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THE PROBLEMS OF THE LIGHT FIELD IN OPTIMIZATION OF THE COST OF AN ELECTRIC LIGHTING SYSTEM

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***Abstract**: The paper presents the problems of the light field analysis applied to optimization of total expenses of electric lighting systems. The light field is described by means of the Fredholm integral equations. For purposes of the cost optimization a modified genetic algorithm is used. The objective function of economic character is formulated, the constraint groups and the method of their application are shown. The example calculation results related to the interior lighting systems are presented.*

Key words: Light field, cost optimization, genetic algorithm

1. INTRODUCTION

A man is surrounded by various forms of electromagnetic radiation, sourced from mobile phones, microwave ovens, wireless networks, and light sources. In case of the last among the above mentioned examples the electromagnetic field is a visible radiation (the wavelength from 380 to 780nm), being its one of the most frequently met forms.

Many scientists and many organizations perform intensive research on the effect of the electromagnetic radiation on human health and life, inclusive of the safety and reliability of technical equipment. Many standards and recommendations have been formulated in order to state allowable levels of basic EMF parameters. They define the type and the research methods and tests related to the devices admitted for sale.

What concerns the visible radiation, its appropriate parameters in the work stands where people use their visual abilities, increase general level of safety and effectiveness. This improves visual efficiency and, in consequence, gives better comfort. Importance of the radiation in this range is evidenced by many standards of European meaning that concern the parameters and methods required for various types of such objects.
Prolongation of human activity (inclusive of professional occupancy) to evening and night hours imposed the need of using artificial light sources. The electric power is changed into the radiation energy of visible range based on various transformation processes. Common use of artificial light sources was conducive to large electric power consumption for the lighting purposes. In highly developed countries this part of power consumption reaches up to 20 percent of its entire production. In consequence, people are for a long time subject to this type of the field. The first among the aspects results in emission of harmful substances to the environment (in conventional power plants). Therefore, the need arises to search the lighting systems of possibly low power consumption, that should meet the normative requirements. Additionally, it should be noticed that the cost of the electric power is a chief component of the entire expense. Thus, a system of minimal entire cost born for these purposes should be found [9].

In order to minimize the whole cost of a lighting system an effective optimization method should be chosen, in connection with accurate and quick method of light field analysis, to be carried out at each stage of the optimization process [1,2,5] . This leads to the need of elaboration of effective optimization procedures and light field analysis modules.

2. CHARACTERISTICS OF THE LIGHT FIELD

In the Ω domain L sources of electromagnetic radiation in the visible range may be defined as a light field. The paper assumes that all the field sources are of artificial type. Each of them occupies the ψ_i area (i=1,2,…,L). Hence, for L sources it may be stated that the area subject to the light field analysis, beside interiors of the sources, amounts to Ω-ψ,where $\psi=\sum_{i=1}^{N}\psi_i$. The field defined this way is a vectorial field the basic values of which are intensities of the electric and magnetic fields [4]. Their use for purposes of analysis of the lighting systems is uncomfortable, as usually the distribution of basic photometric values is sought (i.e. illumination E, luminance L, luminous flux Φ, etc). Therefore, the notion of the radiation vector is formulated, that is used in the analysis of distribution of the radiation energy in space [4].

Usually in the area of the light field interaction some material bodies occur that reflect, absorb, and/or transmit the visual radiation. For purposes of the light field analysis used in optimization of the lighting systems and control of basic normative parameters a simplified assumption is made, i.e. only light reflection is taken into account, with the ρ coefficient of reflection of dissipated (Lambertian) character.

In many cases, particularly of internal systems, the phenomenon of multiple reflections must be considered. The radiation sources emit a luminous flux incident directly on various surfaces existing in the Ω domain. Such a flow is considered as a direct one and denoted by Φ'. The phenomenon of reflection of the visible radiation from surfaces of the materials having the reflection coefficient ρ>0 is conducive to occurrence of some indirect photometric values. These values are denoted by Φ''. In result of multiple reflections of the luminous flux between the parts of the *S* surface, the total luminous flux Φ incident on this surface equals to the sum of the direct Φ' and indirect Φ'' components [7]:

$$\Phi = \Phi' + \Phi'' \tag{1}$$

One of possible descriptions of the light field consists in the use of differential notation. In such a case divergence and rotation of the radiation vector (div**E** and rot**E**) are defined inside the Ω domain. Their values allow for defining four classes of the fields [4]. In most cases distribution of the **E** vector in the Ω domain is sought beyond the excitation domains (the sources), provided that the geometric and outer characteristics of their radiation is known. Many modern excitations include the sources of non-uniform characteristics, giving rise to a solenoidal and vorticity field.

