Algorithmic Solution of Indoor Luminaire Placement

Rudolf Bayer*, Michal Brejcha†, Zuzana Panská*
*CTU in Prague, Faculty of Electrical Engineering, Department of Electrical Power Engineering
Praha 6, Technická 2, 166 27
Email: bayerrud@fel.cvut.cz, pelanzuz@fel.cvut.cz
†CTU in Prague, Faculty of Electrical Engineering, Department of Electrotechnology
Praha 6, Technická 2, 166 27
Email: brejcmic@fel.cvut.cz

***Abstract*—The paper discusses a way to deploy luminaires in a model room to provide required illuminance levels and uniformity of the working plane by using a genetic algorithm. The problems about determining the adequate DNA structure and fitness function are introduced and solved. The reflections from walls, ceiling and floor are taken into account in the calculations and further discussed. The output results of the algorithm are judged by requirements of the standard ČSN EN 12464-1 and from the lighting system designer's point of view.**

Keywords - genetic algorithm, lighting, design, illuminance

I. Interior Lighting Design Considerations

Designing interior lighting systems for indoor working places from a photometric point of view 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 [4], 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 typewriters, reading and processing data according to reference number 5.26.2 in [4]. 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 [4] for the model room, reference plane's average illuminance must be $\overline{E}_m$ or greater at all times over the course of operation. To calculate the initially needed illuminance values, the Maintenance Factor has to be calculated [5]. 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 [4]. 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.

Research sponsored by SGS13/197/OHK3/3T/13

II. Photometric Value Calculation

To evaluate the lighting system's quality of the model room in terms of standard [4] four parameters have to be observed listed in section I. In this project only uniformity and illuminance will be used. 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 3). The process of reflections can be repeated as many times as needed. During each reflection a portion of the

978-1-4673-6788-2/15/$31.00

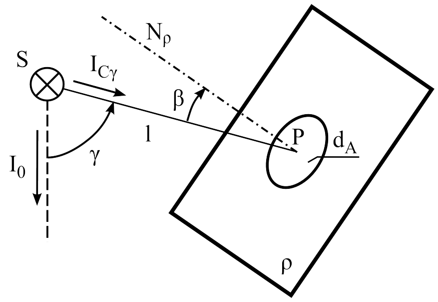


Figure 1. Light source S illuminates point P of plane ρ.

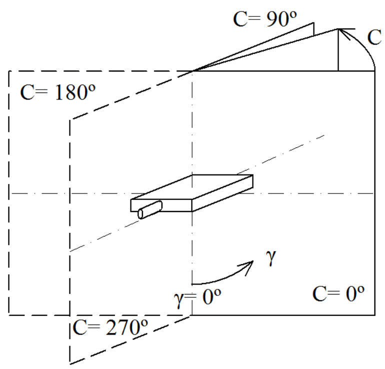


Figure 2. $C-\gamma$ polar coordinate system with luminaire in center.

incident luminous flux is consumed by the illuminated surface as defined by its reflectance. Therefore after several reflections the reflected luminous flux becomes negligible.

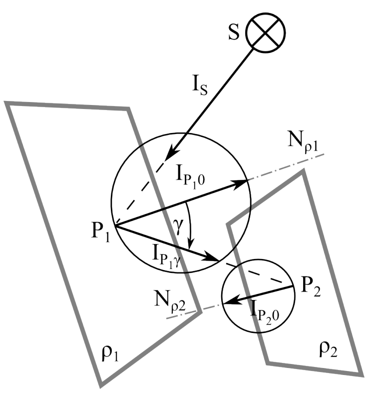


Figure 3. Multiple reflections between planes $\rho 1$ and $\rho 2$ with Lambertian reflectance.

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 facet's normal N_ρ and the line of center points of both facets. The model room's 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 [1]:

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

where:

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

After obtaining I_0, the luminous intensity curve of a facet of Lambertian reflectance will be:

$$I_\gamma = I_0 \cdot \cos(\gamma) \quad (\mathrm{cd}; \mathrm{cd}, -) \tag{4}$$

where:

I_γ	is the luminous intensity in direction γ,
I_0	is the luminous intensity in direction of facet's normal,
γ	is the angle between the facet's normal and the line of center points of the source and destination facet.

