Algorithmic Solution of Indoor Luminaire Placement

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***Abstract*—The paper deals with lighting road design. The demands on illuminance are defined in standard ČSN EN 13201 in case of Czech Republic. There are several parameters that a designer can change to get the optimal solution to fulfill the standard. The distance between pillars, their heights, the lamp overlap and tilt have to be defined. Such number of parameters make the optimization difficult. This paper solves the optimization via genetic algorithm. The fitness function that is convergent to good solutions is a vital point for this type of algorithms. The paper shows that solutions found by the genetic algorithm fulfill the demands and it also shows the way, how the fitness function can be created.**

Keywords - genetic algorithm, lighting, design, illuminance

I. Interior Lighting Design Considerations

Designing interior lighting systems for indoor working places requires fulfilling two contradictory criteria, i.e. providing enough light for persons occupying the given room at a reasonable power consumption. These and more parameters have been taken into account while composing standards such as [11], being mandatory on the territory of the Czech Republic.

For this project an administrative model room has been chosen of dimensions 5×10 meters, 4 meters high with luminaires 3.5 metres above the floor. The model room's purpose has been chosen to be handwriting, writing on type-writers, reading and processing data according to reference number 5.26.2 of [11]. For this kind of room there are several conditions that have to be met by the lighting system:

$\overline{E}_m$	Maintained Average Illuminance of 500 lux
UGR_L	Unified Glare Rating 19
U_0	Lighting Uniformity 0.6
R_a	General Color Rendering Index 80

To meet the requirements set by [11] for the model room, reference plane's average illuminance must be $\overline{E}_m$ or greater at all times during over the course of operation. To calculate the initially needed illuminance values, the Maintenance Factor has to be calculated [12]. For this instance, MF has been chosen to be 0.75. The reference plane is defined as a horizontal plane 75 cm above the floor for generic office tables as suggested in [11]. UGR_L will not be included in calculations of this project, for the task area and view directions of users are unknown. R_a is a parameter of light sources and luminaires and thus must not be incorporated into calculations.

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II. Photometric Value Calculation

To evaluate the lighting system's quality of the model room in terms of standard [11] four parameters have to be observed listed in section I. TODO(remove sentences) For simplification reasons parameter UGR_L will not be calculated. R_a is a parameter of the chosen luminaire and is not affected by the model room. Uniformity U_0 is calculated by the following equation:

$$U_0 = \frac{E_{min}}{\overline{E}} \quad (-; \mathrm{lx}, \mathrm{lx}) \tag{1}$$

where:

E_{min}	is the minimum illuminance of the working plane,
$\overline{E}$	is the average illuminance of the working plane.

Illuminances can be acquired by measurements or calculations in certain points of working planes that are chosen in accordance to the purpose of the room. To calculate the illuminance in a given point of the working plane contributions of all light sources illuminating the given point have to be summed up. This can be achieved by using luminous intensities of all the light sources pointing from the light source towards the point (as seen in figure 1):

$$E_{P\rho} = \sum_i \frac{I_{C\gamma i} \cdot \cos\beta_i}{{l_i}^2} \quad (\mathrm{lx}; \mathrm{cd}, -, \mathrm{m}^2) \tag{2}$$

where:

$I_{C\gamma i}$	is the luminous intensity of the light source pointing towards point P of plane ρ, i.e. luminous intensity of plane C at angle γ ($C - \gamma$ angular coordinate system),
β_i	is the angle between the normal of plane ρ and the light ray from light source S_i,
l_i	is the distance of point P from the light source.

Luminous intensity curves are stored in eulumdat files supplied with luminaires to make light scene calculations possible. For most indoor luminaires the $C - \gamma$ angular coordinate system is used as found in figure 2.

To achieve more accurate simulation results of light scenes, reflections have to be included. From point's P point of view (figure 1), walls, ceiling and floor will become light sources of reflected light. Using the finite element method, surfaces of the model room will be divided into smaller facets. These facets, after illuminated, will become secondary light sources

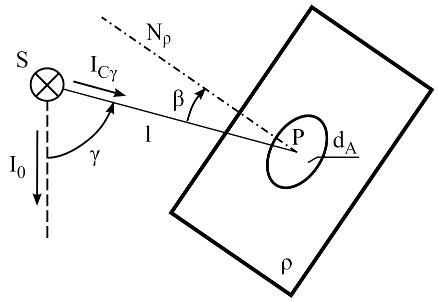

Figure 1. Light source S illuminates point P of plane ρ.