As the rotation is not equal to zero (*rot* **E**≠0) the scalar potential must not be used. Nevertheless, the notion of vectorial potential **A** may be introduced instead, that is defined by:

$$rot\,\mathbf{A} = \mathbf{E} \tag{2}$$

The definition (2) and the assumption that *rot* **E=–K(x)**≠0 enable formulating the vectorial Poisson equation for the 3rd class light field:

$$\nabla^2\mathbf{A} = -\mathbf{K}(\mathbf{x}) \tag{3}$$

where: **K**(**x**) – a known vectorial function.

In order to solve the equation (3) in the Cartesian coordinate system the following three scalar equations should be solved:

$$\nabla^2\mathbf{A}_x = -\mathbf{K}_x,\quad \nabla^2\mathbf{A}_y = -\mathbf{K}_y,\quad \nabla^2\mathbf{A}_z = -\mathbf{K}_z \tag{4}$$

Based on the solution of (4) and the relationship (2) the distribution of the **E** vector in the Ω domain may be found.

For a certain group of the 3rd class fields the use of vectorial potential **A** may be replaced with a scalar value, i.e. a so-called quasi-potential ϕ_Q. The necessary and sufficient condition for existence of the quasi-potential of the light field consists in satisfying the equation [4]:

$$\mathbf{E}\cdot rot\,\mathbf{E} = 0 \tag{5}$$

In such a case the quasi-potential may be described by the relationship:

$$\mathbf{E} = -\frac{1}{\xi(\mathbf{x})}\,grad\,\phi_Q \tag{6}$$

where: $\xi(\mathbf{x})$ – is a known coefficient of integration.

Determination of divergence of the **E** vector defined by (6) enables formulating the Poisson and Laplace equations for the light field [4]. In consequence, existence and use of quasi-potential reduce the size of the computation job and simplify the analysis.

One of basic tasks of the light field analysis consists in searching the distribution of photometric values at some selected surfaces of the considered system. Very often analysis of the entire Ω domain is not required. In case of differential description provided by the relationships (2) to (6) the numerical analysis of the light field is conducive to discretization of the whole Ω domain that results in remarkable size of the computation job. Therefore, an integral formulation may be used, similarly like in other electrotechnical problems. This is characterized by such features as combination of the equations and boundary conditions, easy account of the phenomenon of multiple reflections of the luminous flux, and reduction of the size of the computation job by one rank as compared to differential formulation. Additionally, the integral formulation better approximates the considered physical phenomena.

In order to describe the light field the 2nd kind Fredholm integral equations may be used. They may be formulated for the radiation vector **E** or for the scalar value Φ of the luminous flux. In case of the radiation vector the integral equation takes a general form:

$$\mathbf{E}(r) = \mathbf{E}'(r) + \int_S \rho(r')f(r,r')w(r,r')\mathbf{E}(r')dS \tag{7}$$

where: r – the computation point; r' – the reference point; **E** – (total) radiation vector; **E'** – direct component of the radiation vector; S – the surface surrounding the Ω domain; ρ – the reflection coefficient from the S surface; w – the visibility coefficient (w ∈ {0,1}); f – the coupling (configuration) coefficient.

The coupling coefficient f_{AB} between the S_A and S_B surfaces characterizes geometry of the system and is defined by the formula:

$$f_{AB} = \frac{1}{\pi S_A}\int_{S_B}\int_{S_A}\frac{\cos\beta_A\cdot\cos\beta_B}{R^2}\cdot dS_A\cdot dS_B \tag{8}$$

where: R – the distance between the middles of the elementary surfaces dS_A and dS_B β_B – the angle between the line connecting the middles of the dS_A and dS_B elements and the direction $\mathbf{n_B}$ normal to the dS_B surface; β_A – the angle between the line connecting the middles of the dS_A and dS_B elements and the direction $\mathbf{n_A}$ normal to the dS_A surface; S_A – area of the S_A surface.

