Road lighting design by means of genetic algorithm

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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. INTRODUCTION

Lighting system designs of public roads in the Czech Republic have to meet among others the Czech Technical Standard [2]. For this project a road for mainly cyclists but also for pedestrians has been chosen, that is according to [1] lighting situation C1 and lighting class S4. Road lighting conforming to this class must meet in terms of [2] the requirement of maintained average horizontal illuminance $\overline{E}_M \geq 5$ lx, minimum maintained illuminance $E_{min,M} \geq 1$ lx and uniformity so that the actual $\overline{E}_M$ must not exceed 1.5 times the minimal allowed $\overline{E}_M$ for the given lighting class, which is for class S4 $\overline{E}_{max,M} = 7.5$ lx.

The maintenance factor MF is another entry that has to be taken into account. This factor defines the depreciation of the design level, in this case the depreciation of illuminance $\overline{E}$ and E_{min} over the course of operation of the road lighting. Luminaire Atos from Schréder has been chosen to be used in this project, its maintenance factor can be calculated from [3]:

$$MF = LLMF \cdot LSF \cdot LMF \tag{1}$$

Where:

$LLMF$	is the lamp lumen maintenance factor
LSF	is the lamp survival factor
LMF	is the luminaire factor

The Atos luminaire's are fitted with high pressure sodium lamps. For this project Osram NAV-T 70 W super 6Y has been chosen to operate for a period of 12000 hours before replacement. Looking up the product datasheet [5] of the 70 W Osram lamp, $LLMF = 0.89$ and $LSF = 0.97$ can be obtained. The IP Code of the luminaire's optical system is IP66, meaning that for an environment of medium air pollution and cleaning intervals of 2 years $LMF = 0.89$ can be found in table NA.1 of [3]. According to equation 1 the final maintenance factor can be calculated as follows:

$$MF = 0.89 \cdot 0.97 \cdot 0.89 \doteq 0.786 \tag{2}$$

To obtain design illuminances from $\overline{E}_M$ and $E_{min,M}$ at the beginning of the road lighting operation, maintenance factors have to be taken into account:

$$E = E_M \div MF \tag{3}$$

Where:

E	is the general illuminance value calculated or measured at the beginning of the operation cycle
E_M	is the maintained illuminance value assumed at the end of the operation cycle
MF	is the maintenance factor

Having calculated the maintenance factor, design illuminances can be specified:

$$\overline{E} = \overline{E}_M \div MF \doteq 6.36 \text{ lx} \tag{4}$$
$$\overline{E}_{max} = \overline{E}_{max,M} \div MF \doteq 9.55 \text{ lx} \tag{5}$$
$$\overline{E}_{min} = \overline{E}_{min,M} \div MF \doteq 1.27 \text{ lx} \tag{6}$$
$$\tag{7}$$

II. ILLUMINANCE CALCULATION

Illuminance E of a planar surface is the areal density of luminous flux incident on the surface [6]:

$$E = \frac{d\Phi_i}{dA} \tag{8}$$

Where:

$d\Phi_i$	is the luminous flux incident on a surface
dA	is the surface area

Luminous intensity I is the amount of luminous flux contained in a given solid angle. For a direction defined by angle γ is luminous intensity of this angle defined as follows [6]:

$$I_\gamma = \frac{d\Phi}{d\Omega} \tag{9}$$

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Where:

$d\Phi$	is the amount of luminous flux contained in the solid angle $d\Omega$
$d\Omega$	is the solid angle with its axis pointing in direction γ

Illuminances mentioned in section I need to be calculated. Photometric properties of luminaires are defined in eulumdat files [9], containing luminous intensity distribution curves.

