sustainability

MDPI

Article

Unconventional Luminaire Layout Design by Genetic Algorithms

Zuzana Panska [1], Marek Balsky [1,*], Rudolf Bayer [1] and Michal Brejcha [2]

[1] Department of Electrical Power Engineering, Faculty of Electrical Engineering, Czech Technical University, 166 27 Prague, Czech Republic; bayerrud@fel.cvut.cz (R.B.)
[2] Department of Electrotechnology, Faculty of Electrical Engineering, Czech Technical University, 166 27 Prague, Czech Republic; brejcmic@fel.cvut.cz
* Correspondence: balskmar@fel.cvut.cz

Abstract: The dominant part of energy performance of a building consists of the consumption of heating and lighting. Both the heating and lighting systems of buildings work at their designed efficiency for most of the buildings' lifetimes. Interference with existing systems is costly considering replacements and construction adjustments. Therefore, considerable effort must be put into the design of these systems during the building design phase. The article is focused on luminaire layout design strategy, which affects the number of luminaires in a building and therefore their power consumption and the sustainability of the building. A genetic algorithm with radiosity implemented has been used to find suitable placements of luminaires of a single type in a model room to decrease the number of luminaires as much as possible. The use of a genetic algorithm can reduce the number of luminaires by using an irregular grid of luminaire placement, and therefore decrease the power demand and increase the sustainability of the lighting system. Three outcomes of an optimal luminaire layout design are presented in this paper, including the design strategy conclusions. The results of the calculation outcomes were verified by software DIALux that is commonly used for designing lighting systems.

Keywords: lighting design; genetic algorithm; luminaire layout design; luminous intensity curve

check for updates

Citation: Panska, Z.; Balsky, M.; Bayer, R.; Brejcha, M. Unconventional Luminaire Layout Design by Genetic Algorithms. *Sustainability* **2024**, *16*, 7689. https://doi.org/10.3390/su16177689

Academic Editor: Chiara Burattini

Received: 1 August 2024
Revised: 28 August 2024
Accepted: 2 September 2024
Published: 4 September 2024

1. Introduction

While designing lighting systems for indoor working places, a designer must take several requirements into account. As far as illumination [1], visual comfort [2], and performance of occupancy [3] are considered, it can be said in general that the illumination levels provided by the lighting system (artificial lighting, daylighting) must be suitable for the activities for which the indoor space is intended [4]. This and more are taken into account by the European Standard EN 12464-1 [5] mandatory on the territory of the European Union.

The initial phase of lighting design for a specific environment prioritizes the establishment of illuminance requirements. This adheres to European Standards [5] and is achieved by calculating the required luminous flux and the corresponding number of luminaires. Lighting software facilitates an initial, uniform grid-based layout of these luminaires, each possessing identical luminous flux, the photometric distribution curve, and mounting height.

However, a skilled lighting designer transcends this preliminary analysis. To achieve a comfortable environment, additional factors are integrated into the design process. These encompass the following:

- Spatial distribution of luminance: This ensures a balanced illumination scheme, surpassing a uniform application of illuminance;
- Light directionality: Strategic manipulation of light direction influences mood and accentuates specific spatial features;

- Color Rendering Index (CRI): A high CRI guarantees accurate and natural color perception within the environment [1];
- Chromatic response of materials: The interaction of light with various materials necessitates consideration to optimize the overall visual experience;
- Architectural characteristics: The spatial dimensions, configuration, and intended purpose of the environment all play a crucial role in shaping the final lighting design.

By incorporating these scientific principles, lighting designers create environments that are not only functional, but also aesthetically compelling.

The simplest, and most commonly used, electric lighting system for commercial spaces consists of luminaires only of a single type laid out in a regular symmetric pattern on the ceiling using recessed, surface-mounted, or pendant luminaires. Such design can be obtained by using various professional lighting design software and its wizard feature for indoor spaces. Another way would be to use professional lighting design software for manual irregular luminaire placement where compliance with the standard can be checked by calculating the luminous flux distribution in the chosen indoor space. Finding the optimal luminaire layout design manually can be difficult and its impact on lighting power density [6] is uncertain. The optimal solution found by experts is not usually the energy optimal solution. Research on lighting optimization so far leverages advanced computational techniques, notably neural networks, competition over resource algorithm, evolutionary algorithms and genetic algorithms, to enhance the efficiency and quality of lighting systems in various environments.

The neural network technique was applied in 2013 by Wang et al. [7] to map the relationship among the dimming levels of luminaires grid without optimizing the luminaire layout pattern. In 2017, in addition to dimming, Mendez [8] took into account the total cost of lighting optimization using competition over the resource algorithm [9]. In 2019, Mandal et al. [10] applied particle swarm optimization, an evolutionary algorithm [11], with three decision variables (regular luminaire spacing along the length and width and luminaire mounting height) to find the optimal grid-based pattern of luminaires. The number of luminaires was determined by a loop in the program, which makes the algorithm inefficient. Grid-based luminaire layout design based on particle swarm optimization was verified with DIALux 12 software [12] simulation in 2022 by Ji-Qing Qu et al. [13].

Luminaire layout design is more often solved using genetic algorithms. In 2015, Mattoni et al. [14] used a single-objective genetic algorithm to optimize indoor luminaire layout design by considering energy efficiency, U_0, and UGR with two variable luminaires in a uniform grid-based pattern. In 2016, Madias et al. [15] proposed a multi-objective nondominated sorting genetic algorithm [16] to optimize the two objectives of reducing the energy consumption of buildings by the dimming of one type of luminaire and improving the U_0 of a uniform grid-based luminaire pattern. In 2022, Watini et al. [17] applied genetic algorithms for the economical optimization of school room lighting by optimizing spacing in a grid-based luminaire pattern. Unlike the methods described above, genetic algorithms allow for generating an unconventional luminaire layout design with a non-grid-based luminaire pattern, which could propose a higher luminaire number reduction. Such design was proposed in 2017 by Plebe et al. [18], with a more flexible approach to the interior lighting design by considering $\overline{E}_m$, U_0, and energy consumption, but only with a general omnidirectional light source.