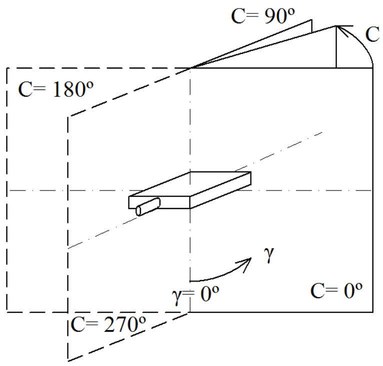

Figure 2. $C - \gamma$ polar coordinate system with luminaire in center.

(figure 3). The process of reflections can be repeated as many times as needed. During each reflection a portion of the incident luminous flux is consumed by the illuminated surface as defined by reflectance. Therefore after several reflections the reflected luminous flux becomes negligible.

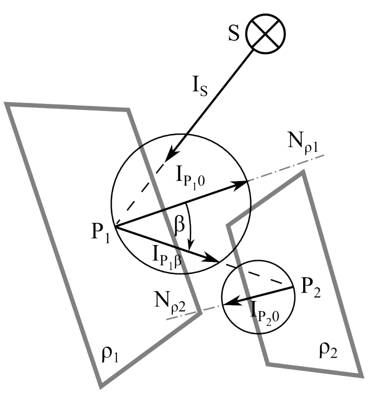

Figure 3. Multiple reflections between planes $\rho 1$ and $\rho 2$ with Lambertian reflectance.

Most common wall and ceiling paints exhibit near Lambertian reflectance properties as depicted in figure 3, meaning that the spacial luminous intensity distribution curve of the facet will only depend on angle β, being the angle between the facets normal N_ρ and the line of center points of both facets. The model rooms surfaces, including the floor, have been chosen to exhibit purely Lambertian reflectance.

After a facet has been illuminated by primary light sources and all the illuminances have been summed up (equation 2), the facet becomes a Lambertian secondary light source of luminous intensity [6]:

$$I_0 = \frac{\rho \cdot E \cdot dA}{\pi} \quad (\mathrm{cd}; -, \mathrm{lx}, \mathrm{m}^2) \tag{3}$$

where:

I_0	is the luminous intensity of the facet in direction of the facet's normal,
ρ	is the facets integral reflectance,
E	is the facet's illuminance,
dA	is the facet's area.

III. Algorithm Description

A. Genetic Algorithm

The algorithm must determine positions and number of luminaries in dependency on target illuminance and uniformity. This is the multicriteria and multiparametric type of the problem. The genetic algorithm offer quite simple way how to solve it, therefore they were used in this case. The genetic algorithms are well known today so only specific settings are further described.

The best solution was saved (elitism) from every population in two specimens. The first one was unable to change its DNA via mutation, the second one had the same probability of mutation like other solutions. Other parent solutions were selected via tournament selection. It consisted of making random group of 4 solutions from the population and take the one with the best fitness. This type of selection had vital role for the algorithm. It avoided premature convergence of the best solution in comparison with the roulette selection. Similar effect was ensured also by recombination probability set less than 1. There was used just one point crossover during the tests. Overview of the all GA settings is shown in table I.

Table I. Genetic Algorithm Settings

First Population	Random logic vectors
Termination Cond.	Maximum number of generations
Number of Gen.	30
Population Size	50
Recombination Prop.	90%
Mutation Prop.	4%
Parent Selec.	Tournament 1 of 4
Mutation Mech.	Inverted bit
Survival Selec.	Elitism

B. Fitness Function

The fitness function defines how good the solutions are. The target value of average illuminance and target value of uniformity are watched in the algorithm. In common case the average illuminance is given especially by number of the luminaires. The uniformity is given especially by placement of the luminaires on the other hand. The count of the luminaires is proportional to the investment cost to the lighting system. So the number of luminaires that exactly fulfill the target average value of illuminance is appropriate. The uniformity is always required as much as possible for defined number of luminaires.