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 algorithms offer quite simple way how to solve it, therefore they were used in this project. 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 in the algorithm. It avoided a premature convergence of the best solution in comparison with the roulette selection. Similar effect was ensured also by setting the recombination probability less than 1. There was used only one point DNA crossover during presented tests. Overview of the 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 maintained illuminance and target value of uniformity are watched in the algorithm. In common case the average illuminance is given especially by a count of the luminaires. The uniformity is given especially by specific positions of the luminaires on the other hand. The count of the luminaires is proportional to investment cost of 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. The fitness function was determined within discussed facts as follows:

$$f_{DNA}\left(\overline{E}_m, U_0\right) = g_1\left(\overline{E}_m\right) + g_2\left(U_0\right) \tag{5}$$

$$g_1\left(\overline{E}_m\right) = \begin{cases} e^{\frac{\overline{E}_m - \overline{E}_{mT}}{\overline{E}_m}} & , \langle 0, \overline{E}_{mT} \rangle \quad (6a) \\ e^{\frac{\overline{E}_{mT} - \overline{E}_m}{\overline{E}_m}} & , \left(\overline{E}_{mT}, \infty\right) \quad (6b) \end{cases}$$

$$g_2\left(U_0\right) = \begin{cases} \dfrac{U_0}{2 \cdot U_{0T}} & , \langle 0, U_{0T} \rangle \quad (7a) \\ 1 - \dfrac{e^{U_{0T} - U_0}}{2} & , \left(U_{0T}, \infty\right) \quad (7b) \end{cases}$$

where:

$\overline{E}_m$	is a calculated maintained average value of illuminance,
$\overline{E}_{mT}$	is a target maintained average value of illuminance,
U_0	is a calculated lighting uniformity,
U_{0T}	is a target lighting uniformity.

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

$$\lim_{\overline{E}_m \to 0+} g_1\left(\overline{E}_m\right) = 0 \tag{8}$$

$$\lim_{\overline{E}_m \to \infty} g_1\left(\overline{E}_m\right) = e^{-1} \tag{9}$$

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

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

$$\lim_{U_0 \to \infty} g_2\left(U_0\right) = 1 \tag{10}$$

So the function $g_2\left(U_0\right)$ has an horizontal asymptote equal to one. Function $g_2\left(U_0\right)$ is linear for values of uniformity less than the target value. The highest slope is obtained here. The slope is smaller for higher values of uniformity due to the saturation effect of the exponential function. Therefore the algorithm is forced to reach target value of the uniformity because of big change in the fitness function at its beginning. Higher values improves the fitness function too, but there is a smaller effect.

Both functions $g_1\left(\overline{E}_m\right)$ and $g_2\left(U_0\right)$ are shown in figure 4 for better understanding.

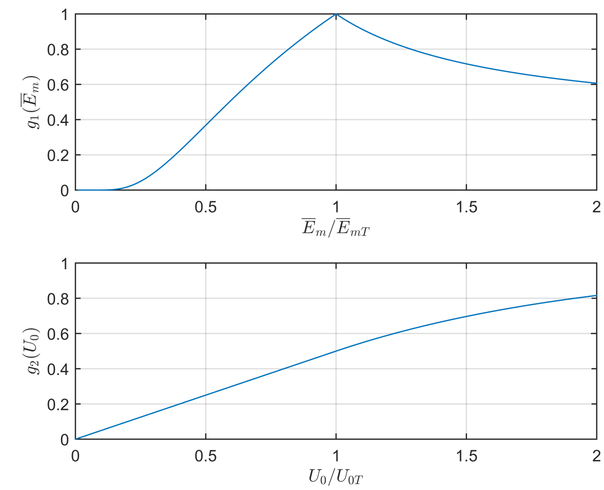


Figure 4. Graphs of parts $g_1\left(\overline{E}_m\right)$ and $g_2\left(U_0\right)$ from the fitness function

IV. Proposed DNA

A. Symmetric Solutions

One of the requirements to the output design was to get the symmetric solutions of luminaires 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 clearly describe how good is the symmetry of the luminairies 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 both 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 outputs were unable to realize in real conditions, so they were not acceptable.

The second approach dealing with introduction of the symmetry in the DNA was chosen at last. The symmetry towards the center (one point) and the symmetry towards both 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 one axis. Similar for the axis symmetry was proposed the position only for one quarter of the room. Other quarters were got by mirroring towards both axis. It is obvious that there must be even number of luminaires in case of center symmetry and number of luminaires divisible by four in the 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 certain luminaire size. The luminaires are placed to the defined grid now to prevent positions grouping. 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 of the ceiling or where the recessed luminaires are used. On the other hand the set of solutions is restricted always only on the grid.

C. DNA structure

The resulting DNA 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:

$$L_{DNA} = \frac{N_G}{2 \cdot sym} \tag{11}$$

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

It have been done several tests of the algorithm. Some interesting features or traps have appeared. The outputs in case of center symmetry had less pretty look than that with the axis symmetry. Human brain simply likes symmetry towards both axis. On the other hand the center symmetry has more degree of freedom. The results were more creative and in the most of the tests reached higher fitness for the same settings. The course of the fitness function history was usually smoother. This can be seen in sample tests in figure 6c and 7c. The curse is like gradual approximation to the top in figure 6c while the curse in figure 7c reminds rather random steps.