In case of the luminous flux the Fredholm equation may be written down as:

$$\Phi(r) = \Phi'(r) + \int_S \rho(r') \cdot f(r,r') \cdot w(r,r') \cdot \Phi(r') \cdot dS \qquad (9)$$

The integral equations and systems of equations often have no analytical solutions. Therefore, they are usually solved with approximate methods. For a certain group of the tasks related to electrotechnical problems (e.g. analysis of electric field distribution, current density in conductors, radiation heat exchange, etc) numerical methods are applied. The most popular of them is the method of moments [6,10].

For analysis of the light field aimed at minimizing total costs of electric lighting systems of interiors the integral equation (9) is used that describes the distribution of the luminous flux. Its solution enables finding the basic lighting parameters and their compatibility with binding requirements and standards.

In order to solve the equation of the form (9) the projection method was applied in which the boundary surface of the considered object was divided into N elementary surfaces ΔS_n for $n=1,2,...,N$. Assuming that the sought value is constant at the ΔS_n element, the equation (9) for m-th surface element takes a form:

$$\Phi_m + \sum_{n=1}^{N} \Phi_n \int_{\Delta S} \rho_n \cdot f_{mn} \cdot w_{mn} \cdot dS = \Phi' \qquad (10)$$

The equation (10) is met for all the N points representing the middles of the elementary surfaces. Hence, for m=1,2,…,N a system of linear algebraic equations may be formulated, the unknowns of which are total luminous fluxes at the ΔS_n elementary surfaces:

$$\begin{bmatrix} 1 & -\rho_2 f_{21} w_{21} & \dots & -\rho_N f_{N1} w_{N1} \\ -\rho_1 f_{12} w_{12} & 1 & \dots & -\rho_N f_{N2} w_{N2} \\ \dots & \dots & \dots & \dots \\ -\rho_1 f_{1N} w_{1N} & -\rho_2 f_{2N} w_{2N} & \dots & 1 \end{bmatrix} \begin{bmatrix} \Phi_1 \\ \Phi_2 \\ \dots \\ \Phi_N \end{bmatrix} = \begin{bmatrix} \Phi'_1 \\ \Phi'_2 \\ \dots \\ \Phi'_N \end{bmatrix} \qquad (11)$$

where Φ'_m – direct luminous flux incident on the m-th element, Φ_m – total luminous flux incident on the m-th element, ρ_m - coefficient of reflection of the m-th surface element, f_{mn} –coupling coefficient of the m-th and n-th dS surface elements.

Taking into account ill-conditioning of the system of linear equations (11) an additional equation is introduced that requires equal values of the sum of direct fluxes Φ at all the elementary surfaces and the sum of all the real luminous fluxes $\Phi_{\dot{z}rp}$ of all L sources belonging to the considered object. The above described model allows computation of the systems with the use of concave surface elements. Detailed information related to required transformations of the system (11) may be found in previous works of the authors, e.g. [5,6]. Taking into account both above mentioned conditions the matrix **A** of coefficients of the system (11) takes a new form […]:

$$A = \begin{bmatrix} 1+\rho_1 \frac{S_{10}}{S_1} f_{1N} w_{1N} & \frac{S_{20}}{S_2}(\rho_2 f_{21} w_{21} - \rho_2 f_{2N} w_{2N}) & .. & -\rho_N \frac{S_{N0}}{S_N} f_{N1} w_{N1} - 1 \\ \frac{S_{10}}{S_1}(\rho_1 f_{12} w_{12} - \rho_1 f_{1N} w_{1N}) & 1+\rho_2 \frac{S_{20}}{S_2} f_{2N} w_{2N} & .. & -\rho_N \frac{S_{N0}}{S_N} f_{N2} w_{N2} - 1 \\ \dots & \dots & .. & \dots \\ 1-\rho_1 \frac{S_{10}}{S_1} & 1-\rho_2 \frac{S_{20}}{S_2} & .. & 1-\rho_N \frac{S_{N0}}{S_N} \end{bmatrix} \qquad (12)$$

where: S_{n0} – closing surface area (the surface closing the n-th concave element), S_n – total surface area of the n-th concave element.

Solution of the (11) system completed by the new form of the matrix **A** of coefficients enables determining the distribution of total luminous flux at the considered elementary surfaces. This provides a basis for determining the photometric parameters making a file of normative constraints in the total cost minimization process of the systems of electric lighting of interiors.

