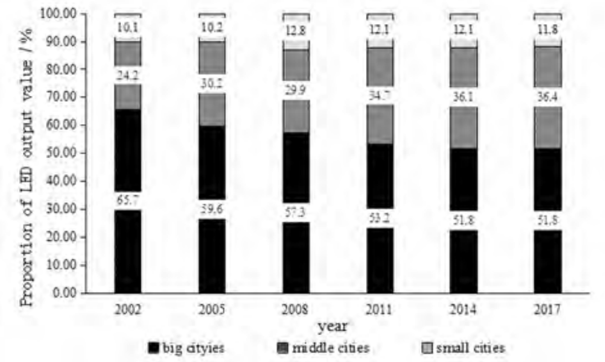

Fig.2. Distributional proportions of LED industrial scales in large, medium, and small cities

The purpose was to obtain the rank-size data pairs of the cities. Logarithms of rank data and size data were used for drawing a 2D scatter diagram for fitting. Goodness of fit was used for the evaluation of the existence of fractal features. Fig. 1 presents the rank-size distribution status of LED industries in various cities within Hangzhou Bay Area. In this figure, most scatter points were fitted on the same straight line, coefficient of determination was R^2 =0.943, and obvious and broad scale-free interval was observed with obvious fractal features. The number of dimensions D_f =0.866<1 was solved according to formulas (2) and (3). The result indicated that LED industries with different hierarchical scales were under a disperse distribution, and the monopoly of first-rank cities was strong. In a similar way, the scale structures of LED industries in Hangzhou Bay Area since 2002 were analyzed, and D_f values over the years were obtained. Notably, coefficients R^2 of determinations of all years reached above 0.9, suggesting that the spatial scale structures of all the LED industries within the Hangzhou Bay Area have obvious fractal features.

As shown in Table 1, the D_f values in all years were smaller than 1, indicating that the overall development degree of the LED industries in the Hangzhou Bay Area was not mature enough. The LED industries had a non-uniform distribution in different cities, and the first-rank cities had strong monopoly. From the time sequence, the D_f values initially presented an increasing evolution trend before levelling off. The D_f values from 2002 to 2010 increased obviously, showing that the balance degree of LED industries in space within Hangzhou Bay Area gradually increased. This spatial structural evolution trend promoted industrial development in medium and small cities and facilitated the functional coordination in the entire LED industry. Since 2011, D_f values have been basically stabilized at 0.86. This result, on the one hand, suggests the oversaturation state of investment and construction of medium and small cities and gradual increase of LED industrial scales in various cities. On the other hand, this outcome indicates the "marginal challenge" effect in LED industrial space within the Hangzhou Bay Area.

Table 1. D_f Values of LED Industries in Hangzhou Bay Area since 2002

Year	R^2	D_f	Year	R^2	D_f
2002	0.946	0.642	2010	0.926	0.823
2003	0.942	0.683	2011	0.923	0.845
2004	0.938	0.737	2012	0.922	0.862
2005	0.934	0.746	2013	0.938	0.865
2006	0.931	0.732	2014	0.918	0.866
2007	0.928	0.763	2015	0.923	0.869
2008	0.925	0.752	2016	0.935	0.868
2009	0.934	0.778	2017	0.928	0.866

Table 2. Associated structural dimensions of LED industries in Hangzhou Bay Area

k/km	C(k)	k/km	C(k)	k/km	C(k)
30	0.121	180	0.348	330	0.835
60	0.162	210	0.467	360	0.866
90	0.198	240	0.584	390	0.913
120	0.247	270	0.676	420	0.952
150	0.289	300	0.789	450	1

For the further analysis of spatial pattern evolution of LED industries in Hangzhou Bay Area, the main cities were divided into large, medium, and small types. The distributional proportions of LED industrial scales among the three-type cities are illustrated in Fig. 2.

Overall, the scale structures of LED industries in the Hangzhou Bay Area had obvious monopoly features over the years. In the scale ranking, Shanghai occupies approximately 50 % of the entire LED industrial scale. From time sequence evolution, LED industries gradually migrated from large cities to medium and small cities. The LED output value increased obviously especially in small cities, and the spatial structure of the entire LED industry tended to be optimal and stable. In 2002–2011, the proportion of the LED output values in large cities remarkably decreased, whereas those of medium and small cities increased obviously with continuously optimized spatial structure. After 2011, change trends of proportions of LED output values in various types of cities were becoming small, and the proportion of LED output values in small cities even slightly decreased. The spatial structure of the entire LED industry in Hangzhou Bay Area also tended to be stable.

4.2. Analysis of Associated Structure

For the construction of a 10×10 matrix, Euclidean distances between every two industrial clusters (straight-line distance) in the sample cities were measured by using a geographic information system platform. Step length k =30 km was used as a scale, and a series of $C(k)$ values were obtained by changing k value, as shown in Table 2. On this basis, the number of dimensions and coefficient of determination of associated structure were obtained as D_g =1.143 and R^2 =0.968 with favourable goodness of fit. The number of dimensions of associated structure was approximately 1. This value indicated that LED industries in the cities were concentrated within a single linear spatial range with strong spatial correlation. This finding was in accordance with the realistic situation. This linear space was largely a supply chain channel constructed by connecting "Shanghai–Hangzhou" Huhang line and "Hangzhou–Ningbo" Hangyong line but also indicated that LED industries in inland cities were not developed enough. Thus, high requirements had been proposed for improvement of inland supply chain network and industrial competitiveness within Hangzhou Bay Area.

4.3. Research and Judgment of Development Trend

Year 2002 was taken as the base point, and R/S analysis method was used to analyze time sequence evolution trend of numbers D_f of dimensions of LED industries within Hangzhou Bay Area as shown in Table 3. Overall, *Hurst* index presented a descending trend, indicating continuously weakened persistence of change of D_f values in the same direction but with gradually minimized descending amplitude. Before 2013, index was always

Table 3. *Hurst* indexes of spatial evolution of LED industries within Hangzhou Bay Area

Period	**2002–2006**	**2002–2007**	**2002–2008**	**2002–2009**
H	0.784	0.649	0.658	0.732
Period	2002–2010	2002–2011	2002–2012	2002–2013
H	0.633	0.562	0.532	0.515
Period	2002–2014	2002–2015	2002–2016	2002–2017
H	0.485	0.498	0.506	0.497

greater than 0.5, and D_f value evolution would present persistent development trend. This result suggested a continuous growth. After 2011, index was approximately 0.5, and D_f value evolution would present stable trend with small fluctuation. In summary, as *Hurst* index continues to fluctuate at 0.5, the spatial structure of LED industries in Hangzhou Bay Area would not change greatly within a period in the future.