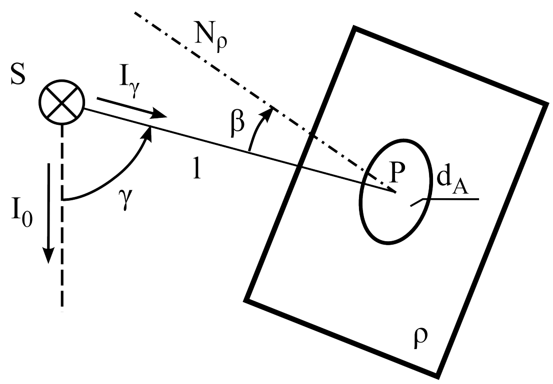


Figure 1. Facet ρ illuminated with light source S

According to [6] illuminance at point P (as seen in figure 1) illuminated by light source S can be obtained by the following equation:

$$E_{P\rho} = \frac{I_\gamma \cdot cos\beta}{l^2} \tag{10}$$

Where:

I_γ	is the luminous intensity in the given direction γ
β	is the angle between the plane's normal N_ρ and the SP point join l
l	is the distance between the light source S and the point P of facet dA of plane ρ

Luminous intensity distribution curves are presented in eulumdat files [9] in the $C-\gamma$ coordinate system (figure 2). For photometric calculations in the situation of road lighting it is more suitable to use the $B-\beta$ coordinate system (figure 3), therefore it was necessary within the frame of this project to apply $B-\beta$ to $C-\gamma$ coordinate system conversion methods, allowing illuminance calculation algorithms to access the eulumdat file of the specific luminaire through the $B-\beta$ coordinate system.

III. Luminaire Parameters

For the calculations one type of luminaire has been chosen. From a wide range of outdoor luminaire procuders and distributors at the Czech market the luminaire Atos of the Schréder company has been chosen.

Atos luminaires are nowadays widely used for public outdoor lighting and can be fitted with light sources from 50 W to 150 W, making it suitable for road lighting of lower lighting classes, e.g. pedestrian zones, cycleways, emergency lanes etc.

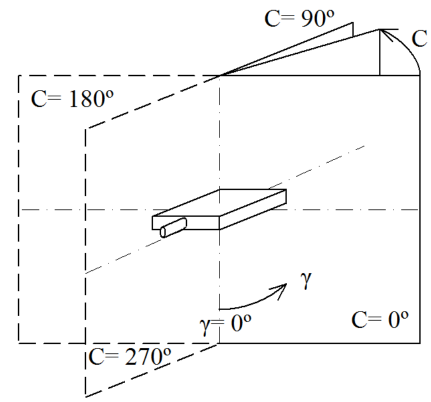


Figure 2. $C-\gamma$ coordinate system

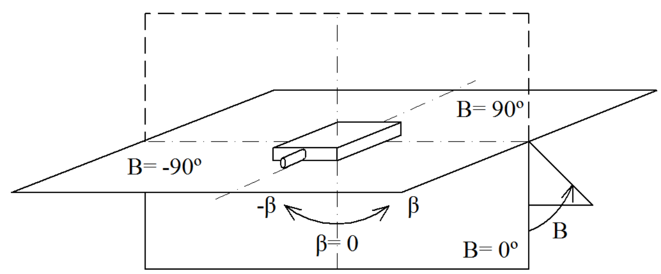


Figure 3. $B-\beta$ coordinate system

The adjustment of luminous intensity distribution curves of Atos is achieved by changing the lamp position inside the luminaire with identical reflectors 1627 [10]. The luminaire Atos offers 12 different positions of the light source inside the luminaire (A1 to A4, B1 to B4 and C1 to C4), therefore 12 different luminous intensity distribution curves for each C-plane can be obtained.

IV. Genetic Algorithm

A. Description of the solution

The genetic algorithms are currently well known so only the introduction of the presented solution is further done.