3. THE SYSTEMS OF ELECTRIC LIGHTING OF INTERIORS

A system of electric lighting is a set of devices (like the sources, fittings, ignition systems, electric wiring, assembling parts, etc) that serve for purposes of providing visible radiation to the Ω space. The use of the above mentioned equipment enables shaping the light field distribution in the space (particularly at the selected working planes) with a view to achieving the lighting parameters required by the recommendations and standards. One of the types of the systems of electric lighting are complex interior lighting systems. They include the inside objects in which some sub-areas are defined, according to geometric structure of the object, functional differentiation, and normative requirements. In such systems a file of **A={**$A_1, A_2, ..., A_K$} (for k=1,2,…,K) sub-domains is selected, that is related to arrangement of the lighting fittings, and the file of **B={**$B_1, B_2, ..., B_P$**}** computation fields (for p=1,2,…,P) in which the lighting parameters subject to the control are calculated. Figure 1 shows an example of a system including two sub-domains of fitting arrangement and three computation fields, The B_1 and B_2 fields are located in the A_1 sub-domain, while the B_3 field in A_2.

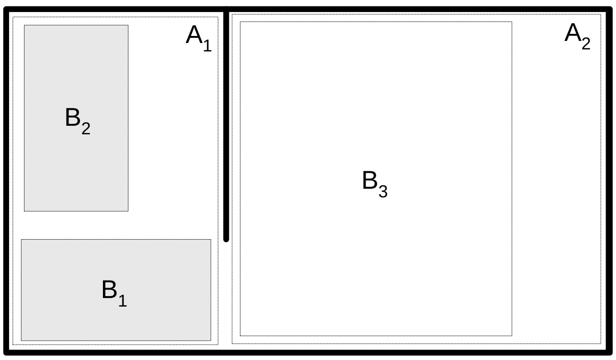

Fig. 1. Location of the fitting arrangement sub-domain (file A) and the computation fields (file B) of a complex lighting system – filled with grey colour

4. OPTIMIZATION OF TOTAL COST OF THE INTERIOR LIGHTING SYSTEMS

The optimization job consists in finding an optimal solution to a certain function J(**x**) with a known searching criterion. The J(**x**) function is called objective function or quality (cost) function and is a scalar function of the **x** decisive variables:

$$J(\mathbf{x}) = J(x_1, x_2, ..., x_n) \qquad (13)$$

Values of the components of the vector **x** of decisive (independent) variables belong to a so-called file of allowable solutions X, that is defined based on many factors related directly to the subject of the considered optimization. In order to carry out the optimization job the number and types of the decisive variables, the form of the objective function, and optimization method must be determined.

For the lighting systems the lifetime T_e of which usually exceeds ten years it is assumed that the criterion of quality assessment is related to economic aspects. It was stated that the objective function J(**x**) should depict total cost of the lighting system within its whole exploitation time T_e, being a sum of two main components: the investment (time-independent) expenses $J^0(\mathbf{x})$ and exploitation (time-dependent) costs $J^t(\mathbf{x})$.

Searching minimal total expenses of a lighting system is an optimization task with constraints, among which there are the normative ones (i.e. including allowable levels of the lighting parameters required by recommendations and standards), hardware ones (admissible types of the fittings, sources, etc), structural ones (related to the object to be lighted), and esthetic ones (imposed by the investor). Therefore, detailed determination of the number, types, and method of accounting of the constraints in the optimization process is necessary. As a method for taking into account the existing set of the equality and inequality constraints in the form

$$X = \{\mathbf{x} : f_o(\mathbf{x}) = 0, \quad g_p(\mathbf{x}) \le 0, o = 1,2,...,O \; p = 1,2,...,P\} \qquad (14)$$

where: $f_o(\mathbf{x})$ – are the functions of equality constraints of the X file for $o=1,2,...,O$; $g_p(\mathbf{x})$ – are the functions of inequality constraints of the X file for $p=1,2,...,P$, the method of external penalty function was used. In such a case a new, modified form of the objective function $J_a(\mathbf{x})$ may be presented as:

$$J_a(\mathbf{x}) = J_i^{(0)}(\mathbf{x}) + J_e^{(t)}(\mathbf{x}) + \sum_{j=1}^{O+P} F_{kj} \qquad (15)$$

where: F_{kj} – are the penalty functions for O equality and P inequality constraints.

The vector of decisive variables is defined for a single *k*-th domain of the fittings arrangement and includes: the fitting type – $x_1^{(k)}$; source type – $x_2^{(k)}$; reflector type – $x_3^{(k)}$; the ignition system – $x_4^{(k)}$; and the height of the fitting assembly $x_5^{(k)}$. The other variables result from the method of arrangement of the fittings within the A_k sub-domain. A block method is here assumed, consisting in symmetric arrangement of the fittings in a predefined rectangular A_k sub-domain (Fig. 2).