Therefore the fitness function was determined within discussed facts as follows:

$$f_{DNA}(E_{avg}, U_0) = g_1(E_{avg}) + g_2(U_0) \tag{4}$$

$$g_1(E_{avg}) = \begin{cases} e^{\frac{E_{avg}-E_{avgT}}{E_{avg}}} & , \langle 0, E_{avgT}\rangle \quad (5a) \\ e^{\frac{E_{avgT}-E_{avg}}{E_{avg}}} & , (E_{avgT}, \infty) \quad (5b) \end{cases}$$

$$g_2(U_0) = \begin{cases} \frac{U_0}{2 \cdot U_{0T}} & , \langle 0, U_{0T}\rangle \quad (6a) \\ 1 - \frac{e^{U_{0T}-U_0}}{2} & , (U_{0T}, \infty) \quad (6b) \end{cases}$$

where:

E_{avg}	is a calculated average value of illuminance,
E_{avgT}	is a target average value of illuminance,
U_0	is a calculated uniformity,
U_{0T}	is a target uniformity.

The function $g_1(E_{avg})$ has peak value equal to 1 at target value of average illuminance. Because the illuminance cannot be less than zero, the function reaches two limits:

$$\lim_{E_{avg}\to 0+} g_1(E_{avg}) = 0 \tag{7}$$

$$\lim_{E_{avg}\to\infty} g_1(E_{avg}) = e^{-1} \tag{8}$$

Both limits have different values and the limit in infinity is higher than that in the 0. This means that it is preferred the solution with the higher average illuminance for the same absolute difference from the target value.

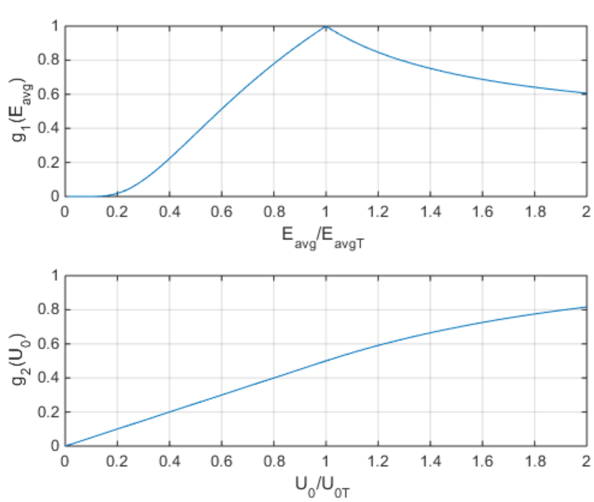

Figure 4. Graphs of parts $g_1(E_{avg})$ and $g_2(U_0)$ from the fitness function

The function $g_2(U_0)$ reach the value 0.5 at target value of uniformity. It has a bound at 0 for values less then target value. There is a limit for values in interval higher than target value:

$$\lim_{U_0\to\infty} g_2(U_0) = 1 \tag{9}$$

So the function $g_2(U_0)$ has an horizontal asymptote equal to one. Function $g_2(U_0)$ is linear for values of uniformity less than the target value. The highest slope is obtained here. For higher values of uniformity is the slope smaller due to the saturation effect of the exponential function. Therefore the algorithm is forced to reach target value of uniformity because of big change in the fitness function. Higher values makes the fitness better too but there is smaller effect. Both functions $g_1(E_{avg})$ and $g_2(U_0)$ are shown in figure 4 for better understanding.

IV. Proposed DNA

A. Symmetric Solutions

One of the requirements to the output design was to get the symmetric solutions of luminaire placement. There seemed to be two approaches how this might be done. The First counts with introduction of the symmetry in the fitness function. On the basis of the fitness equation evaluation the algorithm can prefer symmetric solutions more than others. Unfortunately this approach was very difficult due to unknown function that could describe how good is the symmetry of the luminaire placement. Best experience came from using least squares method. After adding the sum of squares of the differences towards the average value of illuminance, a lot of output results showed the symmetry towards axis or center. However some types of luminous intensity distribution curves were very sensitive to create a tight groups of luminaires in specific positions. This type of solutions were unable to realize in real conditions. At last the second approach dealing with introduction of the symmetry in the DNA was chosen. The symmetry towards the center and the symmetry towards the axis were further studied. The center symmetry was reached by proposing the luminaire positions only for one half of the room. The another half of positions were got by mirroring towards both axis. Similar for the axis symmetry was proposed the position only for one quarter of the room. Other quarters were got by mirroring. It is obvious that there must be even number of luminaires in case of center symmetry and number of luminaires divisible by four in case of axis symmetry. This approach works well but the designer must keep in mind that he never gets results for odd number of luminaires respectively for numbers of luminaires that are not divisible by four.