The optimization of lighting design through genetic algorithms is mostly presented in connection with the reducing energy consumption and CO_2 emissions of buildings [14,17,19,20]. The main aim is to reduce the environmental impact of buildings. Energy consumption for the lighting of homes and buildings represents almost 20% of overall building energy demand [19]. Older lighting installations which do not use LED light sources consume 20% to 40% of overall energy [14]. Direct measurements in modern Czech Republic households shows that the lowest energy consumption with energy-efficient LED light sources is about 4%, but without passing any regulations for home lighting. Another visual comfort aspect is missing [20,21].

Genetic algorithms were also used for the lighting optimization of outdoor lighting [19], plant lighting [21], and street lighting [22].

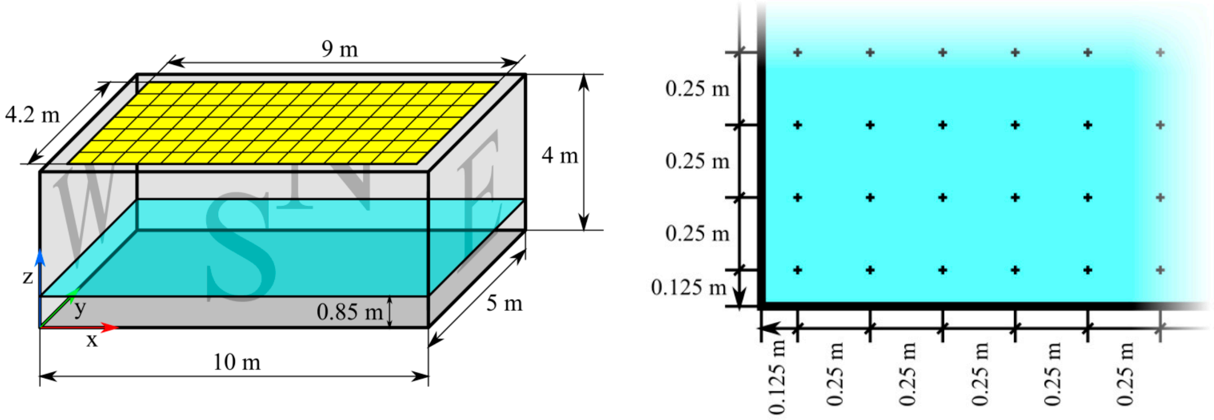
In this paper, we proposed a method to obtain the most optimal luminaire layout design by running a genetic algorithm script based on real luminaires and independent of the conventional grid-based luminaire pattern, and allows for an irregular grid of luminaire placement. The goal is to meet the requirements of technical standards while reducing the number of luminaires needed, and consequently, to increase lighting installation sustainability. Another benefit of the proposed method could be the architecturally interesting unconventional non-grid luminaire layout design. In this paper, only artificial lighting is considered.

2. Model Room

A cuboid-shaped test model room has been chosen to be used for luminous flux distribution calculations for the defined luminaire layout of the chosen type. These calculations were carried out using DIALux 12 software [12] and our own implementation of the global illuminating algorithm radiosity, requiring the room's surfaces to reflect light diffusely. To acquire specific requirements for the lighting system of the model room from the mentioned standard, we chose a room used for handwriting, writing on typewriters, and the reading and processing of data according to reference number 34.2 [5]. There are several specific conditions required by the standard that have to be met by the designed lighting system:

- $\overline{E}_m$—maintained average illuminance of 500 lx;
- U_0—illuminance uniformity 0.6;
- R_{UGL}—unified glare rating RUG limit value 19;
- R_a—color rendering index (CRI) 80.

Besides the walls, floor, and ceiling of the model room, a reference plane was used. In this specific case, the reference plane represented the work surfaces of the room, i.e., top surfaces of desks used in the room. Since the placements of desks were ignored in this project, which is an approach often used in lighting system designs, the horizontal reference plane filled the whole model room 0.85 m above the floor, as suggested in standard [5]. The model room configuration is shown in Figure 1, where Figure 1a shows the dimensions of the room, and Figure 1b details the reference plane and the measurement points for calculation.



(**a**) (**b**)

Figure 1. Model room configuration (N—northern, W—western, S—southern, E—eastern wall): (**a**) model room dimensions, raster ceiling yellow (possible luminaire placements), reference plane cyan; (**b**) reference plane and measurement (calculation) points.

According to standard ČSN EN 36 0011-1 [23], the values of $\overline{E}_m$ and U_0 should be measured in a grid on the reference plane starting 1 m away from the walls with spacing from 0.5 m to 2 m between adjacent points. However, we used a denser grid (Figure 1b) to make the calculated values of $\overline{E}_m$ and U_0 more precise. Also, this grid of the calculation points is suggested by default by DIALux.

The model room will meet the stated average illuminance requirement $\overline{E}_m = 500$ lx if the reference plane's average illuminance will not drop below this value over the course of operation of the lighting system. The initially needed average illuminance $\overline{E}_{init}$ is calculated by using the maintenance factor MF [24]. MF indicates the depreciation of the luminous flux emitted from luminaires and reflected from surfaces at the end of the maintenance period. To get initial illuminances, maintained illuminances need to be divided by the maintenance factor, $\overline{E}_{init} = \overline{E}_m / MF$. The value of MF has been set to 0.8, as suggested for very clean indoor spaces by DIALux. Lighting uniformity U_0 is the ratio of the minimum maintained illuminance to $\overline{E}_m$ of the reference plane and, as required, must be greater than the stated value.