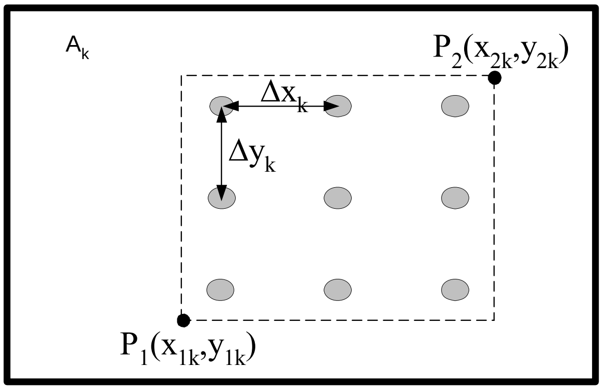

Fig. 2. Parameters defining the method of arrangement of the excitation in the A_k sub-domain of the lighting system

According to Fig. 2. the parameters Δx_k and Δy_k, i.e. the distances between the rows and columns of the excitations, and the points P_1 and P_2 delimiting the arrangement rectangle determine arrangement of the fittings within the block and entire number of the fittings M_k in the A_k sub-domain. At the same time, they are denoted as the decisive variables $x_6^{(k)}$, $x_7^{(k)}$, $x_8^{(k)}$, $x_9^{(k)}$, $x_{10}^{(k)}$, $x_{11}^{(k)}$. The last group of the variables make angular arrangements of a fitting (i.e. the rotation, elevation, and torsion angles) $x_{12}^{(k)}$, $x_{13}^{(k)}$, i $x_{14}^{(k)}$. The above mentioned variables are related to each of the excitation arrangement domain. In case of K domains the length of the **x** vector amounts to 14*K.

According to the general relationship (15) in case of a complex system of electric lighting of interiors the economic objective function takes the form presented below. The investment component $J_i(\mathbf{x})$ is as follows:

$$J_i(\mathbf{x}) = k_i \cdot \sum_{k=1}^{K} \sum_{m=1}^{M_k} (C_{omk} + W_{zmk} \cdot C_{zmk}) \qquad (16)$$

where: k_i – coefficient of electric wiring cost; k – the index of the fittings arrangement sub-domain (k=1,2,…,K); m – index of the fitting m=1,2,…,M_k for k=1,2,…,K; mk – index of the m–th fitting in the k-th sub-domain, $C_{o\,mk}$ – the price of the mk-th fitting [€]; $C_{z\,mk}$ – the price of a single source for the mk-th fitting [€]; $W_{z\,km}$ – the number of sources in the mk-th fitting.

The exploitation part $J_e(\mathbf{x})$ of the objective function is provided by the relationship:

$$J_e(\mathbf{x}) = \sum_{k=1}^{K} \sum_{m=1}^{Mk} \left(T_s \cdot P_{omk} \cdot C_{en} + C_{kmk} \right) \cdot T_e + \sum_{t=1}^{T_e} \left(\sum_{k=1}^{K} \sum_{m=1}^{Mk} \left(w_{zmk} \cdot int[y] \cdot \left(C_{zmk} + C_{wmk} + C_{umk} \right) \right) \right) \qquad (17)$$

where: t – the index of the year of exploitation; T_e – operating time of the lighting system [years]; T_s – yearly operation time of the system [h/year]; P_{omk} – power of the mk-th fitting [kW], C_{en} – the price of 1 kWh of electric power [€]; C_{kmk} – the price of yearly maintenance of the mk-th fitting [€]; w_{zmk} – the number of sources of the mk-th fitting [pcs], C_{zmk} – the price of a single source of the mk-th fitting [€]; C_{wmk} – the price of exchange of one source of the mk-th fitting [€];C_{umk} – the price of utilization of one source of the mk-th fitting [€]; int[y] – integer part of the expression:

$$\left[\frac{t \cdot T_s}{T_{zmk}} - int\left[\frac{(t-1) \cdot T_s}{T_{zmk}} \right] \right] \quad (18)$$

taking the value 1 or 0 (the 1 value determines the time of exchange of the sources included in the mk-th fitting); T_{zmk} – lifetime of the source in the mk-th fitting.