B. Grid of Allowed Positions

Some types of luminous intensity distribution curves were prone to place the luminaires to groups with almost the same coordinates as it was mentioned in the section IV-A. Very close distances are not allowed because of defined luminaire sizes. To fix this behavior of the algorithm, the luminaires are placed to the defined grid now. Positions out of the grid intersections are not allowed.

Grid of allowed positions also let the designer to define specific shape of area for the luminaire independently on the shape of the room. This might be useful for rooms with complex design on the ceiling or where the recessed luminaire are used. On the other hand the set of solutions is restricted always only on the grid.

C. DNA structure

The resulting DNA just defines logic vector of luminaire presence in the specific grid intersection. The length of the DNA depends on the number of grid intersections and on the type of the symmetry:

$$L_{DNA} = \frac{N_G}{2 \cdot sym} \tag{10}$$

where:

N_G is number of grid intersections,
sym is the chosen symmetry that is equal to 1 for center symmetry and equal to 2 for axis symmetry.

Table II. STRUCTURE OF THE DNA

$\{0,1\}$ for $[x_1, y_1]$	$\{0,1\}$ for $[x_2, y_1]$	...
$\{0,1\}$ for $[x_1, y_2]$	...	$\{0,1\}$ for $[x_n, y_m]$

The proposed structure of DNA lets the algorithm determine needed number of luminaires. Therefore the designer just sets target value of illuminance, target value of uniformity, the luminous intensity distribution curve for chosen luminaires and the grid.

V. PROGRAM BEHAVIOR

dva typy symetrie. Pro stredovou jsou vysledky vice kreativni. Pro stredovou symetrii je hladsi prubeh fitness funkce. Velka souvislost mezi delkou DNA a nastavenou mutaci. Pro velkou mutaci program spatne konverguje. optimalne je pro 200 0.01 Pro nekolik behu vraci program ruzne vysledky, coz v dusledku znamena, ze vice uskupeni splnuje cilove parametry. Nekdy je vhodne mirne hybat s cilovou hladinou osvetlenosti, jelikoz vzhledem k ostre definici fitness funkce muze dojit k ovlivneni rozmisteni svitidel.

VI. EXAMPLE OF THE RESULTS

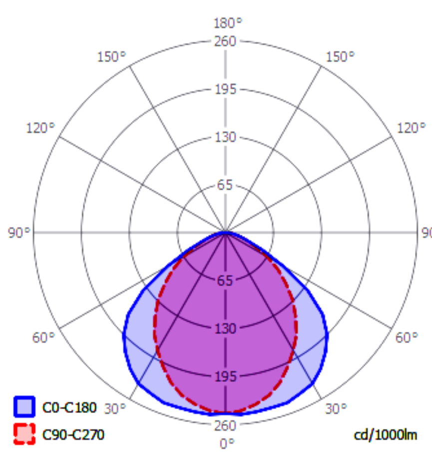

Figure 5. Luminous intensity distribution curve of the luminaire sample

VII. CONCLUSION

Here comes conclusion.

Table III. TARGET VALUES AND SETTINGS

$\overline{E}_m$ (lx)	510
U_0 (-)	0.6
MF	0.75
Luminaire axis vector	$\langle 010 \rangle$
Grid ($N_x \times N_y$)	16×8
Grid distance from the walls (m)	$D_x = 0.5, D_y = 0.4$

Table IV. RESULT VALUES

Parameter	**Central sym.**	**Axis sym.**
$\overline{E}_m$ (lx)	526.9	511.8
U_0 (-)	0.81	0.71
Luminaire count (-)	18	16