5. DYNAMIC MECHANISM OF SPATIAL EVOLUTION OF LED INDUSTRIES IN THE HANGZHOU BAY AREA

5.1. External Factors

The external influence factors of spatial evolution of LED industries are mainly manifested at three aspects. The first aspect is the driving effect of associated industries [10]. LED products are important supporting products of various manufacturing industries. The Hangzhou Bay Area is a developed manufacturing industry, and the development of industries, such as automobile, requires a large quantity of LED products. This phenomenon has provided enormous demand market for the LED industry [11]. The second is governmental policy support. Governmental guidance is a decisive factor of the spatial evolution of LED industries [12]. In recent years, the local government of the Hangzhou Bay Area has planned multiple LED industrial parks and industrial bases and attracted many LED enterprises by providing preferential policies to form enormous agglomeration effect. The third is agglomeration of scientific and technological innovation elements [13]. LED industry development cannot go without support from scientific studies. Hangzhou Bay Area is agglomerated with many famous colleges, universities, and scientific research institutes with dense intelligent elements. Domestic top-end LED R & D centre has also been formed. R & D and patent service can provide guarantee for spatial agglomeration and development of LED industries in this area.

5.2. Internal Factors

Internal influence factors of spatial evolution of LED industries mainly include three aspects. The first is competition and cooperation between enterprises. Internal competition between enterprises is the direct cause for "marginal challenge" [14]. With the improvement and elevation of their own environments, medium and small cities have adopted a series of strategies, such as price competition, policy support, and fiscal subsidies to attract LED enterprises to set up production and R & D bases to dilute industrial resources of large cities and narrow regional gaps. Meanwhile, industrial-chain cooperation is formed between cities to promote joint growth of LED industrial scales in these cities, and this growth usually presents high synchronization and promotes stability of spatial structure of LED industries. The second is core technological control. LED industries have strong technological orientation. Enterprises with strong R & D abilities within the industry usually control core technologies and patents in this industry. These enterprises can become core enterprises on LED industrial chain and can constitute and develop the entire industrial chain to decide the spatial layout of the regional industry. The third is industrial talents. LED industry involves multiple disciplines, such as light, electricity, and heat. Thus, a large number of comprehensive professional and technical talents are needed. Nowadays, shortage of high-end talents has become the key bottleneck restricting LED industrial development in Hangzhou Bay Area. The cities that can provide good development environment for talents can attract related technical talents and attract agglomeration of high-end enterprises in the industrial chain to form an industrial development highland.

6. CONCLUSIONS

LED industry in Hangzhou Bay Area was taken as an example in this research, and fractal method was used to analyze the spatial structure and evolution trend of LED industry. The research shows the following: (1) spatial structure of LED industry in Hangzhou By area is not only of monopoly feature but also of "marginal challenge" spatial effect and generally tends to be optimal and stable; (2) LED industries in Hangzhou Bay Area are distributed within a linear range with strong interaction between main cities; (3) persistence of spatial structural fluctuation of LED industries in Hangzhou Bay Area decreases and finally tends to be stable; and (4) the abovementioned dynamic mechanism of spatial structure and its evolution is not only related to peripheral economic environment and policy environment of LED industry but also is closely related to internal development factors within LED industry.

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TECHNOLOGICAL INNOVATION AND LED LIGHTING INDUSTRY DEVELOPMENT IN CHINA

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ABSTRACT

Current lighting industry faces a new situation, and that is rapid progress of technology in the world, rise of emerging applications, acceleration of market penetration and adjustment of competition pattern. The concentration of China's industries has been further improved. Leading enterprises have accelerated their expansion, and overseas market expansion has accelerated. Integrating mergers and acquisitions becomes the mainstream. The study combed present development situation and current problems of China's LED lighting industry. A case was chose to analyze technological innovation's effect on development of LED lighting industry, and the suggestions for further developing China's LED lighting industry were put forward. Results show that the key technology of lighting industry makes a significant breakthrough in China and optimizes product structure.

Keywords: LED, lightning industry, technological innovation

1. INTRODUCTION

As the global consensus on developing low carbon economy, LED lighting industry with its performance advantages in the field of saving energy and reducing consumption will usher in the rapid development of the precious opportunity [1]. At the same time, advantages of LED lighting are incomparable. As a new generation of light source in the world, LED is regarded as the most promising green lighting source in the 21st century due to its advantages of energy saving, environmental protection, good colour rendering and long life [2].

Technological innovation is becoming a huge driving force for the rapid development of LED lights. LED industry developed rapidly and a large number of leading enterprises had sprung up in recent years. Kingsun Optoelectronic Corporation and State Key Laboratory on Integrated Optoelectronics and of Tsinghua University built Semiconductor Lighting Technology Research Institute together, which meant the enterprise of science and technology transformation and university research technology closely linked. It contributed to promoting the development of LED industry to the depth field [3]. Research and development of its core function was through construction of technology innovation platform, technology promotion and service platform, technical personnel and enterprise incubation platform, service platform, technological product with LED encapsulation and testing service centre, LED lighting applications and service centre, LED optical application and test centre for hardware support. It provided scientific research, technology, human resources and industrial investment services for

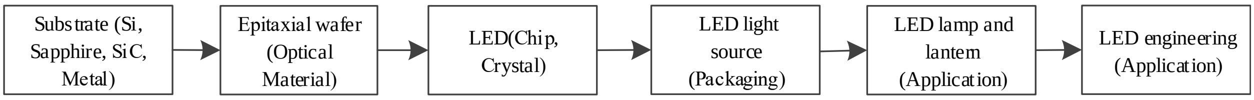

Fig.1. Industrial chain of China's LED

LED industry cluster in all aspects, and promoted steady and rapid development of LED industry [4].

2. DEVELOPMENT STATUS ANALYSIS OF LED LIGHTING INDUSTRY IN CHINA

2.1. Industrial Chain

Epitaxial wafer and chip patents in upstream are monopolized by Japanese, European and American enterprises, which will lead to excessive production of LED chips, especially in China. In the packaging process of the middle reaches, Korean enterprises rise rapidly, and good supply and demand of the industry will enhance the added value of packaging products [5]. Domestic enterprises with help of government and local advantages can compete with international well-known enterprises in application links in downstream. After years of development, China's LED industry chain has been gradually improved, and enterprises are all over the substrate, epitaxy, chip, package and application, Fig. 1. In view of the overall industrial chain, because the upstream industry has a high demand for technology and capital, it is rarely involved in domestic enterprises. Therefore, there are few enterprises and small scale characteristics in the industry [6]. By contrast, due to the downstream packaging and application of funds for enterprises and technical requirements are relatively low, this matches the characteristics of domestic enterprises, namely rather less money with weak technology. As a result, large number of enterprises engaged in packaging and application. The uneven distribution of enterprise structure leads to the majority of low-end products in China's LED industry, and the enterprises are faced with severe price pressure in the long run [7].