Figure 4. A photograph of the luminaire Atos

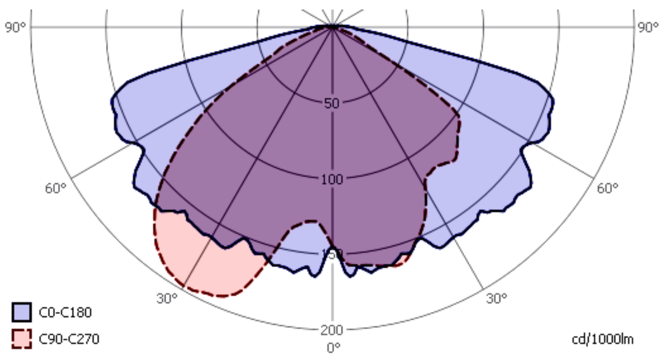


Figure 5. Luminous intensity distribution curves of ATOS/1627/SMOOTH POLYCARBONATE/SON-T 70/-17/100/10° for planes C0, C90, C180 and C270, exported from QLumEdit

Further detail information about genetic algorithms can be found in literature [7] and [8]. Authors chose four parameters to be identified by the algorithm:

- D_X... the distance between the pillars.
- D_Y... overlap of the lamp from the pillar axis. The positive values were considered in the direction getting closer to the sidewalk.
- Z... the pillar high.
- α... the lamp tilt.

The DNA string was made in the order of appearance of each value. The same value limits were chosen for all tested lamps:

$$D_X \in \langle 0.5 \text{ m}, 50 \text{ m} \rangle \tag{11}$$

$$D_Y \in \langle -2 \text{ m}, 2 \text{ m} \rangle \tag{12}$$

$$Z \in \langle 2 \text{ m}, 15 \text{ m} \rangle \tag{13}$$

$$\alpha \in \langle 0^\circ, 20^\circ \rangle \tag{14}$$

The algorithm evaluated the lighting at the sidewalk of length 200 m and width 3 m. The control area was set in the middle of the sidewalk of the length 80 m. Control area consisted of 6000 points evenly covering the whole field with 20 cm distances between each other. These points were used for lighting evaluation and the average value $\overline{E}$ and minimum value E_{min} of illuminance were watched here. The unwanted lightening was evaluated too up to 2 m distance from the sidewalk. This area was set on both sides of the sidewalk with amount of 8000 control points in total. The average illuminance between two pillars $\overline{E}_o$ was calculated here. Author tested both one side and two side placement of the lamps. The distances and arrangements are shown in Figure 6.

There was used one point crossover in the genetic algorithm. The probability of crossovers was set to 80 % and mutation was set to 5 %. Both the parent population size and offspring size were 200. The calculations were finished after 60 births. All these settings were set after several testing to get smooth and fast calculation of the algorithm.

B. Fitness function

Suitable fitness function is the key factor for genetic evaluation. This function is used for determination which results

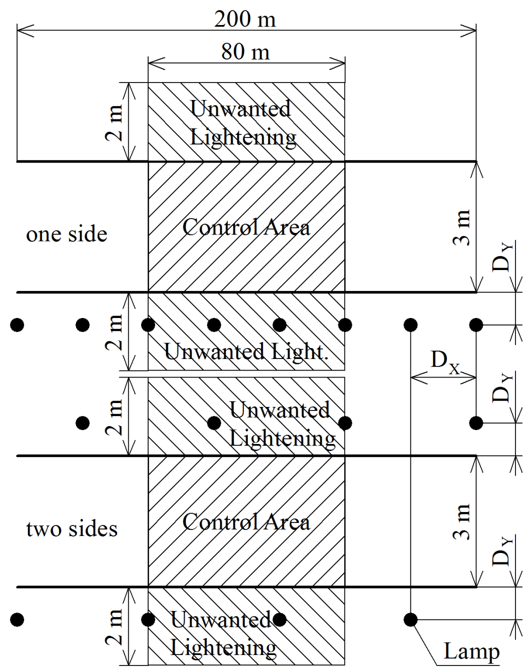


Figure 6. Dimensions of studied sidewalks

are better than others. It is set up by known features of target solution in common cases. However there is no cookbook which would define how to create such function.

Authors decided to create several weights $w(x)$ based on exponential function and these weights multiply one with each other to get resulting fitness function. The basic function was defined by the equation:

$$w(x) = e^{-a \cdot x} \tag{15}$$

where:

- x... is watched variable and
- a... is parameter which defines the slope (first derivation) of the function.