Algorithm returns different results sometimes for several runs. That might be consequence of not exactly defined requirements. There might exist multiple solutions of luminaire placement for defined illuminance and uniformity. Another possible reason is quite small population size or few count of generation. For bigger population size (100 members and more) the solutions were often more similar.

The evaluation of the algorithm takes quite long time due to complex calculation of illuminance and reflections. It took about 20 minutes to obtain a result for settings in table I, 4 reflections and amount of 3520 wall facets.

A trap is hidden in target maintained illuminance $\overline{E}_{mT}$ adjustment. This value affects also the resulting luminary placement. If the value is changed a little bit then the count of luminaires usually does not change. However the algorithm puts the luminaires for example close to the middle of the room then, although it put them close to the walls for the previous target value. This effect is caused especially by the definition of the part $g_1\left(\overline{E}_m\right)$ in the fitness function (5). The target value has a very sharp extreme. Therefore the algorithm tries to reach it at any cost. The average illuminance is dependent not only on the count of the luminaires but a little bit also on the positions of the luminaires. So if the designer is not satisfied with the output of the algorithm, he could try change the target value of average maintained illuminance $\overline{E}_{mT}$.

The convergence of the algorithm is strongly affected by the rate of mutation. Both the big and the small rate prevents the algorithm from successful finding of the solution. The optimal value was determined experimentally to approximately 4%.

VI. EXAMPLE OF THE RESULTS

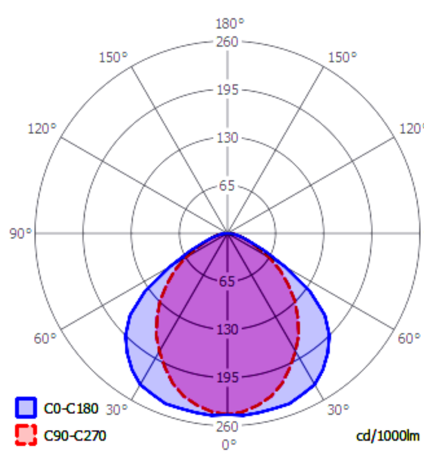
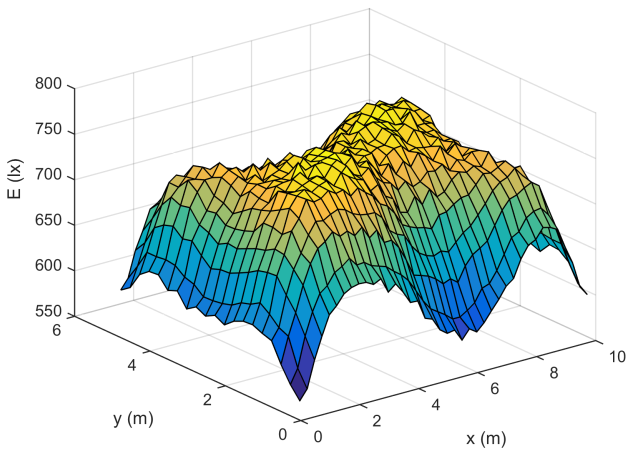


Figure 5. Luminous intensity distribution curve of the luminaire sample

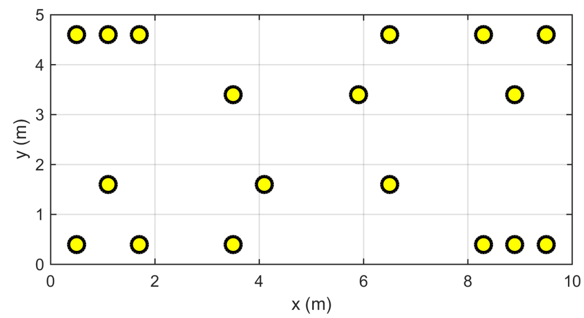
Table III. TARGET VALUES AND SETTINGS

$\overline{E}_m$ (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)	$D_x = 0.5, D_y = 0.4$

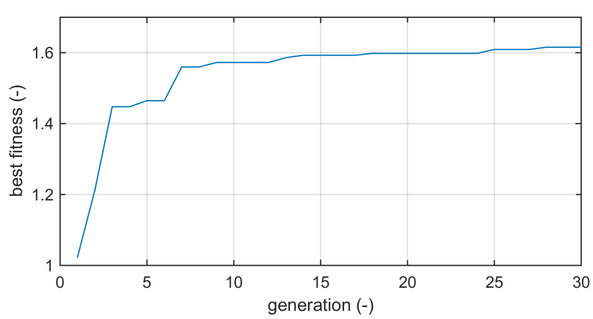
An example of the results was made for luminaire MSTR SLB 4x18W. Elumdata were taken from a software „Building Design“. The luminous intensity curve is shown in the figure 5. The grid distances were chosen 600 mm to