2.2. Industrial Distribution

China's LED lighting industry distribution is centralized, which has initially formed four regions of the Pearl River delta, the Yangtze River delta, southeast areas, north area, such as Beijing and Dalian. Each region basically forms relatively complete industrial chain. Four regions, namely Dalian, Shenzhen, Xiamen and Nanchang, have mature LED production base. Overall, South China's LED industry pattern of industrialization degree is higher. The Pearl River delta and the Yangtze River delta are the most concentrated areas of domestic LED lighting industry [8]. The middle and lower reaches of industry chain is more complete, which gathers more than 80 % of China's related businesses. While, north area relies on a large number of universities and scientific research institutions, and product research and development strength is relatively strong.

2.3. Industrial Scale

In recent years, China's lighting industry generally has continued to rise. In 2016, whole output

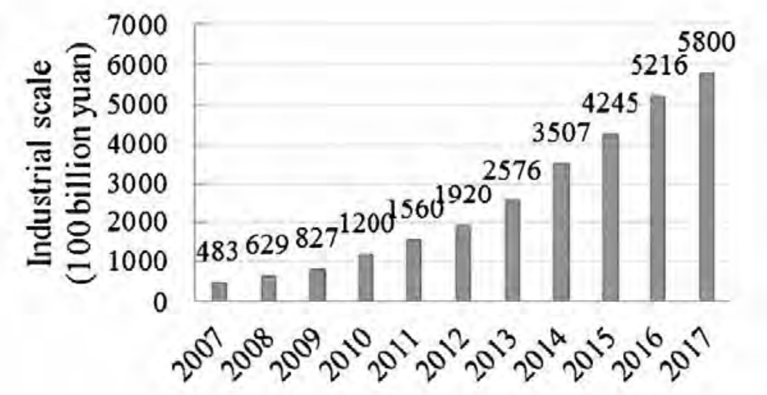

Fig.2. Industrial scale of China's LED

value of China's lighting industry reached 521.6 billion yuan, increasing 22.8 % compared with 2015. The growth rate was slow down, shifting from "ultra-high speed" to "medium". In 2017, overall sales of the industry were about 580 billion yuan, with 11.20 % increase from 2016, shown in Fig. 2. The main reason is influenced by the significant dollar depreciation. Although export grows from $38.8 billion in 2016 to $41.2 billion in 2017, the contribution to overall sales growth has been limited.

3. DEVELOPMENT PROBLEMS OF LED LIGHTING INDUSTRY IN CHINA

At present, China's LED lighting has many applications in general lighting areas, such as tunnel lighting, road lighting, airport lighting and underground lighting. It emerges a batch of demonstration significance for application projects, such as semiconductor lighting energy-saving renovation project of the great hall, LED lighting of water cube and Shanghai World Expo pavilion, etc. However, overall market share of LED lighting is still small, and the application is still in the early stage of exploration, and there is still a long way to go for large-scale promotion. The following problems need to be solved:

1) The price of LED lighting is still too high. Although the state finance has relevant subsidies, it is still difficult to reach the degree that most engineering projects and ordinary people can accept. This requires further technological innovation and development, reducing costs and developing products that can be industrialized at a low price.

2) Current testing methods and standards of semiconductor lighting products are lagged behind, which is far behind technology and product upgrading. This leads to the result that quality of products on the market is uneven. It's difficult for users to discern whether product is good or bad, even the defective goods in circulation market share is bigger [9].

3) Industrial resources are not centralized. The market is more chaotic, and phenomenon of disordered and low-price malicious competition is widespread, which affects long-term and orderly development of the whole industry.

4) Energy saving awareness in some areas of the society is not strong enough, and the cognition of energy saving effect brought by semiconductor lighting is not yet in place. For LED lighting applications, there are also problems such as light decay, heat dissipation and light distribution, etc. Besides, system circuit board, control and drive are also included.

3.1. Development of Related Lamps and Lanterns

For energy-saving lamps, although energy saving is an important function, their more important status is the lamp. In modern homes and cities, the role of lights is not only illumination, but also a decoration. Different places, such as shopping malls, hotels, restaurants, supermarkets, and the family houses lighting has different requirements, and if energy-saving lamps on the appearance design, functional design, lack of innovation and breakthrough cannot take the initiative to meet the needs of the diversity of consumers, it is difficult to get market acceptance.

3.2. Patent Problem

At present, core patents of the LED industry are mainly controlled by several foreign companies. These companies use their respective core patent, adopt horizontal (entering several countries simultaneously) and vertical (perfect design for subsequent application) extension way, and decorate the rigorous patent worldwide network. Several international LED factories make full use of the intellectual property related to LED to achieve the goal of striking opponents and to maintain their own market position. Developed countries are taking advantage of patent weapons to seize the market of China, forming the trend and pressure of "peripheral blockage" of Chinese enterprises.

3.3. Localization of MOCVD

MOCVD is metal organic chemical vapour deposition equipment, which is the most critical equipment for LED epitaxial. The purchase cost is about two-thirds of that of whole LED production line. Rapid development of semiconductor lighting industry appears, and demand of the MOCVD equipment continues to increase. More than 90 % of MOCVD markets around the world have been controlled by AIXTRON Company in Germany and VEECO Company in the United States. At present, China totally dependents on imports of production-oriented MOCVD equipment each year, and needs to invest heavily to buy such equipment. Maintenance and spare parts procurement have so much inconvenience [10].

4. CASE STUDY

Hannway Technology Corporate captured the beginning period of LED industry. On the one hand, it established industrialization through capital investment. On the another hand, through cooperation with scientific research institutes of colleges and universities, it introduced Shanghai Academy of Astronautics as technical support. It had breakthrough constant current driver with high reliability, high efficiency heat dissipation, integrated optical engine, LED indoor and outdoor lighting industrialization technology difficulties. It introduced a series of LED lighting products in Shanghai, in the office building, hospital, school, the subway, road, tunnel, hotel, etc. In the lighting renovation, satisfactory energy-saving effect was obtained. The good product quality, humanized design and high quality service made enterprise product to be promoted quickly in the market, and also to be paid attention by the traditional lighting giants. Under the condition of good market record, enterprise development had always been to “scientific and technological innovation” as the source of enterprise progress. Through external exchanges and cooperation, increase investment in research and development, continuously upgraded products. No matter from quality LED lighting products, performance and cost performance, the corporation always was a market leader. It had invested heavily to deepen cooperation with Shanghai Space Academy and explored new application fields. With the help of science and technology commission, scientific research got achievements successively.