The calculation of R_{UGL} has not been implemented into our algorithm. Whether the output luminaire layout from the algorithm meets the R_{UGL} requirement is instead validated by DIALux by using horizontal calculation areas, filling the whole model room at the height of 1.2 m above the floor using 10 cm calculation point spacing with views toward the north, south, west, and east walls (Figure 1a).

R_a is a parameter of light sources and luminaires that is dependent on their light spectrum, but independent of the model room and its luminaire placements, and as such, it was not included in the calculations. All the used luminaire types and their light sources met the minimum R_a requirement. The presented genetic algorithm was developed and tested using a model room of dimensions 10 m × 5 m × 4 m (Figure 1a). No barriers or equipment were considered. As generally assumed while designing lighting systems for indoor working places, the surfaces of the model room showed uniform diffuse reflections with reflectance ρ (ratio of reflected and incident light) of the following defined values:

- floor reflectance $\rho_f = 0.2$;
- wall reflectance $\rho_w = 0.5$;
- ceiling reflectance $\rho_c = 0.7$.

The rendering algorithm radiosity has been implemented to be used by the genetic algorithm for the objective function feedback, calculating the given luminaire layout design's quality. As radiosity is an application of the finite element method, the model room's surfaces had to be divided into smaller facets (rectangular facets of dimensions 0.2 m × 0.2 m were used). These were used by our implemented radiosity method for spacial luminous flux distribution calculations, including six reflections. The number of reflections was limited to six after several radiosity test runs using only a single luminaire of type MSTR SLB 4 × 18W (exported from software BuildingDesign–Wils library [25]) placed in the model room in the center of the ceiling for illuminances of the facets were affected by less than 10% using more than six reflections by the algorithm. The radiosity reflection test run results are graphically shown in Figure 2. The first part of figure shows the differential increase in the mean illuminance of the individual surfaces with each reflection, and the second part shows the total mean illuminance of the individual surfaces after each reflection.

A rectangular grid of evenly spaced control points—used for illuminance calculations—was placed on the reference plane with 25 cm distances between neighboring points (Figure 1b). Luminaires were placed in the plane of the model room's raster ceiling starting 0.5 m from the eastern and western wall, and 0.4 m from the northern and southern wall, as depicted in Figure 1a, with available positions spaced 0.6 m apart. Three luminaire types were used in this project from the manufacturer Trevos, i.e., TT LED, PSV PISA T8 OP, and PSV PISE T8 PAR (Figure 3), all being designed for a 600 × 600 mm gypsum or raster ceiling. All placed luminaires were oriented identically, with their planes C0°–C180° [26] parallel to the room's y-axis, as depicted in Figure 1a.

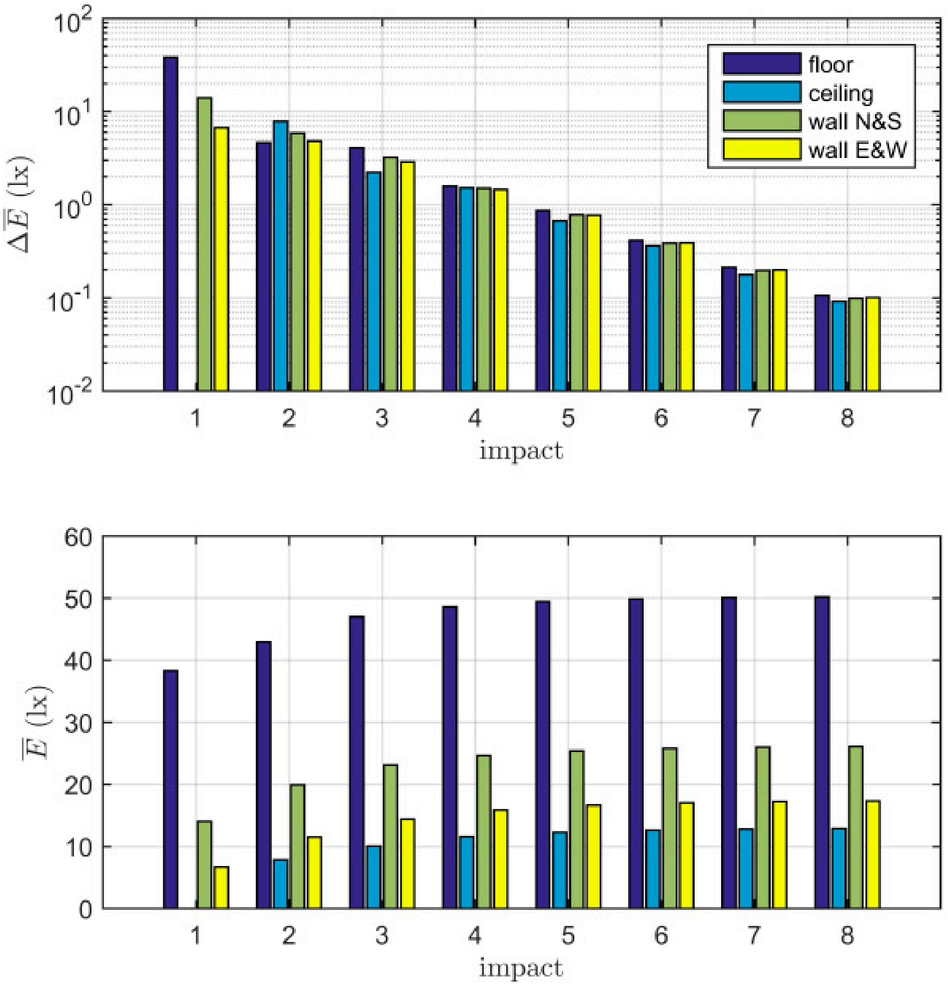
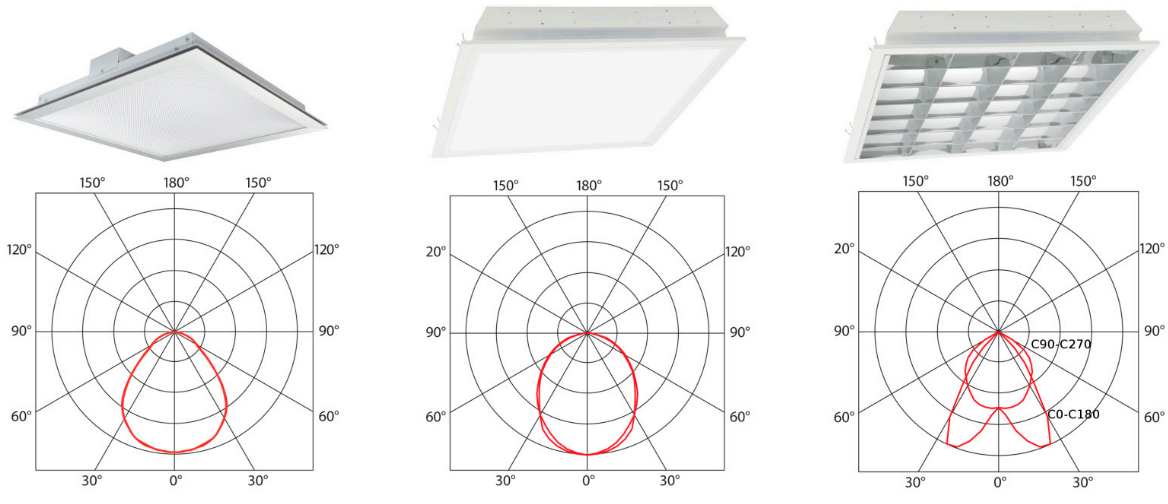