(a) 3D graph of the illuminance

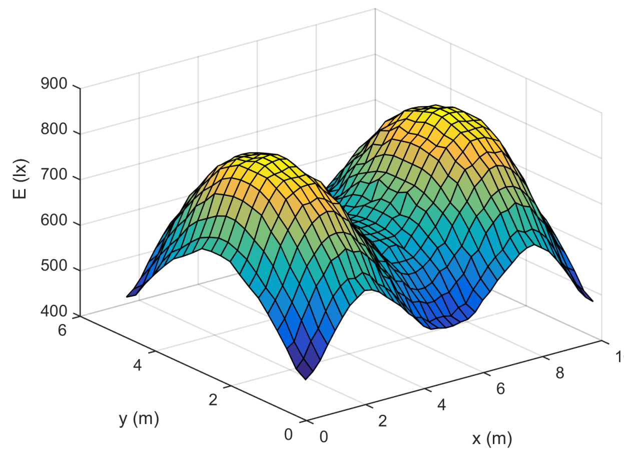


(b) Luminaire positions



(c) Best fitness during optimization

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



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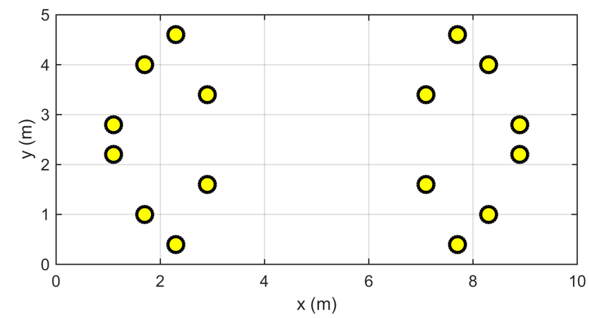
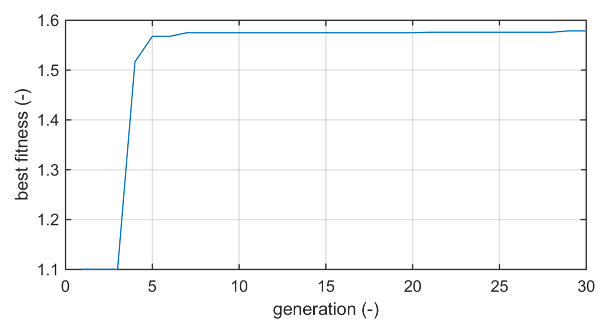


(b) Luminaire positions



(c) Best fitness during optimization

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

respect the luminaire dimensions. The luminaire dimensions were $595 \times 595 \times 80$ mm.

The target maintained illuminance was set to 510 lx to make sure that the result overcome the minimum value 500 lx. The maintenance factor MF was set to 0.75 by author's choice. There is only little effect of this parameter on processing of the algorithm. So it does not matter on the value to much in fact. Whole settings are summarized in table III. All luminaires have the same orientation defined by a „axis vector“. The vector is the normal vector of the $C0° - C180°$ plane. The facet's area on all walls, ceiling and floor was rectangular with length of a side 250 mm.

The results of the calculations are shown in the figure 6 and the figure 7. There is presented one of the outputs for the center and the axis symmetry. Calculated outputs are presented in table IV. Both 3D graphs (6a and 7a) represent the illuminance without MF correction. Therefore most of the values of illuminance are higher than the output maintained average illuminace $\overline{E}_m$.

According to the fitness in table IV, the center symmetry solution is better. Its advantage is related especially to higher uniformity. However this solution uses two more luminaires in comparison to the solution with the axis symmetry. Higher fitness in the case of center symmetry is common but it

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
Fitness (-)	1.616	1.579

does not occur under any circumstances. Because of the symmetry behavior, the axis symmetry solution is capable to add luminaires by 4 while center symmetry solution add luminaires by 2. The value of maintained illuminance $\overline{E}_m$ is closer to the target value in the case of axis symetry solution. Adding 4 more luminaires would make this value too high. The resulting fitness would be smaller even though the uniformity would be possibly better.

It seems that the fitness function still does not respect all designer's requirements. Even the higher fitness is in the case of center symmetry solution, the better solution would possible be the one with the axis symmetry. First of all the positions of luminaries are in prettier and more traditional form here. The uniformity is lower, but since it fulfills the standard's requirements, it does not matter. At last the count of luminaires is lower. That conclude to less investments to a lighting system and its costs.

VII. CONCLUSION

The solution of the algorithm, that determines count and positions of the luminaries in the tested room was introduced in the paper. The algorithm takes into account the multiple reflection for Lambertian surfaces. The outputs satisfy the requirements of the standard [4]. There are still some problems discussed in the paper like long time of calculation or connection between setting target illuminance and positions of the luminaires. Authors still work on improvements that would lead to better correspondence with designer's requirements.

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