There were several reasons to choose the rule (15). However the main advantage is that the function is equal to 1 at zero and the limit at infinity is equal to zero. The specific weights were defined as follow:

$$w_1(E_{min}) = \begin{cases} e^{10 \cdot (E_{min} - E_{mT})} & , \langle 0, E_{mT} \rangle \quad (16a) \\ e^{\frac{E_{mT} - E_{min}}{10}} & , (E_{mT}, \infty) \quad (16b) \end{cases}$$

$$w_2(\overline{E}) = \begin{cases} e^{\overline{E} - \overline{E}_T} & , \langle 0, \overline{E}_T \rangle \quad (17a) \\ e^{\overline{E}_T - \overline{E}} & , (\overline{E}_T, \infty) \quad (17b) \end{cases}$$

$$w_3(\overline{E}_o) = e^{\frac{\overline{E}_o}{100}} \tag{18}$$

where:

E_{mT}... is target illuminance minimum defined by the standard [2]

$\overline{E}_T$... is target average value of illuminance in the control area. It was determined from the minimal average value $\overline{E}_M$ in the standard [2] as $1.25 \cdot \overline{E}_M / MF$

The priority of each weight is set up by parameter a in the exponential function. The lowest priority is in case of equation (18). The highest priority is to get the minimum illuminance over the defined limit so the highest parameter is in case of equation (16a).

There is another parameter, which was watched by the fitness function. The number of lamps per unit distance is proportional to maintenance cost. So it is also demanded to get as few lamps per unit distance as possible. There is not linear dependency between maintenance cost and number of lamps. Therefore authors use the quadratic function to model it. The last weight was then defined by the equation:

$$w_4\left(D_X\right) = \left(\frac{D_X}{D_{XM}}\right)^2 \tag{19}$$

where:

D_{XM}... is the upper limit defined in equation (11).

Because all weights assumes values between zero and one, the fitness function will assumes the values in the same interval. The fitness function is then given by the equation:

$$\mathit{fitness} = w_1 \cdot w_2 \cdot w_3 \cdot w_4 \tag{20}$$

C. Elitism

There appeared effect of losing best offspring in case of earlier solution of the genetic algorithm. Authors added an elitism to fix this problem. The elitism means to take the best offspring always to the next generation. After adding the elitism, the algorithm showed smoother convergence. The output solutions were also of higher fitness and therefore the whole calculation was able to last less generations.

V. Results Consideration

A. Output of GA for tested lamps

The results of genetic algorithm are shown in tables I and II. The results should be considered as solutions close to a optimum specified by the fitness function. Genetic algorithms are capable of multi parametric optimization, but they are also unable to give exact solutions ([7], [8]). The perfect optimum must be searched by some method with tighter limits around found optimum. Very often is used an combination of genetic algorithm to get close to optimum and then some other stochastic or deterministic algorithm to find the perfect optimum.

The algorithm found different solution during the testing, that fulfill defined constraints. This is normal behavior of the genetic algorithms. If more than one solution exist with close maximums of the fitness, then the algorithm randomly found one of them. The designers can have some preferences. For example they might prefer that the pillars highs cannot be more than 10 m or that the distances between the pillars must be as far as possible an so on. These preferences must be then somehow included to set limits of searched values or in the composition of the fitness function. Authors set pretty lose limits, therefore there are more than one close to optimal solution for some types of the lamps. Other possible solutions are not presented in table I nor in table II.

Table I. Results for one side lamp placement

Type	D_X (m)	D_Y (m)	Z (m)	α (°)	$\overline{E}$ (lx)	E_{min} (lx)	$\overline{E}_o$ (lx)
ATOS 70W A1	39.8	0.67	6.22	3.15	8.14	1.31	7.40
ATOS 70W A2	41.8	-0.73	6.54	2.43	8.13	1.42	7.25
ATOS 70W A3	44.9	-1.69	6.47	3.34	8.15	1.36	6.86
ATOS 70W A4	47.9	-0.41	6.97	3.59	8.14	1.36	6.72
ATOS 70W B1	36.8	0.09	6.86	2.77	8.13	1.31	7.70
ATOS 70W B2	41.1	-1.29	7.28	1.69	8.14	1.34	7.17
ATOS 70W B3	45.4	-1.40	7.76	1.29	8.14	1.55	6.84
ATOS 70W B4	49.5	-1.59	7.69	2.54	8.13	1.72	6.76
ATOS 70W C1	37.6	-0.60	6.23	6.57	8.13	1.38	7.65
ATOS 70W C2	41.14	-0.59	6.72	1.86	8.14	1.50	7.30
ATOS 70W C3	45.1	-0.75	6.56	5.49	8.14	1.31	6.91
ATOS 70W C4	48.0	0.03	6.85	6.70	8.14	1.36	6.92