Figure 2. Increase in average wall illuminances with a single luminaire MSTR SLB 4×18W mounted in the center of the model room's ceiling depending on the count of light impacts, i.e., number of reflections −1, calculated using radiosity.



(**a**) (**b**) (**c**)

Figure 3. The used luminaire types from the manufacturer Trevos, their luminous intensity curves (red lines), luminous flux ϕ, and power consumption P from their respective Eulumdat files: (**a**) TT LED ϕ = 4340 lm, P = 33 W; (**b**) PSV PISA SDK T8 OP ϕ = 2970 lm, P = 72 W; (**c**) PSV PISA SDK T8 PAR ϕ = 3132 lm, P = 72 W.

3. Genetic Algorithm

Genetic algorithms (GAs) are capable of reaching the vicinity of optimal or suboptimal solutions. There are several reasons why outputs of GAs are rarely optimums. The main are random algorithm behavior and difficulties to overcome suboptimal solutions. Therefore, the designer's corrections are required after getting an output in order to get closer to the global or local optimum. A great advantage of GAs is that there is no need to describe the functional dependency of the genotype on the phenotype [27]. While getting the resulting parameters from input strings is quite easy (for example, by calculations or experiments), the opposite procedure is much more difficult or impossible due to several possible solutions or the complexity of the task. This is also visible in the presented paper, where getting illuminance and uniformity values from known luminaire positions was relatively easy to calculate, but evaluating luminaire positions from known illuminance and uniformity values was significantly more complex.

Genetic algorithms are designed to search for solutions in a search space, iteratively making improvements in generated solutions until an optimal solution is found. This makes them suitable for the problem at hand to generate the new placement solutions of luminaires in the model room. A slight disadvantage of GAs is that the generating of solutions must be fine-tuned in order not to end up at a suboptimal solution.

3.1. Grid of the Possible Solutions

A grid of the possible luminaire positions was defined. Such grid actually represents raster ceilings widely used in office buildings. The grid also respected the size of the used luminaires, meaning that they could never overlap.

The possible luminaire positions were numbered and ordered as a string. The presence of the luminaire at a given position was represented by a Boolean value 1 (True) and absence was represented by a Boolean value 0 (False). This approach enabled the optimization of both the luminaire layout and the luminaire count.

3.2. Recombination

A simple one-point crossover based on a random selection of a string splitting point can result in an offspring being completely different from its parents. Consider, for example, the extreme case where both parents are solutions with luminaires concentrated into opposite halves of the luminaire grid, i.e., the first parent's string consists of ones the whole first half and zeros the second half; the latter parent's string consists of zeros the first half and of ones the second half. If the splitting point is then chosen to be the middle of the parents' strings, one offspring solution will have only zeros in the string, the other only ones, i.e., one offspring solution will not contain any luminaires whatsoever, and the other will contain luminaires in all possible positions. Both offspring solutions will not be similar even in terms of the resulting illuminance, and the uniformity compared to their parents. Even though the parents might fit the criteria for the model room's lighting system, both their offspring solutions are unusable solutions.

In order to ensure that such pathological behavior does not occur, one-point crossover has been modified in such a way that not the whole parts of parents' strings were switched. Instead, the luminaire positions following the crossover point up to a limit were switched to create the offspring strings. This way, only a few luminaires, at most, are added or removed from the solution after the crossover is applied, as seen in Figure 4. In Figure 4, luminaire positions are only switched. As the outcome of the presented custom one-point crossover depends on the order of the two input solutions, two offspring solutions are created, switching the order of the input parent solutions.

