IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

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To cite this article: P S Romanov and I P Romanova 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **224** 012029

The Selecting of Environmentally Friendly Lighting System for Electrical Equipment Repair Shops

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Abstract. Today one of the Federal programs implemented in Russia at the state level, is a program of energy conservation and energy efficiency to reduce the specific consumption of fuel and energy resources. Electricity for lighting accounts for 15% global power consumption and about of 13% power consumption in Russia. The article deals with the approach to lighting systems design on the basis of energy-saving technologies. Switching to energy-efficient lighting is one of the fastest ways to decrease cost of lighting. The paper proposes a new approach to evaluate ecological safety and economic efficiency of three most popular options of the lighting systems. In order to confirm the advantages of this approach to energy savings in industrial premises were undertaken the calculations. The article presents the results of the selection of the most appropriate environmentally friendly lighting system for electrical equipment repair shops using the analytic hierarchy process.

1. Introduction

On 23 November 2009 in Russian Federation was adopted the Federal law on energy conservation and energy efficiency (261-FZ), which aims to reduce the intensity of electricity, heat, water and gas consumption in order to help Russia approach European consumption levels by 2020 [1]. Major objectives include widespread introduction of energy efficiency measures and technologies, that will allow to increase the competitiveness of the Russian economy. Nowadays electricity for lighting accounts for 15% global power consumption and about of 13% power consumption in Russia. The main lighting sectors are residential, commercial and industrial buildings and outdoor. To ensure the increasing electricity demand a huge amount of coal, oil, gas is burned, which, firstly, leads global environmental pollution, and secondly, the necessity of new coal and oil fields development. In order to solve environmental problems in the production of electricity, it is proposed to apply relatively environmentally friendly sources of electricity: nuclear, solar, wind, tidal, geothermal power plants, but these measures are not enough. Another possibility to solve this problem is the development and application of energy saving technologies. Another important aspect of environmental protection is the reduction of pollution related to the used lighting systems recycling. That's why the organization of rational lighting of industrial premises and workplaces, in particular electrical equipment repair shops, requires a lot of attention. Properly designed and executed industrial lighting increases productivity and improves product quality, helps to reduce visual fatigue and improves the functional state of the organism, increases safety and reduces injuries [1].

Industrial premises are usually equipped with general and local artificial light, which should ensure an adequate level of illumination and even distribution of light in the workplace, protect the eyes from the glare of the light sources and too high brightness. The three main categories of electric lights are incandescent lamps, gas-discharge lamps and light-emitting diodes lamps (LEDs) [2].

Incandescent lamps are sources of light-thermal radiation, in which a filament is heated to a temperature at which a fraction of the radiation falls in the visible spectrum. They are the most common because of its light quality (the optimal emission spectrum, which provides eye comfort, lighting without flickering, absence of a warmup period), usability, strength and safety (they are made of safe materials and can be thrown out with ordinary garbage, making it easier to dispose of used ones), but they have some disadvantages: low luminous efficacy of about 7 lumens/watt (this means that approximately 95% of energy is converted to heat and only 5% is left to light) and small lifetime (about 2000 hours) [3].

Gas-discharge lamps generate light by sending an electrical discharge through an ionized gas (noble gas or metal vapor). There are three basic categories of lamps that operate under this principle: high pressure discharge lamps, low pressure discharge lamps and high-intensity discharge lamps [4].

High pressure discharge lamps have gas with higher than the atmospheric pressure inside the tube (the metal halide lamps, the high pressure sodium lamps and the high pressure mercury-vapor lamps). They are used to illuminate large industrial premises, streets and open spaces.

Low pressure discharge lamps have gas with lower than the atmospheric pressure inside the tube (fluorescent lamps, neon lamps). They are used to illuminate small enclosed spaces.

High-intensity discharge lamps produce light by means of an electric arc between the tungsten electrodes (metal halide lamps, the sodium vapor lamps, the mercury-vapor lamps, the ceramic discharge metal halide lamps, the xenon arc lamps and the ultra-high performance (UHP) lamps) [5,6].