At present, Hannway Technology Corporate had been awarded Shanghai metro, hospital, university and other major lighting projects through continuous market development. Construction of network construction in the field of drainage channels has also been effective. The market share gradually expands, and the sales increase year by year. It can achieve today’s results, more inseparable from strategy guidance of “innovation driven, transformation development”. It will bear in mind that science and technology is the first productive force, and the spirit of innovation as the soul of the enterprise.

5. DEVELOPMENT STRATEGY CHINA’S LED LIGHTING INDUSTRY BASED ON SCIENTIFIC AND TECHNOLOGICAL INNOVATION

5.1. Improving Standard System for Industrial Technology and Cooperation

On the one hand, China’s LED equipment industry is a lack of complete technical standard system in the process of foreign competition. On the other hand, cooperative innovation of China’s LED production equipment enterprise is also a lack of unified template and standardized system of cooperation. In industry standard system, China’s government should play a fundamental role. Although there have been “CBS” system in the United States and “Muse” system in Japan, for growth of China’s LED lighting industry, perfect market mechanism brings a few standard monopoly and market growth and the possibility of cooperative innovation.

Therefore, government should plan and coordinate different chain link, segmentation, local and central standards of LED industry. Through extensive international cooperation and market research, China should occupy the commanding heights of global LED industry standards. Taking construction of LED standard system as an opportunity, it should gather the standard cooperation and verification of LED equipment enterprises and production enterprises. At the same time, the standard should be kept open.

China’s LED equipment enterprise technical level has got greater ascension, but due to the use of habits and credit related problems, production enterprises are not willing to cooperate with equipment enterprise. Therefore, the government needs to increase conversion efficiency of scientific research achievements, reduce the cost and risk of LED production enterprises, and fully realize the value of China’s equipment enterprises.

5.2. Strengthening Scientific and Technological Innovation to Improve Achievement Efficiency

Due to the failure of high-end manufacturing equipment in the trial process, loss to LED manufacturers will be huge. Even equipment maker agreed to let free trial of LED production enterprises, it can affect LED manufacturing enterprises’ willingness to try, due to technical workers brought by inappropriate use of inertia and trial enormous losses. Therefore, many LED lighting companies do not have the confidence to try out domestic equipment. Companies tend to have no confidence to try homebred MOCVD equipment, because production process also involves a lot of raw materials and artificial cost. Once waste is produced, manufacturing enterprises need to bear a great loss. Provision of free equipment and costs may be beyond capacity of device makers. Subsidy fund or a risk compensation fund should be set up to try and design a well-designed subsidy policy for equipment of China's LED manufacturers. It is encouraged to jointly build production line of LED equipment enterprises and production enterprises, which will be funded by the government or provided with other financial and administrative support to strengthen the trial intention of LED manufacturers.

5.3. Building a Symbiosis Innovation Ecology with Leading Enterprise as the Core

Foreign enterprises' specialized degree is high, and they generally plough in the field of LED equipment for decades deeply. Due to companies' own development ability is strong, more important is foreign industry development and cooperative innovation is leading enterprises as the core. Upstream cooperation with a batch of technical ability of small and medium-sized enterprises, colleges and universities, and research institutions is quite important. Downstream cooperation with a batch of leading enterprises and users is necessary. Development of leading enterprises returns to these small and medium-sized enterprises and partners, forming a positive cycle. Under such a symbiotic relationship, the system can continuously create blood and innovation.

Therefore, government needs to guide and support China's LED industry through strategic planning, tax incentives, credit support and special funds. Lighting enterprises should cooperate with each other to deal with the technological innovation challenge and the impact of foreign competitors. Attention should be paid to industrial chain of vertical integration and building LED equipment leading enterprises as the core, to support small and medium-sized high-tech enterprises and production application enterprises. In the process, government and other organizations should ensure service collaborative innovation pattern. It should make full use of regional potential, gather technology and application resources, reduce transaction costs and credit crisis, and extend the LED industry chain.

6. CONCLUSIONS

With rapid development of lighting technology, technological innovation becomes the key period of lighting industry power. In planning guidance, key technology of lighting industry in China will continuously breakthrough and optimize product structure. LED industry has expanded steadily and concentration has gradually increased. The field of application is constantly broadened. The market environment is more standardized. The business model transcends innovation, and the independent brand is bigger and stronger, which lays a solid foundation for China's development from big power of lighting industry to the great power.

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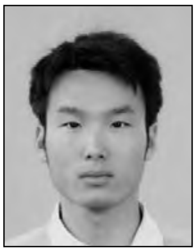

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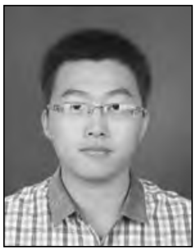

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ADVANTAGES OF LED LIGHTING SYSTEM IN COMPARISON WITH TRADITIONAL FLUORESCENT LAMPS FOR SIMPLE EXAMINATION ROOMS IN HEALTHCARE FACILITIES

Canan Perdahci

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ABSTRACT

This paper presents a detailed comparison between a new type of antibacterial LED panel and fluorescent lamps connected to electronic ballast in a simple examination room, which requires 300 lx in a healthcare facility. Within the study, power consumption (W), luminous flux (lm) and luminous efficacy of both light sources were measured. Luminous flux values were then compared to the amount of power they consumed. Electrical power consumption of these luminaires was also analyzed. To enable an objective comparison between these two types of luminaires ReluxDesktop_2017.1.10.0 simulation program was used. To verify the results obtained by the ReluxDesktop, photometric measurement results of the products were also obtained. The results obtained by the study have shown that the LED panel to be used in the healthcare facility may decrease the maintenance and lighting costs by saving energy while maintaining the illumination levels required by the healthcare facility lighting standards.

Keywords: healthcare facility, lighting, energy efficiency, LED

1. INTRODUCTION

In terms of energy consumption, healthcare facilities can be considered as one of the energy intensive buildings because of the lighting requirements and of being 24/7 living structures. Therefore, they consume a very high amount of electricity, which equals to 11 % of the commercial electricity. When compared to the share of lighting in total energy consumption (16 %), the share of lighting in healthcare facilities reaches up to 44 % [1]. Thus, it is crucial to create a design, which will sustain the required lighting levels for patients and the hospital staff in different parts of the healthcare facilities while decreasing the energy consumption for the lighting requirements of them.