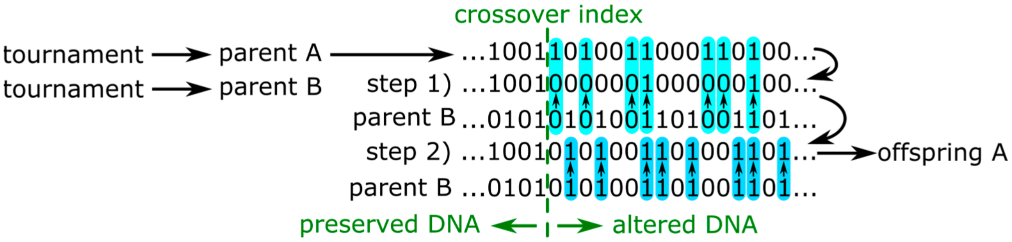


Figure 4. Custom crossover, switching luminaires in DNA string after the generated crossover index (dashed green vertical line) between two parents. Parents A and B are obtained by two tournaments. Obtaining offspring A: parent A's DNA is used and all 1's (luminaires) replaced after the crossover index with what is in parent B at these positions (step 1). Then, parent's B DNA is used to add all 1's (luminaires) from the crossover index on to the altered DNA (step 2).

3.3. Mutation

As in the crossover, a similar issue occurs in mutations. A simple inversion of an element of the solution's string affects the luminaire count, i.e., a luminaire would be added or removed. Better results in terms of output solution convergence toward the optimum and time efficiency were achieved by implementing a permutation that changes the luminaire layout only, i.e., luminaire count does not change, only the string elements are switched. In the final form of the algorithm, up to three permutations were allowed per solution and generation.

3.4. Objective Function

A simple objective function was defined for solution optimization. In the case of our project, GA was minimizing the outcome of the following equations:

$$f\left(S, \overline{E}_m, U_0\right) = \begin{cases} \max(S_1, S_2, \ldots, S_N) + 1, & if\ \overset{=}{\overline{E}}_m < \overset{=}{\overline{E}}_{mT} \quad or \quad U_0 < U_{0T}, \\ S + (1-\alpha) \cdot \frac{\overset{=}{\overline{E}}_m}{\overset{=}{\overline{E}}_{mT}} + \alpha \cdot \frac{U_0}{U_{0T}}, & if\ \overset{=}{\overline{E}}_m < \overset{=}{\overline{E}}_{mT} \quad or \quad U_0 < U_{0T}, \end{cases} \tag{1}$$

where

- $\overset{=}{\overline{E}}_m$ and U_0 are the calculated values of average illuminance and lighting uniformity;
- $\overset{=}{\overline{E}}_{mT}$ and U_{0T} are the target calculated values of average illuminance and lighting uniformity;
- α is the preference factor;
- S denotes the sum of used luminaries (sum of 1s in the string);
- N is the population size.

The objective function was set up to include and optimize the luminaire count, being a dominant factor. By doing so, solutions were evaluated from the point of view of power consumption, preferring solutions containing fewer luminaires if the average illuminance and lighting uniformity requirements are still met.

The implemented preference factor α is a number between 0 and 1 that corresponds to the designer's wish to prefer average illuminance over lighting uniformity or vice versa with the defined weight. The authors tried several settings of the factor, but the results differed just slightly. Only values of α close to bounds 0 or 1 had a significant influence on the outcome. The presented results were always optimized with a balanced preference, i.e., α was set to 0.5.

The raster ceiling design allowed for a limited number of positions of luminaires to be placed, which enabled us to pre-calculate illuminance values of the reference plane in calculation points for single luminaires in all available positions. Calculating the reference plane illumination values for a lighting system design (multiple luminaires) was then simply achieved by summing up the pre-calculated illuminance values for the used luminaires.

Since these calculations were used for each solution's evaluation, the GA running time was considerably shortened.

3.5. GA Settings

All settings of the used GA are summarized in Table 1. Parents for the offspring solutions are chosen using tournament 1 of 4, i.e., from the whole generation, four solutions are chosen and the one with the highest fitness is picked. This procedure is carried out twice (two parents are needed), creating two offspring solutions using custom recombination (Section 3.2) with a probability of 90%, as mentioned in Table 1. Furthermore, mutation is applied to both offspring solutions with a probability of 1%, followed by the permutation of one, two, or three element pairs of the solutions' strings with probabilities defined in Table 1.

Table 1. Genetic algorithm settings.