The most common are fluorescent lamps having the shape of a cylindrical pipe. The inner surface of its phosphor, which converts ultraviolet radiation into visible light. Depending on the distribution of the spectral components of the light bulbs are daylight (DV), fluorescent light with improved light output (LDTS), cold white (LIB) [7].

One of the options of gas-discharge lamps is a compact fluorescent lamp (CFL), which is designed to replace an incandescent light bulb. CFLs are simply miniature versions of full-sized fluorescents. They screw into standard lamp sockets, and give off light that looks similar to the common incandescent bulbs. Compared to general-service incandescent lamps giving the same amount of visible light, CFLs use one-fifth to one-third the electric power, and last eight to fifteen times longer [8].

The main advantages of the gas-discharge lamps are the high luminous efficacy (100 lumens/watt), long lifetime (up to 12.000 hours) and a wide range of colors. But they are more complicated to manufacture and require auxiliary electronic equipment such as ballasts to control current flow through the gas. In addition, the lamps contain mercury vapor in an amount of 2.3 mg to 1 g and therefore they require complex utilization (it is necessary to carry out demercurization), disregard of disposal rules leads to environmental pollution. Some gas-discharge lamps also have a perceivable start-up time to achieve their full light output (about 15 minutes). Another disadvantage of gas-discharge lamps is stroboscopic effect or intermittent light – flickers (flicker is the constant fluctuation of light output from on to off). Flickers make it difficult to work with the moving and rotating objects [9].

LEDs produce light when voltage is applied to negatively charged semiconductors, causing electrons to combine and create a unit of light (photon). The emitted light may be in the infrared, visible, or near-ultraviolet region of the spectrum, depending on the composition and condition of the semiconducting material used. A mix of red, green, and blue LEDs is typically used to make white light [10]. LEDs emit light in a specific direction, reducing the need for reflectors and diffusers that can trap light. This feature makes LEDs more efficient for many uses such as recessed downlights and task lighting. With other types of lighting, the light must be reflected to the desired direction and more than half of the light may never leave the fixture. Furthermore LEDs emit very little heat. In comparison, incandescent bulbs release 90% of their energy as heat and CFLs release about 80% of their energy as heat [11].

Thus, the main advantages of LEDs are:

high energy efficiency (the typical LED requires only 30-60 milliwatts to operate, LED light source with the same lighting intensity consumes up to ten times less energy than an incandescent lamp, the luminous flux directivity allows to improve the lighting fixture efficiency up to 100%);

durable, shockproof and corrosion-resistant unlike glass bulb lamp types;

long lifetime (about 100 000 hours);

absence of mercury in the lighting fixture elements makes disposal simple and environmentally safe;

the lighting fixture instant switching and attainment of projected power;

high lighting intensity values;

closeness of the lighting to the natural light;

lower dazzling effect;

luminous intensity without changes in any supply voltage range;

high color rendering index, providing better visibility and contrast;

absence of stroboscopic effect (flicker) make the lighting fixtures irreplaceable in industry.

recycling of lamps is simple

The main disadvantage of LEDs is sensitivity to great variations in summer/winter temperatures [12].

Lighting of industrial premises can be natural, artificial and combined. The main purpose of lighting in industrial premises is to create the best conditions for the object overview. This problem can be solved by using the lighting system meeting the following requirements [13]:

1. the illumination should match the visual work, which is defined by the following parameters: the smallest object to be discern, its individual parts and defects; brightness difference between the object and its surrounding background; glare of the object.

2. the amount of light must be constant in time.

3. the directivity of a light flux and spectral composition of light should be optimal.

4. all the elements of lighting installations must be durable, electro, explosion and fireproof.

2. Experimental section

In order to choose the optimal lighting system for electrical equipment repair shops, it is necessary to evaluate ecological safety and economic efficiency of three most popular options of the lighting systems:

1 – conventional, on the basis of incandescent lamps for both general and local lighting;

2 – on the basis of energy-efficient CFL bulbs lighting for general lighting and incandescent lamps for local lighting (energy-efficient CFL bulbs can't be applied for local lighting because of the luminous flux oscillations);

3 – on the basis of LED panels for general lighting and LED lamps for local lighting with the installation of rectifier device to a group of LED panels in 220 V alternating current electrical shield instead of LED driver in each lamp.