The objective function used for purpose of minimizing total cost of electric lighting systems of interiors is a sum of the expressions (16) and (17).

The algorithm hereby elaborated proposes consideration of two basic constraint groups. The first of them includes checking of the normative parameters, i.e. according to PN-EN 12464-1:2004 the exploitation illumination E_m(lx), uniformity of the lighting E_{min}/E_{avg}, the UGR Unified Glare Rating, and the colour rendering factor R_a. The above mentioned constraints are surveyed separately for each of the computation fields B_p. The other group of constraints results from the geometry and design details of the object. It includes the height range, the assembling areas, and the types of the fittings and sources.

As the pattern of the objective function remains unknown (i.e. a part of the decisive variables is not explicitly expressed in the objective function), the number of decisive variables is important, and many possible local extrema may occur, that was evidenced by experience, a method of modified genetic algorithm was proposed [3,7,8] in order to search minimal total cost of an electric lighting system.

Characteristic feature of the optimization process carried out with the method of genetic algorithm consists in searching an optimal solution by simultaneous dealing with larger number of the solutions (the number of the solutions is strictly defined). A single solution is represented by a so-called individual that is a set of components of the vector of decisive variables. A set of individuals makes a generation. The next generations are so derived (generated) from the previous ones that their individuals have better features from the point of view of the predefined criterion. The goal is achieved with the use of three basic genetic operators of random character: a selection (the choice of the best adapted individuals to be included in the next generation), crossover (with the probability p_m), and mutation (random exchange of a certain number of genes - with the probability p_k). Features of the individuals are defined based on the values of so-called fitness function. The function is equivalent to the objective function known from classical optimization methods. The methods of transformation of the objective function into the fotness function are available in the literature, e.g. in [2,7].

The method of genetic algorithm as an example of random optimization is distinguished by two main faults: the achieved results are unrepeatable, while the solution found usually only approximates the optimal point [2,7]. As the considered problem is determined by continuous and discrete decisive variables, it is assumed that good results of data encoding may be obtained only by binary coding. Additionally, it was assumed that all the decisive variables make a single chromosome of the length equal to the sum of lengths of particular variables. The lengths of binary series representing particular decisive variables were determined based on the resolution required.

Effectiveness of the genetic algorithm applied to the optimization process is to a remarkable degree related to the choice of the set of operators used for this purpose, i.e. selection, crossover, and mutation. Apart from the classical operators described by Holland [8], many modified operators are used too. The algorithms making use of such operators are referred as the modified ones [2,7]. In the algorithm used for searching minimal value of total cost of electric lighting systems of interiors the following elements modifying the classical genetic algorithm have been applied: scaling of the fitness function, tournament selection with randomly predefined tournament size, four-point crossover, and the elements of exclusive strategy, allowing for leaving at least one individual distinguished by the best adaptation that occurred up to now.

The implemented module of light field analysis enables accurate computing of the distribution of selected photometric parameters at the planes of computation fields, for definite geometry and structure of the object. The values determined this way make a basis for controlling the normative constraints. In case of excess in each of the constraints defined by the algorithm a penalty is imposed, the value of which depends on the size of the excess and the number of the generation. Value of the penalty grows together with the generation number that is conducive to quicker rejection of weak solutions in final stage of the search. The group of constraints related to geometry and structure of the object has been introduced to the algorithm by reduction of the range of respective decisive variables Figure 3 shows a block diagram of the optimization algorithm developed for this purpose, with the block of light field analysis.

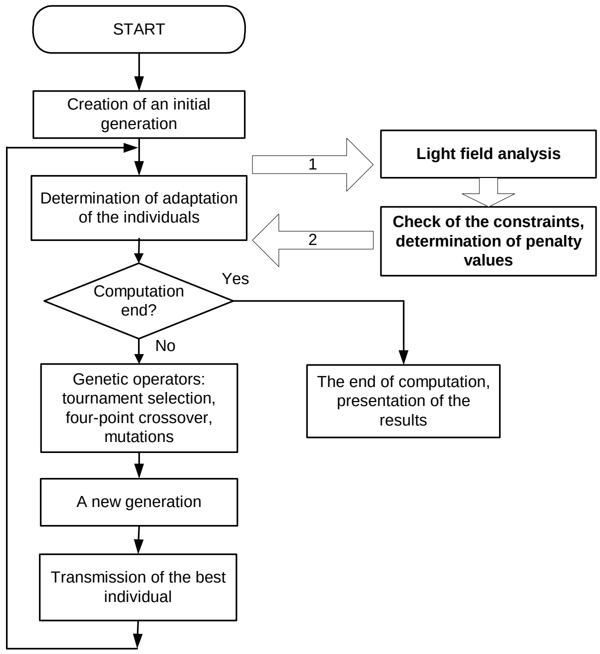

Fig. 3. Block diagram of the genetic algorithm applied for the job (1 – data transmission to the numerical procedures of light field analysis; 2 – transmission of the analysis results and determined penalty values)