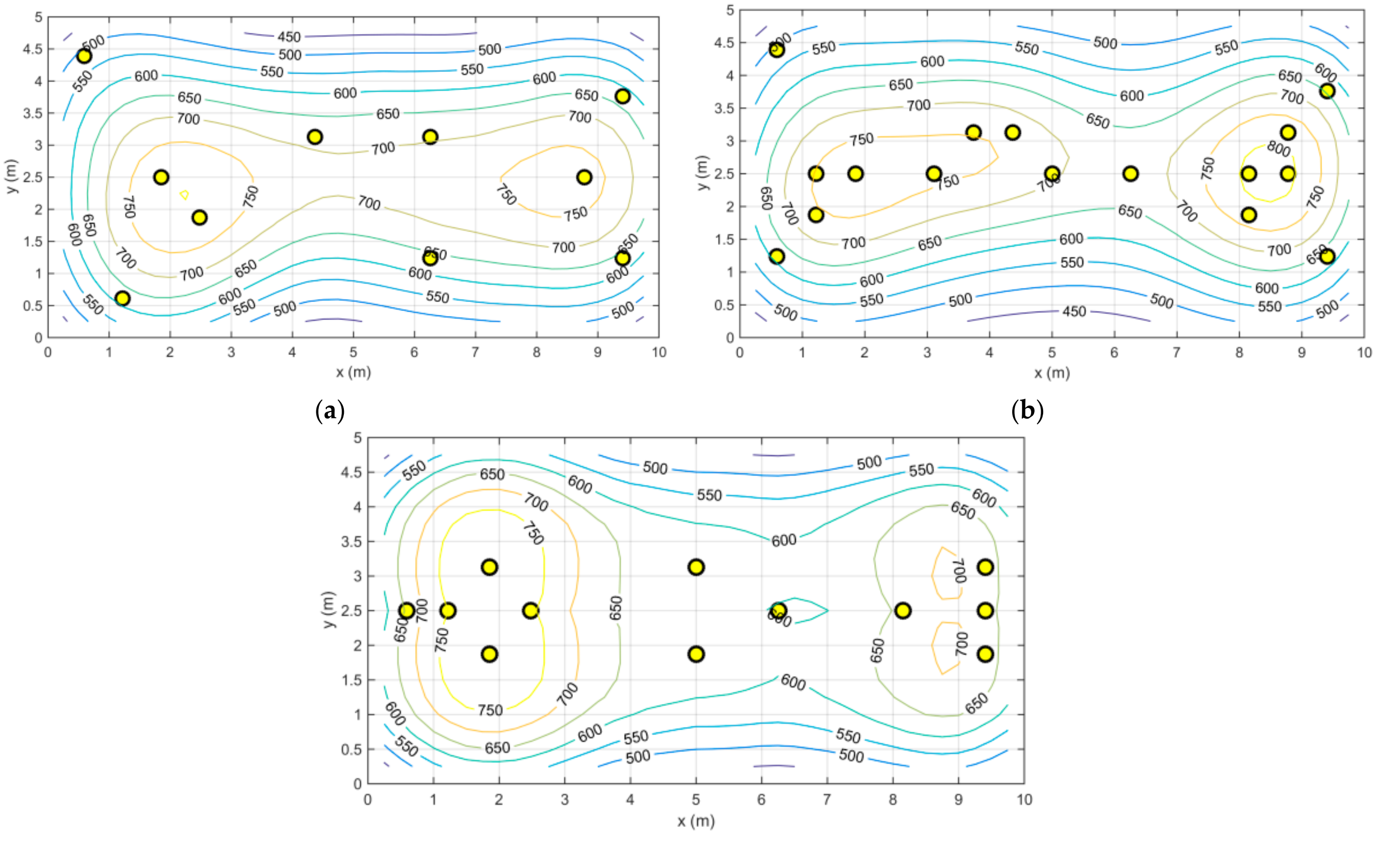
First Population	Random logic vectors
Termination Cond.	Defined count of generations
Count of Gen.	500
Population Size	500
Parent Selection	Tournament 1 of 4
Survival Selection	Elitism
Recombination Type	One point, random count of 1
Recombination Prob.	90%
Mutation Method	Bit inversion and permutation
Mutation Prob.	1%
Permutation Prob.	10% (perm. ≥ 1) 0.349% (perm. ≥ 2) 0.004% (perm. = 3)

Elitism was used in the final algorithm, picking the best solution of a generation and preserving it in its original form for the following generation. Then, another copy of this best solution was passed to the following generation undergoing a mutation. This approach was supposed to improve the algorithm convergence; however, no noticeable advantages were observed.

4. Results and Analysis

The sample outputs of the implemented GA are presented in this section. The output solutions were always a little different for a given luminaire type after each run of the GA. This phenomenon was discussed above and is caused by the initial random string generation of the first generation, as well as by random mutations, permutations, crossovers, and tournaments (Section 3). The output solutions are always close to the optimum but almost never the exact optimum. The designer is always supposed to choose a suitable solution after multiple runs of the GA and adjust the luminaire positions if needed.

Although the outputs using a given luminaire type were different, the basic patterns were always similar. Examples of GA outputs using luminaires TT LED, PSV PISA SDK T8 OP, and PSV PISA SDK T8 PAR are shown in Figure 5a, 5b, and 5c, respectively, and Table 2. All results are presented in their raw form as they were generated by GA. The E_m and U_0 values presented in Table 2 were confirmed and UGR_L values calculated by recreating the GA outputs (luminaire placements) in software DIALux [12]. All presented GA outputs complied with the UGR_L requirement across the whole calculation plane, i.e., there were no restrictions for an occupant to work at any desired place in the model room with view directions toward the north, south, west, or east wall.



(**a**) (**b**) (**c**)

Figure 5. Top–down view of the model room with black–yellow circles representing luminaire positions in the ceiling plane and isolux diagram of the reference plane (initial illuminance values): (**a**) TT LED; (**b**) PSV PISA SDK T8 OP; (**c**) PSV PISA SDK T8 PAR.

Table 2. GA output examples, where Φ_{total} is the total luminous flux and P_{total} the total power consumption of all installed luminaires of the given output solution.

Luminaire Type	**Count**	$\bar{E}_m(lx)$	$U_0(-)$	$\Phi_{total}(lm)$	$P_{total}(W)$
TT LED	10	504	0.68	43400	330
PSV PISA SDK T8 OP	16	505	0.67	47520	1152
PSV PISA SDK T8 PAR	12	500	0.70	37584	864

As expected, the luminaire count was dependent on the output luminous flux of the given luminaire type and its luminous intensity curve shape (Figure 3). Looking at Table 2, the total output luminous flux of all placed luminaires of type PSV PISA SDK T8 PAR was 37584 lm, while in the case of luminaire type PSV PISA SDK T8 OP, it was 47520 lm, making the first mentioned type more efficient for the chosen model room. Both luminaires use the same light source with slightly different luminaire light output ratios [28], but their luminous intensity curves are different, as seen in Figure 3b,c. Looking further at the total power consumption of the used luminaire types, the solution using TT LED luminaires compared to PSV PISA SDK T8 OP luminaires required 3.5 times less electrical power for the lighting system to meet the set requirements.

Luminaire Placement Dependency on Luminous Intensity Curve Shape

The luminaire positions of the GA solutions are dependent on their luminous intensity curves. Luminaires with narrower luminous intensity curves, i.e., luminaires emitting luminous flux predominantly in the vertical direction, were placed close to the corners of the model room to ensure the required uniformity of the illuminated reference plane. This effect can be seen in the case of luminaires TT LED and PSV PISA SDK T8 OP (Figure 5a,b). There are four luminaires in very similar positions near the corners in both cases. On the other hand, luminaires of type PSV PISA SDK T8 PAR have a wide luminous intensity curve in a direction parallel to the model room's y-axis, which enables GA to place them closer to the x-axis (longitudinal) of the model room (Figure 5c).