Energy saving is an ever changing and growing concept with the rise of LED lighting systems. It is not difficult to raise the savings up to 70 % in LED lighting systems with intelligent automation systems.

The improvement of LED technology changed a great deal of things in lighting field. Obviously, the most significant change is the energy efficiency that LED lamps can provide. The LED lamp consumes almost half of the energy of a conventional lamp while providing the same illuminance level [2]. This huge energy saving could also save a lot of natural resources and reduce carbon emission severely [3].

Performance and comfort limits in healthcare facilities defined by the relevant standards must be considered before applying a new lighting system. This will definitely enhance patient's comfort as well as staff's performance. The lighting requirements of healthcare facilities, in particular, hospitals are not only effectual to the patients but to the medical and non-medical staff as well when their

Table 1. Light Requirements for Different Hospital Areas According to EN12464–1

Task or activity	E_{av}(lx)	UGRL	U_0	R_a
General lighting	100	19	0.4	80
Simple examinations	300	19	0.6	80
Examination and treatment	1.000	19	0.7	90
Bathrooms and Toilets for Patients	200	22	0.4	80

tasks are taken into consideration. It is important to reduce mistakes and increase their performance via effective usage of lighting [4]. Moreover, the effects of lighting on people can also be both physiological and psychological [5].

The lighting system must be specified according to many properties which are: the illuminance level, the illuminance uniformity, the luminance distribution, the daylight availability, the prevention of glare, the colour rendering and the correlated colour temperature (CCT)[6]. The lighting requirements for each area in hospital have been set by EN12464–1 standard [7].

Hygiene is another important factor in healthcare facilities and the luminaire used in them is no exception. Thus, IP 65 luminaries should be applied to curtail maintenance costs and keep the dust and bacteria away from the luminaires. Coating the luminaire with antibacterial paint prevents bacterial growth [8].

By integrating different automation systems into different lighting applications in various parts of the healthcare facilities, it will be possible to save on energy and money and reach the desired efficiency. This study focuses on the most appropriate lighting type which will be visually and financially viable. Lighting for hospitals and healthcare facilities must be shaped in accordance with the economical, hygienic considerations stated above.

2. PROPERTIES OF HEALTHCARE FACILITY LIGHTING

In order to fulfil medical tasks, optimal illumination levels must be achieved and maintained at all times. High levels of visual comfort and the absence of glare on the eyes of staff is fundamental to the hospital staff while fulfilling their tasks. Doctors need glare-free lighting systems to perform their task, which is important since their tasks are mostly vital [9]. As well as doctors, nurses also need different illuminance for different tasks and areas to perform. [4]

When taken into consideration, it is vital to use lighting sources with colour rendering close to natural light [10]. This paper deals with simple examination room lighting on the examination plane for nursing tasks and simple examinations in a hospital. DIN EN12464–1 and DIN5035–3 recommend illuminance of around 300 lx on the examination plane for nursing tasks and simple examinations. Uniformity is another aspect in lighting, the ratio of maximum to average illuminance should be minimum 1:2. The lighting requirements of the rooms in hospitals can be found in Table 1.

Table 1 illustrates the most important requirements that have to be met by lighting in terms of parameters such as the illuminance uniformity (U_0), the colour rendering index (R_a) of the lamps and the maximum values of discomfort glare (UGR_L), the minimum values of average maintained illuminance (E_{av}).

Hospital infections have affected millions of people so far and it could not be prevented yet. Therefore, hospitals need to be sterilized all the time. In order to maintain sterilization, luminaires should be painted with anti-bacterial dye [8].

There are psychological and mental effects of lights as well as physiological effects. Researches show that a good psychological health helps people to get better faster. Proper lighting level can encourage healing process [5].

3. CASE STUDY AND METHODS

The case study has been conducted in a simple examination room in a hospital in Istanbul, Turkey. In the design, the hospital is considered to deliver high-quality care, sustainable 24 hours a day, seven days a week. The dimensions of the simple examination room are 12 m, height is 3 m and breadth is 6 m. The reflection coefficients are: 0.5 for the walls,

Fig. 1. Room graphic in 3D

0.2 for the floor and 0.7 for the ceiling. The required illumination measurement was taken on a work plane that has 0.75 m height. The required illuminance level for the simple examination room is 300 lx which has been set by relevant standards mentioned before.

The glare index and the colour rendering index will meet the standards to provide the necessary visual comfort for both patients and medical as well as non-medical staff. The lighting scheme is designed with an assumed maintenance factor 0.9.

The lighting simulation results for the study have been obtained by using ReluxDesktop simulation program, which supports the following standards: EN12464–1 (2013), EN1838 (2014), ASR A3.4 (2011), DIN5034 (1999); and photometric measurement results were taken by using NFMS Goniophotometer LabSphere Sphere System in line with the TS EN13032–1:2004+A1:2012 standards [11].

The examination room has been designed with reference to the given dimensions. Length, width, height, walls and ground material, and reflection factors have been defined. The furniture has been placed: there are 5 beds in the examination room. 2 types of luminaires have been selected from catalogue of ALKAN LIGHTING and placed to provide the illuminance has been defined in standards. ALKAN products: ALKAN, 53.AKSA.418.CPM (53AKSA418CPM.LDT) 4xT26 18W/840 and ALKAN – 7150511 LED Panel [12] were placed and simulated by ReluxDesktop, and then tested by NFMS Goniophotometer LabSphere Sphere System respectively (Scenario 1 and Scenario 2). Simulation and test results have been gathered, and they have been compared in terms of energy efficiency and cost effectiveness.

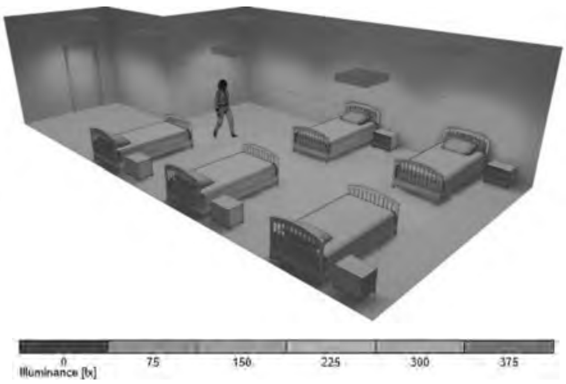


Fig. 2. 3D colour rendering

Table 2. Illuminance Data

Measured Surface	Work Plane Horizontal
E_{av}	330 lx
E_{min}	249 lx
E_{min}/E_{av} (U_o)	1:1.32 (0.76)
E_{max}	372 lx
E_{min}/E_{max} (U_d)	1:1.49 (0.67)
UGR (4H 8H)	<=21.5
Height	0.75 m