Subject of calculations and initial data: room dimensions: h = 2.1 m - maximum spacing to mounting height of the lamp above the working surface, a =12 m - the length of the room, b =6.1 m – the width of the room; background wall and ceiling are light. Table 1 presents the quantitative characteristics of the considered lighting systems [9-13]. The cost of the lighting system includes the costs of: lamps, luminaires, wires, rectifier device and disposal costs for compact fluorescent lamps.

Table 1. Quantitative characteristics of the lighting systems.

Quantitative characteristics	Option 1	Option 2	Option 3
Cost, RUB	7900	11800	22700
Lifetime, h	2000	12000	100000
Energy efficiency, lm / W	7	30	60
Percent Flicker, %	10-15	35-55	3-5
Colour rendering index (CRI)	95-100	80-90	70-80

All of these lighting systems have their advantages and disadvantages, so the task of choosing the optimal option is complex and requires special methods to eliminate the subjectivity of evaluation. One of such methods is the analytic hierarchy process, which allows to solve the problem of choice on set of qualitative and quantitative characteristics [14-17].

The decision problem is decomposed into a hierarchy of more easily comprehended sub-problems, each of which can be analyzed independently. The method is based on constructing a hierarchy starting from the top (goal), through intermediate levels (a group of factors or criteria that relate the alternatives to the goal) to the very bottom level (the list of alternatives for reaching the goal). Each element of the system, except for the top one, is subordinate to one or more other elements. The criteria can be further broken down into subcriteria, sub-subcriteria, and so on, in as many levels as the problem requires.

Then the hierarchy is analyzed through a series of pairwise comparisons: the criteria are pairwise compared against the goal for importance, the alternatives are pairwise compared against each of the criteria for preference. The comparisons are processed mathematically: at each level the set of matrix of pairwise comparisons is built (table 2) [18].

Table 2. Matrix of pairwise comparisons.

	A_1	A_2	A_3	…	A_n
A_1	w_1/w_1	w_1/w_2	w_1/w_3	…	w_1/w_n
A_2	w_2/w_1	w_2/w_2	w_2/w_3	…	w_2/w_n
A_3	w_3/w_1	w_3/w_2	w_3/w_3	…	w_3/w_n
…	…	…	…	…	…
A_n	w_n/w_1	w_n/w_2	w_n/w_3	…	w_n/w_n

$A_1, A_2, \ldots, A_n$ is the set of n elements and $w_1, w_2, \ldots, w_n$ respectively, their weight, or intensity. Weight, or intensity, of each element is compared with the weight or intensity of any other element of the set in relation to the common property or the goal (i.e. w_1/w_1 means comparison, not dividing the weights of these elements).

The comparison of weights can be represented as follows: the elements of any level are compared with each other regarding their effects on guided element on 9-point scale (from 1 – equal importance to 9 – very strong superiority).

If the element A_1 is dominant over the element A_2, the cell corresponding to the row A_1 and column A_2 is filled with an integer, and the cell corresponding to the row A_2 and column A_1 is filled with the integer reciprocal (fraction).

Then at each level the synthesis of priorities is made, i.e. for each row the geometric mean is calculated. The vector of priorities is obtained by dividing each geometric mean by the sum of all geometric means (table 3) [19].

Table 3. Calculating of the vector of priorities.

	A_1	…	A_n	The rating of the eigenvector components by row	Vector of priorities
A_1	w_1/w_1	…	w_1/w_n	$\sqrt[n]{\frac{w_1}{w_1}\times\ldots\times\frac{w_1}{w_n}}=a_1$	$\frac{a_1}{\sum_{i=1}^{n}a_i}=x_1$
…	…	…	…	…	…
A_n	w_n/w_1	…	w_n/w_n	$\sqrt[n]{\frac{w_n}{w_1}\times\ldots\times\frac{w_n}{w_n}}=a_n$	$\frac{a_n}{\sum_{i=1}^{n}a_i}=x_n$