Based on the algorithm presented above a computer software package OptyLight has been developed, designed for purposes of minimizing the total cost of electric lighting systems of interiors, roads, streets, and open areas. The system includes a CAD graphical environment allowing for introducing the data describing geometry of the objects, modules of light field analysis and optimization, a database of the lighting equipment and fittings, and a module of presentation and printing of results. The environment has been developed in the technology of Object Oriented Programming (OOP) in the Delphi language. For purposes of the application an original structure of object classes has been formulated, to be used in all the above mentioned modules.

5. CALCULATION EXAMPLE

An example of the light field analysis and the process of minimizing the total cost of electric lighting systems of interiors has been presented for an industrial object composed of two areas provided with the light fittings, of different height (H_l=10m, H_2=5m) and purpose (a production and warehouse room). In each of them a single computation field has been defined. The sub-areas were separated by a wall that eliminated interaction between the light sources located therein (Fig. 4). In case of the higher, production part of the room it was assumed that the group of high-pressure sodium sources of the height above 5m are allowable. On the other hand, for the warehouse part the requirement of fluorescent sources of the height above 3m has been imposed.

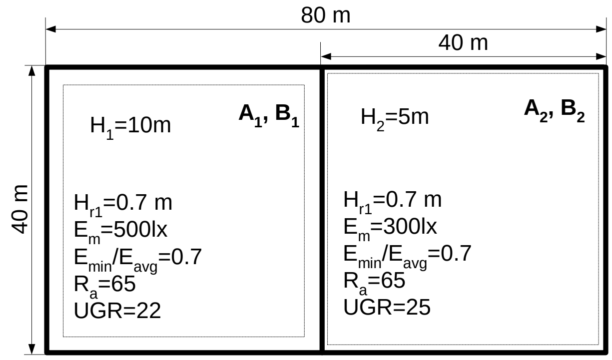

Fig. 4. Geometry and parameters of the object used as an example of light field computation and minimizing the cost of the lighting system – horizontal projection

For these computation fields the heights of working planes have been defined as H_{1r}=H_{2r}=0.7m and the values of lighting parameters required by the standards (Fig. 4). They make a basic optimization constraints. Moreover, it was assumed that the lighting system lifetime T_e amounts to 15 years, with yearly operation time equal to T_s=6000h/year. Expected inflation within this period has been assumed at the level of 2 per cent yearly.

For such definition of geometry of the industrial object (Fig. 4), its reflective parameters, i.e. reflection coefficients of the walls, ceiling, and floor, amounting to 0.4, 0.2, and 0.2, respectively, definite normative parameters, and allowable set of the lighting equipment, the computation has been carried out with the use of the OptyLight software. Minimal cost of the example lighting system was found with the use of the genetic algorithm adopted for this purpose, assuming the generation size of 100 individuals, crossover and mutation probabilities amounting to p_k=0.7 and p_m=0.005, respectively. The computation has been carried out for 100 generations and repeated 20 times. Fig. 5. shows the patterns of average and minimal values of adaptation as functions of the number of generation, for one of the optimization processes.

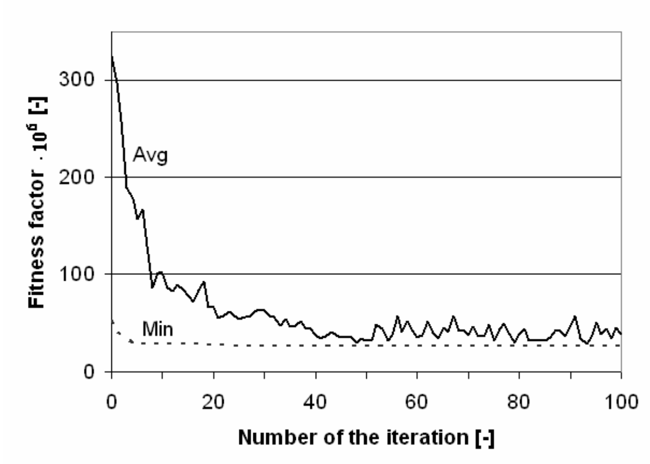

Fig. 5. The patterns of average (Avg) and minimal (Min) values of the fitness factor in optimization of an example lighting system