3.1. SCENARIO 1

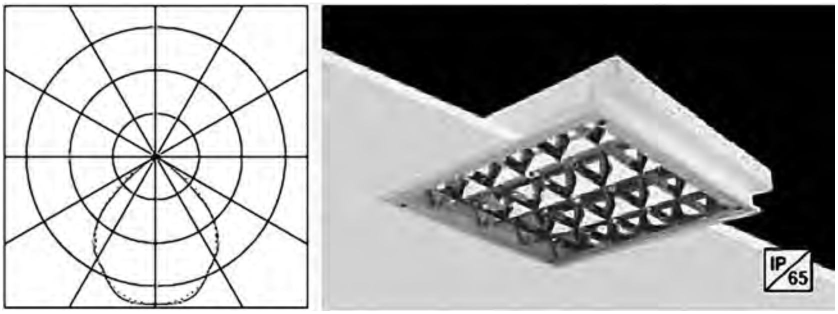
The fluorescent lamps type 53.AKSA.418.CPE produced by Alkan Lighting are used for the illumination of examination room of the hospital.

The lighting distribution values in lx are illustrated in Table 2. The luminous flux of the luminaire is 3507 lm and the total energy consumption of the luminaire is 74 W. The power consumption of electronic ballast is 2 W. The luminous flux of lamps of luminaire is 6400 lm. The energy efficiency can be calculated as: 3507 lm/6400 lm = 0.55

Totally 7 luminaires were used for the study. So, the total luminous flux is the sum of all the fluxes emitted by 7 luminaires and equals to 24549 lm. Also the total power used equals to 518 W.

According to result of ReluxDesktop program, the average illuminance measured at work plane E_{av} = 330 lx, the minimum illuminance measured at work plane E_{min} = 249 lx and the maximum illuminance measured at work plane E_{max} =372 lx.

Results of research are presented in Figs.1–6.



Efficiency of Luminaire	55 %
Efficacy of Luminaire	47 lm/W
Class	A60 100.0 % 0.0 %
CIE Flux Codes	74 99 100 100 55
UGR4H 8H	<10.0 / <10.0
Power:	74 W

Luminous Flux	3507 lm
Size	600 mm × 600 mm × 100 mm
Type	T26 18W/840
Colour	5911
Luminous Flux	3507 lm
Colour Rendering Index	85

Fig. 3. Photometric data

Fig. 1 shows the 3D graphic of the room, Fig. 2 presents 3D colour rendering data, photometric measurement results is in Fig. 3, Fig. 4 presents Value Chart (meter) data, floor plan is shown in Fig. 5, different surfaces reflection is presented in Fig. 6.

3.2. SCENARIO 2

Alkan product ALKAN – 7150511 LED Panel is used for the illumination of patient room of hospital. The lighting distribution values in lx are illustrated in Fig.7. The luminous flux of used luminaire is 4240 lm and total energy consumption of the luminaire is 40 W. The luminaire includes 18×9 LED lamps which make up 162 LED lamps. The driver

Table 3. Data About the lx Levels and Height

Measured Surface	Work Plane Horizontal
E_{av}	355 lx
E_{min}	262 lx
E_{min}/E_{av} (U_o)	1:1.35 (0.74)
E_{max}	414 lx
E_{min}/E_{maks} (U_d)	1: 1.58 (0.63)
UGR (3.4H 6.8H)	<=21.5
Height	0.75 m
Colour Rendering Index	85
CCT	4823

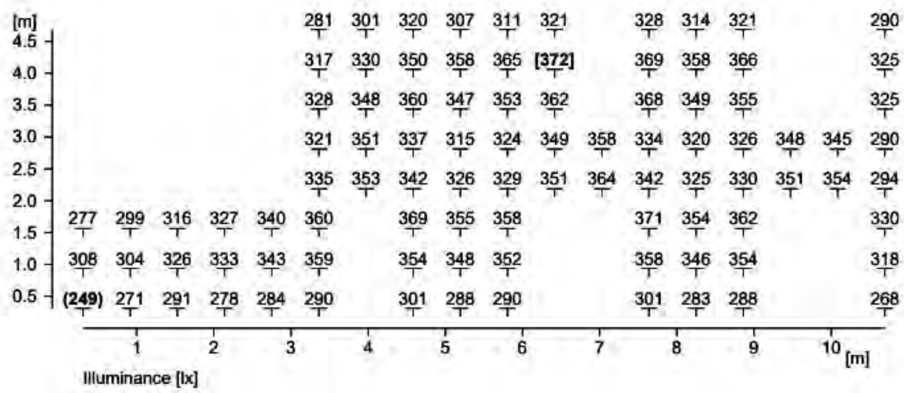


Fig. 4. Value Chart (meter)

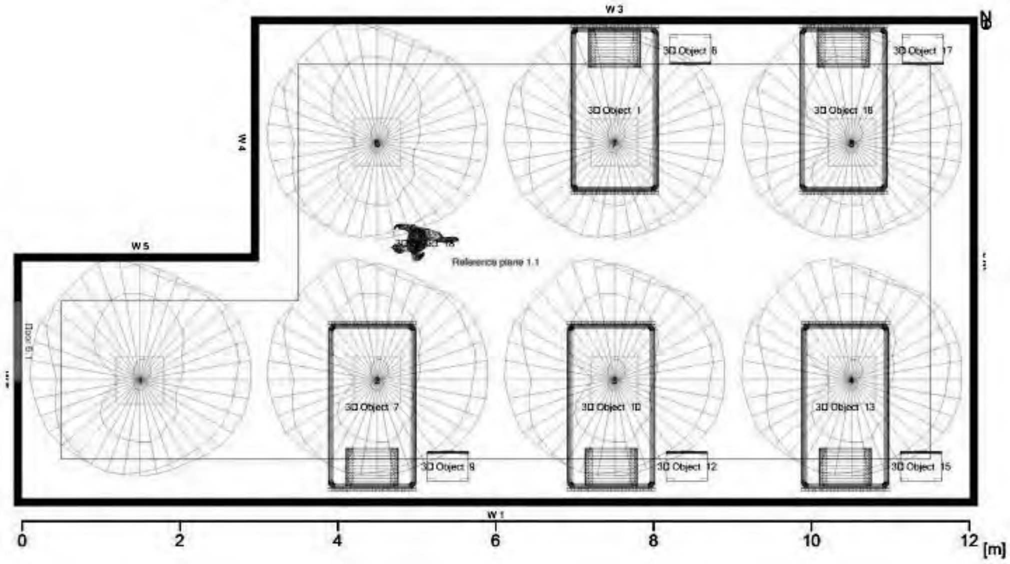


Fig. 5. Floor Plan

Wall	x, m	y, m	Length, m	Reflectance
1	12.00	0.00	12.00	50.0 %
2	12.00	6.00	6.00	50.0 %
3	3.00	6.00	9.00	50.0 %
4	3.00	3.00	3.00	50.0 %
5	0.00	3.00	3.00	50.0 %
6	0.00	0.00	3.00	50.0 %