Multiplication of the matrix by the vector of priorities is as follows:

$$\begin{pmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \ldots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \ldots & \frac{w_2}{w_n} \\ \ldots & \ldots & \ldots & \ldots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \ldots & \frac{w_n}{w_n} \end{pmatrix} * \begin{pmatrix} x_1 \\ x_2 \\ \ldots \\ x_n \end{pmatrix} = \begin{matrix} \frac{w_1}{w_1}x_1+\frac{w_1}{w_2}x_2\ldots+\frac{w_1}{w_n}x_n=Y_1 \\ \frac{w_2}{w_1}x_1+\frac{w_2}{w_2}x_2\ldots+\frac{w_2}{w_n}x_n=Y_2 \\ \ldots \\ \frac{w_n}{w_1}x_1+\frac{w_n}{w_2}x_2+\ldots+\frac{w_n}{w_n}x_n=Y_n \end{matrix} \quad (1)$$

It is important to note that in the matrix of pairwise comparisons there is no ratio w_i/w_j, there are only integers or integer reciprocals from a scale. This matrix in the general case is inconsistent. Algebraically the problem of consistency is the solution of the equation $Aw=nw$, $A=(w_i/w_j)$, and the total task is the solution of the equation $A'w'=\lambda_{max}\cdot w'$, $A'=(a_{ij})$, where λ_{max} is the largest eigenvalue of the matrix of pairwise comparisons A.

To check the consistency of each matrix the eigenvalues of the matrix are calculated (as the sum of the vector components obtained by multiplying the matrix of pairwise comparisons by the vector of priorities):

$$\lambda_{max}=\sum_{i=1}^{n}Y_i \quad (2)$$

Next, the index of consistency (IC) and consistency ratio (CR) are calculated:

$$IC = (\lambda_{max} - n)/(n - 1), \quad (3)$$

where λ_{max} – eigenvalue of the matrix, n – the number of compared elements.

$$CR=IC/RI, \quad (4)$$

where RI – random index.

CR and IC should not exceed 10%. Otherwise, the quality of the judgments should be improved, perhaps by revising the way in which questions are asked when conducting pairwise comparisons.

When conducting assessments it is important to keep in mind all compare items to comparison was relevant. To conduct a reasonable numerical comparisons should not compare more than 7±2 elements.

Then hierarchical synthesis is conducted, i.e. the sum of all the weighted components of the corresponding eigenvectors of the hierarchy level lying before is calculated [20].

3. Results section

The described method was used for selecting of the most appropriate environmentally friendly lighting system for electrical equipment repair shops. Calculations are made for three lighting systems and eight characteristics.

The criteria pairwise comparisons, the vector of priorities and the result of their multiplication Y_i are presented in table 4.

Criteria:

C_1 - energy efficiency, lm / W;
C_2 - ecological safety;
C_3 - lifetime, h;
C_4 - cost, RUB;
C_5 - percent Flicker, %;
C_6 - colour rendering index (CRI);
C_7 - mass-dimensions
C_8 - lamp's strengths.

The eigenvalue of the matrix, IC and CR were calculated by the equations (2), (3) and (4), CR and IC are not exceed 10%.

Table 4. Calculating of the criterion vector of priorities.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	The rating of the eigenvector components by row	Criterion vector of priorities	Y_i
C_1	1	2	3	4	5	7	8	9	3.960	0.330	2.785
C_2	1/2	1	2	3	4	6	7	8	2.823	0.235	1.949
C_3	1/3	1/2	1	2	3	5	6	7	1.951	0.163	1.342
C_4	1/4	1/3	1/2	1	2	4	5	6	1.334	0.111	0.921
C_5	1/5	1/4	1/3	1/2	1	2	4	5	0.872	0.073	0.600
C_6	1/7	1/6	1/5	1/4	1/2	1	2	3	0.494	0.041	0.339
C_7	1/8	1/7	1/6	1/5	1/4	1/2	1	2	0.332	0.028	0.231
C_8	1/9	1/8	1/7	1/6	1/5	1/3	1/2	1	0.240	0.020	0.170
									λ_{max} = 8.337	IC = 0.048	CR = 0.034

The alternatives pairwise comparisons, the vectors of priorities, the results of their multiplication Y_i, λ_{max}, CR and IC for each alternative are presented in table 5.