Luminaires PSV PISA SDK T8 OP and PSV PISA SDK T8 PAR are fitted with exactly the same quantity of the same light sources. However, the resulting total count of placed luminaires in each run of GA differed in both cases needing at least four luminaires less for solutions using luminaires PSV PISA SDK T8 PAR (Table 2), even though in this case, the total luminous flux of all placed luminaires was 20% lower. It appears that the luminaire PSV PISA SDK T8 PAR is more appropriate for the chosen model room. By comparing the illuminance levels of the reference plane of both solutions, it is evident that the illuminance pattern of the luminaire PSV PISA SDK T8 PAR solution is more spread to the sides of the model room along the x-axis, which leads to a better uniformity value even though less luminaires are used (Figure 5c,b).

Luminous intensity curves of luminaire TT LED and PSV PISA SDK T8 OP are quite similar, as obvious in Figure 3. Therefore, the resulting total flux of both solutions is also similar (within 10%, see Table 2). Less total luminous flux is needed in the case of TT LED, since its intensity curve is a little bit more widened between angles ±30° and the requested uniformity is met with greater spacing of the luminaires compared to the PSV PISA SDK T8 OP output solution. The overall low count of TT LED luminaires is given by its higher nominal luminous flux, higher by about 40% than the nominal flux of the other presented luminaires.

In comparison with the regular design made by software DIALux, which is usually used by designers, the differences between a regular and irregular grid of luminaire placement can be significant. For the solution using luminaires TT LED, the regular grid cannot be less than 3 × 4 luminaires in total. In this case, it is not possible to reduce the luminaire by the designer while keeping a regular grid. Consequently, by allowing for an irregular grid, one can advise up to 16% energy savings.

For the PSV PISA SDK T8 OP luminaires, the original DIALux design suggested a regular grid of 4 × 5 luminaires to fulfill the predefined design parameters. In this case, the energy savings with GAs against original DIALux are 20%. By manual adjustment by the designer and further modifications of the luminaire grid, the number of luminaires can be reduced to 16, which is the same number that was calculated for an irregular grid. However, this requires additional interventions that are not always performed in normal practice.

The last variant using the PSV PISA SDK T8 PAR luminaire type shows even greater energy savings of 25% (GAs against original DIALux). For this situation, the DIALux software suggests a 4 × 4 luminaire grid, which cannot be made smaller by regular luminaire placement.

If we approach the design purely from the engineer's/designer's point of view, the preliminary calculation using the flux method by hand requires a luminous flux of $\Phi_{total} = 71$ klm for a room of the given dimensions that meets the predefined parameters. Against the hand design the GA solution allows for up to the 34% to 50% energy savings.

Allowing for an asymmetrical solution of luminaire placement gives us more energy reduction against the regular symmetrical solutions. However, finding a functional solution with an irregular grid of luminaires is very demanding even for experts in terms of observing the parameters, especially meeting the illuminance uniformity, and thus a GA approach is preferred.

5. Conclusions

An optimization method of luminaire placement was presented in this paper with a few sample results (Figure 5 and Table 2). The optimization was based on a genetic algorithm. The presented method settings made it possible to place luminaires in a specified irregular luminaire pattern, which is the main difference from various previous research. The irregular luminaire pattern generated by the genetic algorithm may be very attractive for architects, because the irregular pattern could be influenced by the configuration of the genetic algorithm to achieve different architectonic solutions. Additionally, the possibility of irregular placement can provide additional energy savings compared to layouts with a regular grid.

By using our GA implementation, it is possible to generate single-luminaire-type placements for different luminaire types which can be compared and the most effective solution chosen. Some luminaires may fit specific room requirements more appropriately than other, as shown in the output examples. Investment costs and power consumption can be very different even for designs using different luminaires with the same build-in light sources. Common computer design programs can generate rectangular grid-based luminaire patterns. Although this might be the preferred layout for most lighting systems due to its simplicity, it is very often inefficient in comparison to randomly placed luminaires, for example by the genetic algorithm presented in this paper. The designed GA can also be configured to generate symmetrical solutions, which might be visually more preferable.

Author Contributions: Conceptualization, Z.P. and R.B.; methodology, M.B. (Michal Brejcha); software, R.B.; validation, M.B. (Michal Brejcha), Z.P. and R.B.; formal analysis, R.B.; investigation, R.B.; resources, M.B. (Michal Brejcha); data curation, R.B.; writing—original draft preparation, R.B.; writing—review and editing, Z.P.; visualization, Z.P.; supervision, M.B. (Marek Balsky); project administration, M.B. (Marek Balsky); funding acquisition, M.B. (Marek Balsky). All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Czech Technical University in Prague, grant number SGS23/167/OHK3/3T/13.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Dataset available on request from the authors.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Baniya, R.R.; Tetri, E.; Halonen, L. A study of preferred illuminance and correlated color temperature for LED office lighting. *Light Eng.* **2015**, *23*, 39.
2. Hwang, T.; Kim, J.T. Effects of indoor lighting on occupants' visual comfort and eye health in a green building. *Indoor Built Environ.* **2011**, *20*, 75–90. [CrossRef]
3. Vanus, J.; Martinek, R.; Nedoma, J.; Fajkus, M.; Cvejn, D.; Valicek, P.; Novak, T. Utilization of the LMS Algorithm to Filter the Predicted Course by Means of Neural Networks for Monitoring the Occupancy of Rooms in an Intelligent Administrative Building. *IFAC-PapersOnLine* **2018**, *51*, 378–383. [CrossRef]
4. Van Duijnhoven, J.; Aarts, M.P.J.; Kort, H.S.M. Personal lighting conditions of office workers: An exploratory field study. *Lighting Res. Technol.* **2021**, *53*, 285–310. [CrossRef]
5. *EN 12464-1*; Light and lighting—Lighting of Work Places: Part 1: Indoor Work Places. European Committee for Standardization (CEN): Brussels, Belgium, 2022.
6. Montoya, F.G.; Peña-García, A.; Juaidi, A.; Manzano-Agugliaro, F. Indoor lighting techniques: An overview of evolution and new trends for energy saving. *Energy Build.* **2017**, *140*, 50–60. [CrossRef]
7. Wang, Z.; Tan, Y.K. Illumination control of LED systems based on neural network model and energy optimization algorithm. *Energy Build.* **2013**, *62*, 514–521. [CrossRef]
8. Mendes, L.A.; Freire, R.Z.; dos Santos Coelho, L.; Moraes, A.S. Minimizing computational cost and energy demand of building lighting systems: A real time experiment using a modified competition over resources algorithm. *Energy Build.* **2017**, *139*, 108–123. [CrossRef]
9. Mohseni, S.; Gholami, R.; Zarei, N.; Zadeh, A.R. Competition over resources: A new optimization algorithm based on animals behavioral ecology. In Proceedings of the 2014 International Conference on Intelligent Networking and Collaborative Systems, Salerno, Italy, 10–12 September 2014. [CrossRef]