	Reflectance
Floor	20.0 %
Ceiling	70.0 %
Room height	3.00 m
Height of reference plan	0.75 m

Fig. 6. Reflection of light from different surface

Table 4. Simulation Results Summary

Type	Φ (Lamps)	Φ (Luminaire)	Luminous	Φ Total
	[lm]	[lm]	Efficacy (lm/W)	(7Luminaire) [lm]
FL	6400	3507	47	24549
LED	6222	4240	106	29680

Table 5. Results of Photometric Measurements

Luminaire	E_{av}	E_{min}	E_{max}	U°
FL	330 lx	249 lx	372 lx	0.76
LED	355 lx	262 lx	414 lx	0.74

of the luminaire is 700mA. The power consumption of the driver is 2W and the power consumption of the LED lamps is 38W. The luminous flux of lamps of luminaire is 6222 lm.

The energy efficiency can be calculated as 4240 lm/6222 lm=0.68. Totally 7 luminaires were used for the study. The total luminous flux is the sum of all the fluxes emitted by 7 luminaires and it is equal to 29680 lm. Also the total used power equals to 280 W.

According to the results obtained from Relux-Desktop program, the average illuminance measured at work plane E_{av} = 355 lx, the minimum illuminance measured at work plane E_{min} = 262 lx and the maximum illuminance measured at work plane E_{max} = 414 lx.

Table 6. Luminous Efficasy for FL and LED Luminaires

Type	Power consumed P (W)	Total Power consumed P (W)	Luminaire Efficiency (%)	Total Φ (7 Luminaire) [lm]	Luminous Efficacy (lm/W)
FL	74	518	55	24549	47
LED	40	280	68	29680	106

Table 7. Economic Analysis Cost Comparasion:

	Fluorescent Luminaire	LED Luminaire
Operating Cost		
Luminaire Wattage (W)	74W	40W
Number of Luminaires	7	7
Daily Operating Hours (hrs)	24	24
Kilo-watt-hours per day (kWh)	12,43	6,72
Working Days Per Month	30	30
Total kWh per Month (kWh)	372,9	201,6
Total kWh in 10 years (kWh)	44748	24192
Installation Cost		
Cost of Installation per single luminaire ($)	24	65
Total Installation Cost of System ($)	72	455
Maintenance Cost		
Lamp Lifetime (h)	15.000	50.000
Quantity of the Luminaire in 10 years	6	2
Luminaire cost at the end of 10 years ($)	144	130

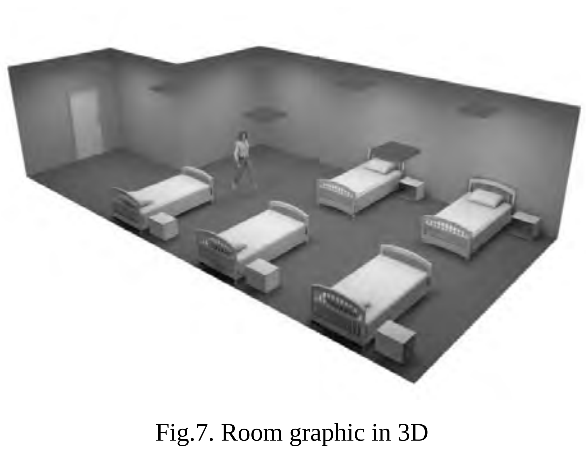


Fig.7. Room graphic in 3D

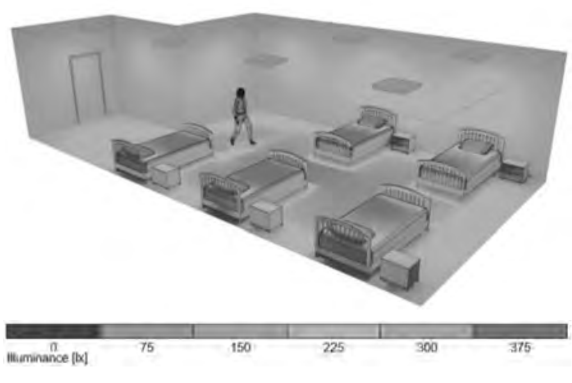
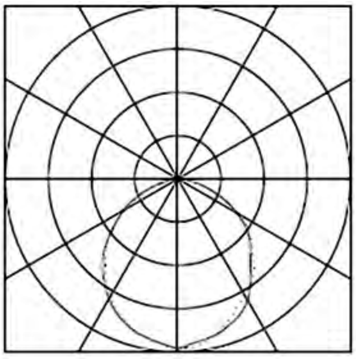


Fig. 8. 3D Rendering

Figs. 7–11 show the results obtained in SCENARIO 2 experiments.

4. RESULTS AND CONCLUSIONS

This study aims to analyze the energy efficiency of two types of luminaires in a healthcare facility by using simulations and making comparisons. The simulations were carried out by using an anti-bacterial LED panel, which was produced by Alkan Lighting Co. as a part of TUBITAK project number 7150511 and a fluorescent lamp connected to electronic ballast. Their power consumption (W), luminous efficacy and luminous flux (lm) were measu-



Luminaire information	
Efficiency of Luminaire	68 %
CIE Flux Codes	51 83 97 100 100
Size	600 mm x 600mm x 70 mm
UGR4H 8H	21.5 / 20.2

Efficacy of Luminaire	106 lm/W
Class	A40 100.0 % 0.0 %
Power	40 W
Luminous Flux	4240 lm