Alternatives are three options of the lighting systems for electrical equipment repair shops:

A_1 – Option 1;
A_2 – Option 2;
A_3 – Option 3.

The eigenvalue of the each matrix, IC and CR were calculated by the equations (2), (3) and (4), CR and IC are not exceed 10%.

Table 5. Calculating of the alternatives vectors of priorities

C_1	A_1	A_2	A_3	The rating of the eigenvector components by row	Alternative vector of priorities	Y_i	λ_{max}, CR, IC
A_1	1	1/4	1/9	0.303	0.063	0.194	λ_{max} = 3.071
A_2	4	1	1/5	0.928	0.194	0.595	IC = 0.036
A_3	9	5	1	3.557	0.743	2.282	CR = 0.061
C_2	A_1	A_2	A_3				
A_1	1	5	1/3	1.186	0.265	0.804	λ_{max} = 3.029
A_2	1/5	1	1/9	0.281	0.063	0.191	IC = 0.015
A_3	3	9	1	3.000	0.672	2.034	CR = 0.025
C_3	A_1	A_2	A_3				
A_1	1	1/3	1/9	0.333	0.068	0.207	λ_{max} = 3.054
A_2	3	1	1/6	0.794	0.162	0.494	IC = 0.027
A_3	9	6	1	3.780	0.770	2.352	CR = 0.046
C_4	A_1	A_2	A_3				
A_1	1	3	9	3.000	0.672	2.034	λ_{max} = 3.029
A_2	1/3	1	5	1.186	0.265	0.804	IC = 0.015
A_3	1/9	1/5	1	0.281	0.063	0.191	CR = 0.025
C_5	A_1	A_2	A_3				
A_1	1	6	1/3	1.260	0.278	0.850	λ_{max} = 3.054
A_2	1/6	1	1/9	0.265	0.058	0.179	IC = 0.027
A_3	3	9	1	3.000	0.663	2.025	CR = 0.046
C_6	A_1	A_2	A_3				
A_1	1	5	9	3.557	0.743	2.282	λ_{max} = 3.071
A_2	1/5	1	4	0.928	0.194	0.595	IC = 0.036
A_3	1/9	1/4	1	0.303	0.063	0.194	CR = 0.061
C_7	A_1	A_2	A_3				
A_1	1	4	1/5	0.928	0.194	0.595	λ_{max} = 3.071
A_2	1/4	1	1/9	0.303	0.063	0.194	IC = 0.036
A_3	5	9	1	3.557	0.743	2.282	CR = 0.061
C_8	A_1	A_2	A_3				
A_1	1	4	1/5	0.928	0.194	0.595	λ_{max} = 3.071
A_2	1/4	1	1/9	0.303	0.063	0.194	IC = 0.036
A_3	5	9	1	3.557	0.743	2.282	CR = 0.061

The result of conducted hierarchical synthesis is presented in table 6.

Table 6. The results of the selecting of the most appropriate building thermal insulation material for residential buildings

Options of the lighting systems for electrical equipment repair shops	Global priorities
on the basis of incandescent lamps for both general and local lighting	0.229
on the basis of energy-efficient CFL bulbs lighting for general lighting and incandescent lamps for local lighting	0.150
on the basis of LED panels for general lighting and LED lamps for local lighting	0.621

4. Discussion section

Thus, the best option by the set of characteristics despite the high cost may be to consider on the basis of LED panels for both general and local lighting. The least successful of the above options can be considered the option on the basis of energy-efficient CFL bulbs lighting for general lighting and incandescent lamps for local lighting. Low cost and high energy efficiency do not compensate such drawbacks as flickers, complexity of utilization, low ecological safety. Incandescent lamps are more appropriate because of its light quality and safety, but their main disadvantage - low luminous efficacy – makes them unpromising for future use.

5. Conclusions

Thus, during the construction of a new or modernization and expansion of the old electrical equipment repair shops it is necessary to consider the trend of the transition to LED lighting. LED lighting should be both general and local. The proposed technique can be applied for selection of the most appropriate technological equipment from the available options based on its qualitative and quantitative characteristics.

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