10. Mandal, P.; Dey, D.; Roy, B. Optimization of luminaire layout to achieve a visually comfortable and energy-efficient indoor general lighting scheme by particle swarm optimization. *Leukos* **2019**, *17*, 91–106. [CrossRef]
11. Kennedy, J.; Eberhart, R. Particle swarm optimization. In Proceedings of the ICNN'95—International Conference on Neural Networks, Perth, WA, Australia, 27 November–1 December 1995; Volume 4, pp. 1942–1948. [CrossRef]
12. DIALux Software. Available online: https://www.dialux.com/ (accessed on 24 July 2024).
13. Qu, J.-Q.; Xu, Q.-L.; Sun, K.-X. Optimization of Indoor Luminaire Layout for General Lighting Scheme Using Improved Particle Swarm Optimization. *Energies* **2022**, *15*, 1482. [CrossRef]
14. Mattoni, B.; Gori, P.; Bisegna, F. A step towards the optimization of the indoor luminous environment by genetic algorithms. *Indoor Built Environ.* **2015**, *26*, 590–607. [CrossRef]
15. Madias, E.N.D.; Kontaxis, P.A.; Topalis, F.V. Application of multi-objective genetic algorithms to interior lighting optimization. *Energy Build.* **2016**, *125*, 66–74. [CrossRef]
16. Deb, K.; Pratap, A.; Agarwal, S.; Meyarivan, T. A fast and elitist multi-objective genetic algorithm: NSGA-II. *IEEE Trans. Evol. Comput.* **2002**, *6*, 182–197. [CrossRef]
17. Watini, U.; Yusuf, M.I.; Kurniato, R. Application of Genetic Algorithm for Economical Optimization of School Room Lighting According to SNI 03-6575-2001. *J. Tek. Elektro* **2022**, *14*, 60–66. [CrossRef]
18. Plebe, A.; Pavone, M. Multi-objective Genetic Algorithm for Interior Lighting Design. In Proceedings of the International Workshop on Machine Learning, Optimization, and Big Data, Volterra, Italy, 14–17 September 2017; pp. 222–233. [CrossRef]
19. Prado-Gonzales, D.; Ruesta-Garcia, P.; Rotta-Saavedra, P. Method Based on Genetic Algorithms for the Optimization of the Number of Luminaires in Apartment Buildings According to Peruvian Regulations and the Total Power Consumed. In Proceedings of the IEEE XXX International Conference on Electronics, Electrical Engineering and Computing, Lima, Peru, 2–4 November 2023. [CrossRef]
20. Corcione, M.; Fontana, L. Optimal Design of Outdoor Lighting Systems by Genetic Algorithms. *Light Res. Technol.* **2003**, *35*, 261–280. [CrossRef]
21. Ferentinos, K.P.; Albright, L.D. Optimal Design of Plant Lighting System by Genetic Algorithms. *Eng. Appl. Artif. Intell.* **2005**, *18*, 473–484. [CrossRef]
22. Shintabella, R.; Abdullah, A.G.; Hakim, D.L. Application of Genetic Algorithm in Optimizing Redesign of Street Lighting. In Proceedings of the 5th Annual Applies Science and Engineering Conference, Online, 21–22 April 2020. [CrossRef]
23. *CSN EN 36 0011-1*; Lighting Measurement in Areas: Part 1: General Regulations. Czech Standardization Agency: Prague, Czech Republic, 2014.
24. *CIE 97: 2005 Guide on The Maintenance of Indoor Electric Lighting Systems*, 2nd ed.; International Commission on Illumination: Vienna, Austria, 2005.
25. BuildingDesign Software. Available online: https://www.astrasw.cz/lighting (accessed on 24 July 2024).
26. Novak, T.; Valicek, P.; Mainus, P.; Becak, P.; Latal, J.; Martinek, R. Possibilities of Software Goniophotometer usage for LED Luminaires Luminous Intensity Distribution Curves Modelling—Case Study. In Proceedings of the 22nd International Scientific Conference on Electric Power Engineering, Kouty and Desnou, Czech Republic, 8–10 June 2022. [CrossRef]
27. Fogel, D.B. *Evolutionary Computation: Toward a New Philosophy of Machine Intelligence*, 3rd ed.; John Wiley and Sons: Hoboken, NJ, USA, 2006.
28. Habel, J.; Zak, P. Energy performance of lighting systems. *Prz. Elektrotech.* **2011**, *87*, 20–24.