The computation ended in finding an optimal solution (characterized by minimal total cost). Table 1 presents specification of total cost of four technically correct solutions (i.e. meeting the normative requirements – Fig. 4. – and other constraints) of the industrial object lighting. At the first position the optimal solution is shown. In case of other solutions the percent growth in total cost as compared to the optimal one has been calculated. Additionally it was assumed that maximal shift with respect to the assumed normative parameters must not exceed 5 percent. Only an excess of these parameters is admitted.

The solution type	*Total cost [€]*	*Cost increase [%]*
Optimal	170896.0	–
1 Non-optimal	180975.3	5.8
2 Non-optimal	200358.0	17.2

Table 1. Results of optimization of lighting system

One of the most important elements of the optimization package is the module of light field analysis. It is started every time in case of accounting of the adaptation factor of every individual and strongly affects the total optimization time.

Example results of the light field distribution analysis in the form of colour maps of illumination (a derivative with respect to the luminous flux Φ) in the B_1 and B_2 computation field planes of the considered object is shown in Figure 6. Figure 6 shows the results of the light field analysis for an optimal variant (Table 1).

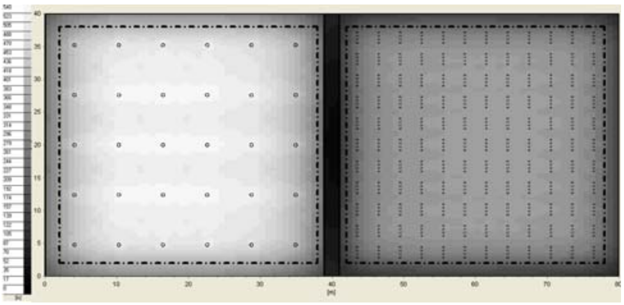

Fig. 6: A 2D distribution of illumination on the planes of computation fields of the considered lighting system (the optimal solution)

6. CONCLUSIONS

The algorithm of electromagnetic field analysis in the visible range used for purposes of optimization of lighting systems, apart from appropriately high accuracy, should operate quickly. As the phenomenon of multiple reflections of the luminous flux should be duly considered, and the photometric values are to be calculated solely at the computation field planes, analysis of the entire Ω domain of the lighting system is not necessary. This allows to relinquish the differential description of the field and replace it with an integral approach.

Analysis of the light field has been carried out with the use of the 2nd kind Fredholm integral equations formulated for a scalar value of the Φ luminous flux. In order to solve the above mentioned equation an approximate method has been used, requiring discretization of the S surface surrounding the Ω domain of the considered object. This, in comparison to the differential relationships, resulted in reduction of the job size and shortening total duration of the light field analysis.

In spite of the use of an effective algorithm of light field analysis its multiple calls in case of the objects of complicated geometry and material structure are conducive to the fact that total time of the optimization process is remarkable. In case of the job presented in the example the time amounted, on the average, to 420 minutes for a Pentium IV 2.8Ghz computer provided with 1GB RAM. Therefore, it seems that the computers of higher computation power should be used, e.g. parallel ones (inclusive of Parallel Virtual Machines). The optimization process of total cost of an electric lighting system of interiors has the features allowing for parallel organization of the algorithm. The works devoted to the topic have been many times published by the authors, that is evidenced by the papers [3,5].

Taking into account that the pattern of the objective function is unknown, the number of decisive variables is considerable (in complex lighting systems this number may even reach hundreds), local extrema may occur, and the independent variables are of very differentiated kind, in order to optimize the total cost of the electric lighting systems of interiors a modified genetic algorithm was applied. The modifications, in particular the tournament selection and four-point crossover, enabled finding the optimal solution usually upon computation carried out for tens generations.

The optimization results are satisfactory, as they allow for considerable reduction of total expense born for new-built and modernized electric lighting systems of interiors. For the example task the cost of the optimal solution is from several to more than ten percent lower than for other technically correct lighting versions.

It means that the algorithm and computer software package developed by the authors considerably aid the work of the lighting system designers.

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