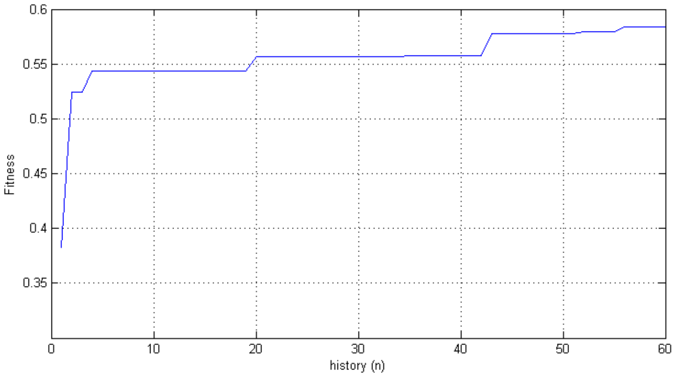
Table II. Results for two sides lamp placement

Type	D_X (m)	D_Y (m)	Z (m)	α (°)	$\overline{E}$ (lx)	E_{min} (lx)	$\overline{E}_o$ (lx)
ATOS 70W A1	39.2	-0.21	6.24	3.85	8.14	1.32	7.55
ATOS 70W A2	40.9	-0.58	6.19	7.60	8.13	1.31	7.40
ATOS 70W A3	44.5	-0.90	6.54	5.40	8.13	1.35	6.98
ATOS 70W A4	45.8	-1.42	6.45	10.51	8.13	1.42	6.82
ATOS 70W B1	36.8	0.07	6.87	3.25	8.13	1.34	7.70
ATOS 70W B2	41.0	-0.46	7.25	0.81	8.13	1.35	7.41
ATOS 70W B3	43.6	-1.11	7.53	5.24	8.13	1.61	7.06
ATOS 70W B4	48.51	-1.49	7.34	8.76	8.13	1.30	6.73
ATOS 70W C1	37.4	-0.45	6.73	0.55	8.14	1.60	7.64
ATOS 70W C2	41.1	-1.28	6.55	3.09	8.14	1.34	7.18
ATOS 70W C3	46.0	-0.76	6.95	1.03	8.13	1.38	6.68
ATOS 70W C4	49.8	-0.14	7.09	1.90	8.14	1.32	6.62

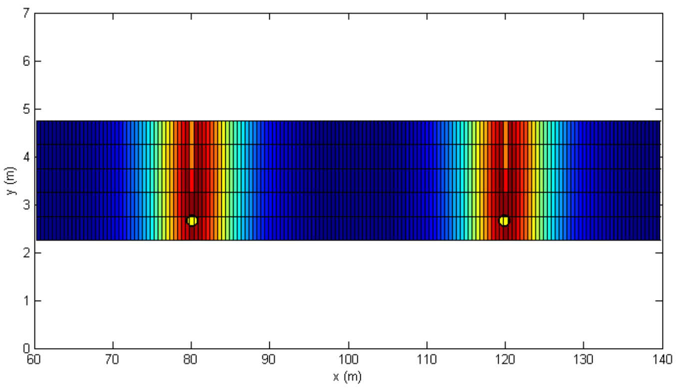
B. Example of specific result for ATOS 70 W A1

The result for the lamp ATOS 70 W A1 is discussed in this chapter. The output parameters of the algorithm can be found in the first row of the tables I and II. The count of tested points in control area were decreased to 960 for better visualization in figures 7 and 8. The distances between points is then 0.5 m in the visualizations.