Fig. 9. Photometric data

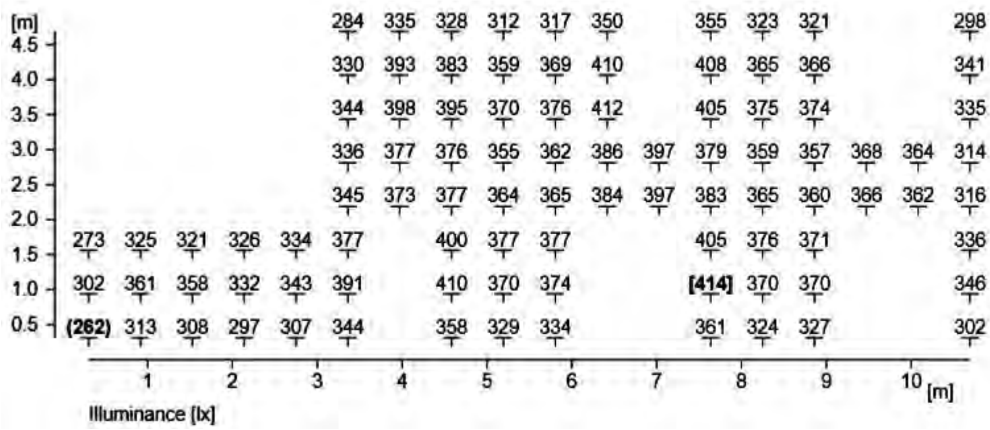


Fig. 10. Value Chart (meter)

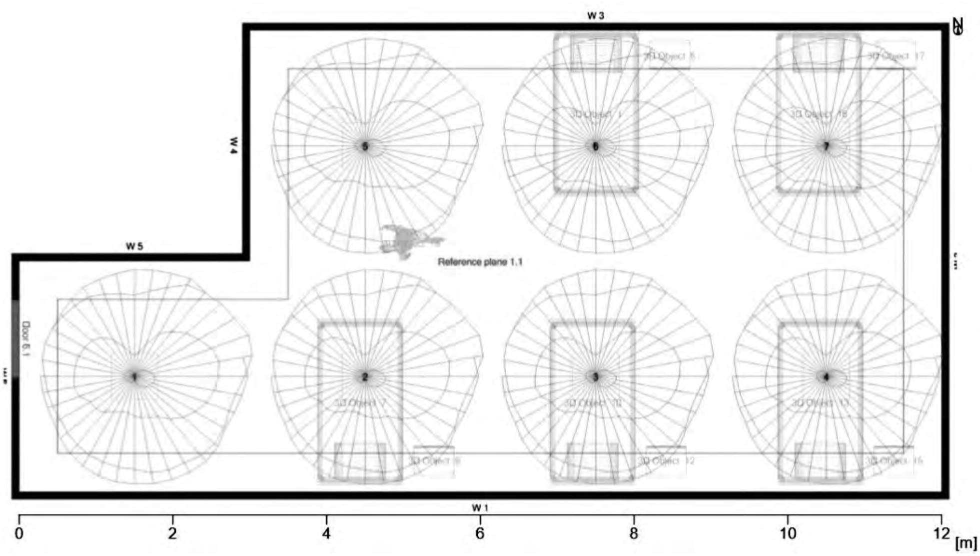


Fig. 11. Floor plan

Wall	x, m	y, m	Length, m	Reflectance, %
1	12.00	0.00	12.00	50.0
2	12.00	6.00	6.00	50.0
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4	3.00	3.00	3.00	50.0
5	0.00	3.00	3.00	50.0
6	0.00	0.00	3.00	50.0

	Reflectance
Floor	20.0 %
Ceiling	70.0 %
Room height	3.00 m
Height of reference plan	0.75 m

Fig. 12. Reflection of light from different surfaces

red. The luminous flux values were then analyzed and compared with the power consumption of these luminaires.

Table 4 shows the results of the simulations of two different lighting systems in summary. The aim of the simulations is to illustrate efficiency of fluorescent lamp and LED. It can be concluded from the Table 2 that fluorescent lamp luminaire (47lm/W) has lower lm/W value when compared with LED luminaire (106 lm/W).

In scenario 1, FLs are utilized and the design consists of 7 luminaires, which give 372 lx levels at maximum. However, in scenario 2, LED luminaires are used in exchange for the fluorescent lamps and consists of 7 luminaires as well. The total amount of maximum level is 414 lx.

In scenario 1, the total luminous flux of the fluorescent luminaire lamps equals to 6400 lm and the luminous flux of the fluorescent luminaire equals to 3507 lm. When the luminous fluxes of the fluorescent luminaires are taken into consideration, it can be concluded that the efficiency of the fluorescent luminaire is 0.55. In scenario 2, the total luminous flux of the LED luminaire lamps equals to 6222 lm and the luminous flux of the LED luminaire equals to 4240 lm. Therefore, the luminous fluxes of the LED luminaires show that the efficiency of the LED luminaire is 0.68. In conclusion, once the luminaire efficiency is conceived, fluorescent lamp luminaires are 13 % less efficient than LED lamp luminaires.

While planning the study, in order to avoid extra expenses and labour, we anticipated to change 7 fluorescent luminaries with the same number of LED luminaires. While doing that, we kept the size of the LED luminaires the same as the fluorescent luminaires so as not to increase cost as a change in size would mean more civil and electrical work to be done, which will mean a rise in the expenses of the healthcare facilities. Thus, the number and the size of the luminaires had to be kept the same during the study.

When all the data collected in this study were examined, they show some striking differences between the commonly used fluorescent luminaires and LED luminaires. First of all, both types of luminaires provide the necessary illumination level (300lx) of a simple examination room. However, LED luminaire is efficient in providing the necessary illumination levels and it is almost two times more effective in this field. Secondly, total power consumption of fluorescent luminaires is nearly twice as much as the power consumption of LED luminaires (518 W/ 280 W). These figures suggest that while using fluorescent luminaires in healthcare facilities, we get almost the same illumination level despite consuming approximately twice much electrical energy compared to LED luminaires used in the study.

The economic performance of the LED luminaires in this study is significantly improved compared to the fluorescent luminaires with electronic ballast due to decreased costs and increased savings.

It can be concluded form Table 8 that lighting parameters UGRL, U_0, and Ra of the LED luminaire has better values then the fluorescent luminaire with electronic ballast.

Lighting up the health care facilities is a substantial duty for the continuity of the services of the facilities as well as for the well-being of the patients there. In order to achieve the required and desired

Table 8. The Values of Qualitative Characteristics

Type	UGR_L	U_0	R_a	CCT
FL	21	0,76	78	6041K
LED	13	0,74	85	5000K

illumination levels in these facilities, anti-bacterial LED luminaires is definitely a better option when compared to its older counterpart, fluorescent lamps in terms of being cost effective, supplying the required illumination level and being anti-bacterial, which will get rid of the unwanted side effects of the heat which causes the germs and microbes proliferate.

In conclusion, changing the fluorescent luminaires with the LED ones would mean not only saving up energy, which will also mean a decrease in energy expenditures, but also mean achieving the required illumination levels while keeping the sanitation high.

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