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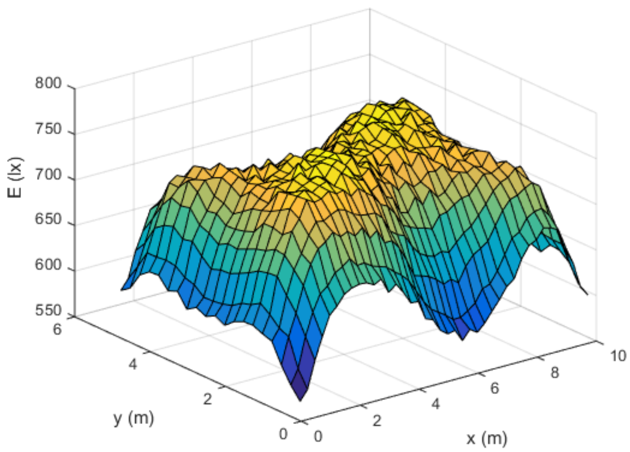
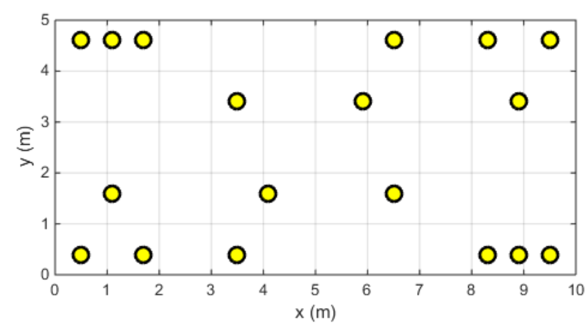
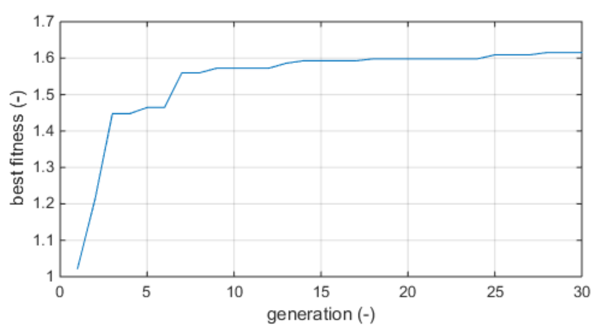


(a) 3D graph of the illuminance

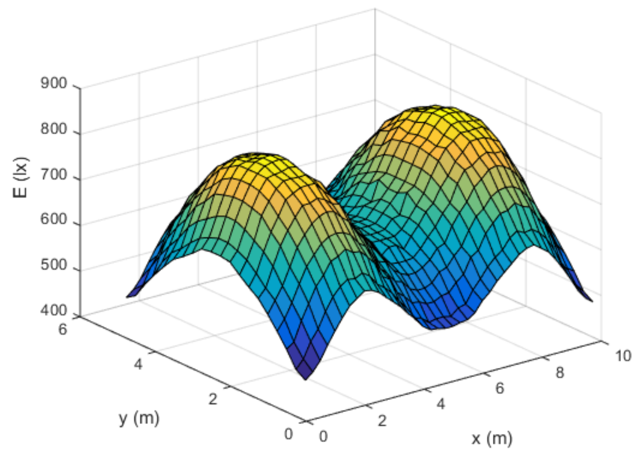


(b) Luminaire positions



(c) Best fitness during optimization

Figure 6. Example of result for lamp MSTR SLB 4x18W and central placement symmetry



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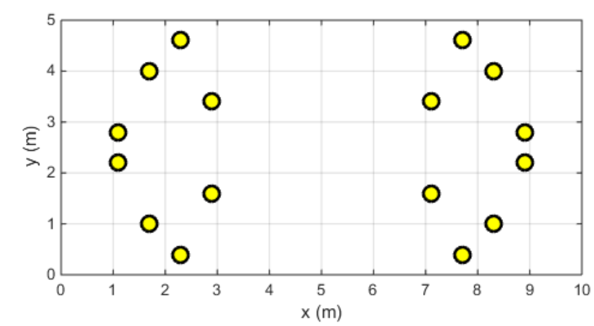
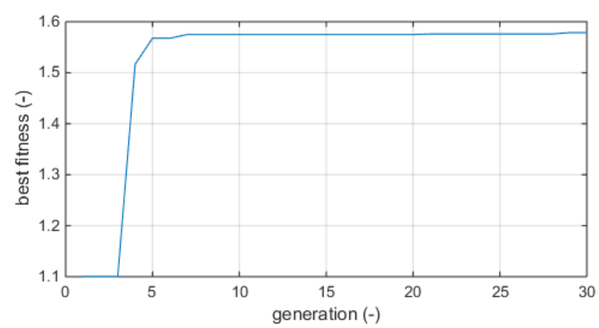


(b) Luminaire positions



(c) Best fitness during optimization

Figure 7. Example of result for lamp MSTR SLB 4x18W and axis placement symmetry