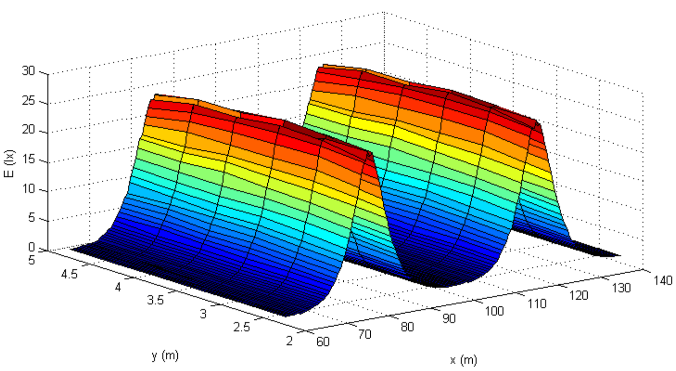
The change of the fitness function during each generation is presented in figures 7a and 8a. The fitness function in case of one side lamp placement has the most typical shape for a most of the done tests. The algorithm found good solution very fast on the beginning of the optimization and then the growth of the fitness function slew down. The shape in figure 8a did not appeared too much. The faster growth at older generations was usually caused by poor initial solutions in very first generations. It was pretty possible event, because



(a) Fitness function during the optimization

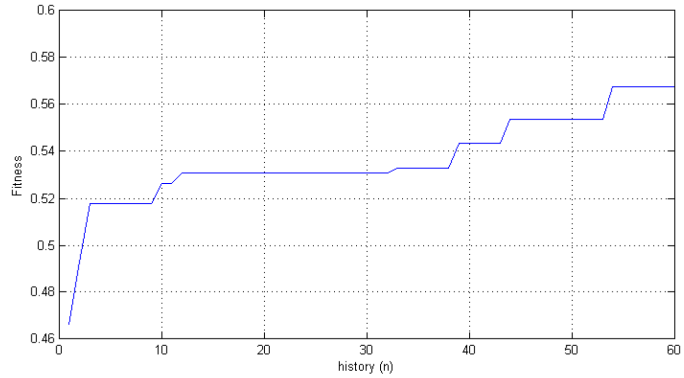


(b) Color map represents illuminance on the road, best offspring

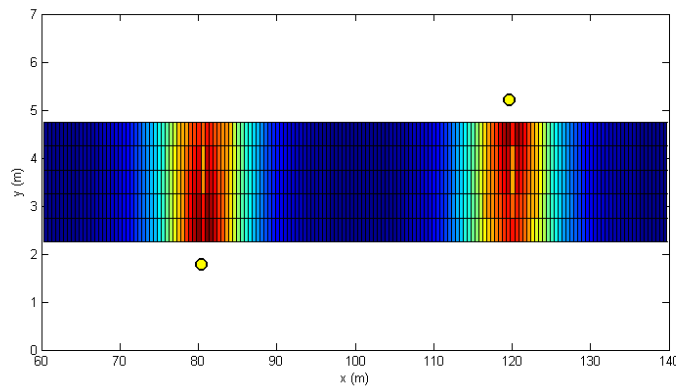


(c) Illuminance on the road, best offspring

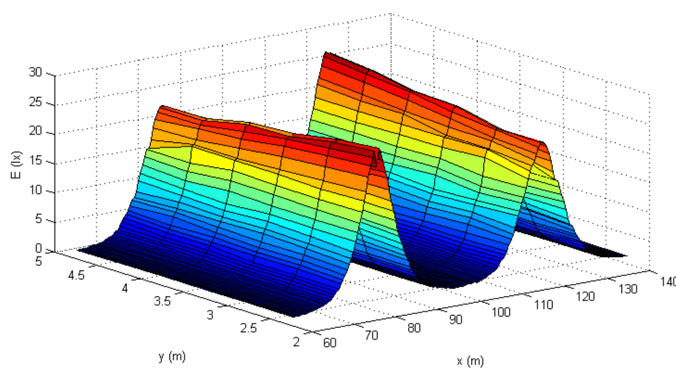
Figure 7. Example of result of lamp ATOS 70 W A1 for one side placement



(a) Fitness function during the optimization



(b) Color map represents illuminance on the road, best offspring



(c) Illuminance on the road, best offspring

Figure 8. Example of result of lamp ATOS 70 W A1 for two side placement

the first solutions in populations were always chosen randomly. However the algorithm is capable to find good solution due to mutation presence in next generations.

C. Comparing Results with DIALux Output

A portion of the results were compared with data obtained from an identical situation simulated in DIALux software, where a street project has been created using luminaires Atos A1 on one side of the road. Horizontal illuminances at road surface level were calculated by DIALux according to [4] as depicted in figure 9 and the output in lux can be found in table III with applied maintenance factor $MF = 0.79$ (see equation 2).

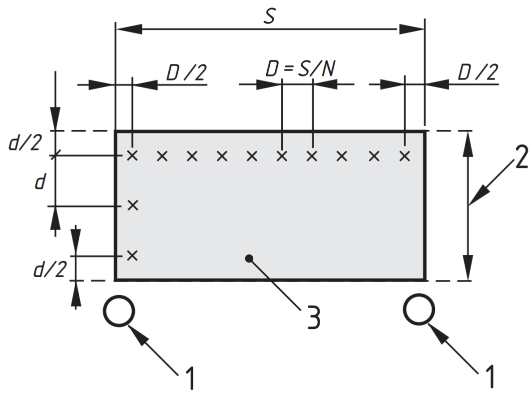
According to standard [4] calculation points shall not be

Table III. DIALUX CALCULATED HORIZONTAL DESIGN ILLUMINANCES IN LUX

(m)	1.421	4.264	7.107	9.950	12.793	15.636	18.479
2.5	24.17	16.54	9.5	4.77	2.91	1.98	1.64
1.5	25.45	15.27	8.59	4.13	2.61	1.78	1.49
0.5	25.45	15.27	7.82	3.72	2.35	1.63	1.36
(m)	21.321	24.164	27.001	29.850	32.693	35.536	38.379
2.5	1.64	1.98	2.91	4.77	9.5	16.54	24.17
1.5	1.49	1.78	2.61	4.13	8.59	15.27	25.45
0.5	1.36	1.63	2.35	3.72	7.82	15.27	25.45

Table IV. DIALUX INPUT DATA AND ILLUMINANCES

Type	D_X (m)	D_Y (m)	Z (m)	α (°)	$\overline{E}$ (lx)	E_{min} (lx)
ATOS 70W A1	39.8	0.67	6.22	3.1	8.52	1.36



1	luminaire
2	width of relevant area W_r
3	field of calculation
x	denotes lines of calculation points in the transverse and longitudinal directions

Figure 9. Calculation points on relevant area [4]

spaced in the longitudinal directions more than 3 m from each other, so 14 calculation points were used during calculations of DIALux instead of 10 depicted in figure 9.

Comparing the first data row of table I and table IV similar values of illuminances $\overline{E}$ and E_{min} can be found calculated by both DIALux and the methods used in the genetic algorithm. Small differences for the Atos 70 W A1 used in the comparison could be caused by input data rounded by DIALux and a vast difference in the amount of calculation points.

VI. Conclusion

Authors presented results of road lightening design using genetic algorithm in the paper. The results were compared with outputs of common used software DIALux. It was proved that found solutions satisfies all demands defined in standards.

Even the algorithm found the solutions in only 60 generations, the calculation last approximately 10 minutes. The reason was lot of calculated points $(8000+6000)$ and relatively large population (200) in each generation. The standards recommend much thinner points concentrations and they do not deal with lighting out of the sidewalk. The algorithm lasted only 2 minutes in case of recommended count of points.

The genetic algorithm can help the designer to find good design even if he is limited by some constraints. These constraints are simply included to limitations of each searched parameter or are taken into account in the fitness function. The fact, that the lighting out of the sidewalk can be taken into account is also very helpful.

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