

OPTIMIZATION OF ENERGY EFFICIENT LUMINAIRE LAYOUT DESIGN IN WORKSPACES

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ABSTRACT

There are several methods used in lighting design. The realistic methods have been developed by computer graphics such as DIALux, VELUX, Radiance etc. These methods use the engineering computational tools and architectural rendering together. Although lighting designers would design an accurate lighting system which provides desired illuminance levels through computer graphics, it is still necessary to propose optimal and alternative solutions by maximizing comfort conditions and minimizing energy consumption by practical techniques. Researchers continue developing and using different methods to find optimum solutions for visual comfort of occupants; to get uniform illuminance, to prevent glare, to control daylight and artificial light by considering the energy performance of buildings. Thus, the purpose of this study is to estimate the most accurate locations of light sources according to visual comfort conditions by applying an optimization model through Excel Spreadsheet and Evolver. It is considered that such a new proposed optimization model would be beneficial, less time consuming, effective and dynamic, if integrated in the early design phase. The optimization model is employed for an office by obtaining photometric data of an energy efficient luminaire from the simulation tool s DIALux. Its performance is also tested by the DIALux models to explore its applicability and validity.

Keywords: optimization, luminaire layout, energy efficiency, workspace

INTRODUCTION

Lighting design of a workspace is a complicated task that includes multiple criteria based on many physical and psychological aspects. Occupants spend a large part of their time at their workspaces. So, they need to work in comfortable and healthy environments [1]. Appropriate lighting conserves eye health, increases the work performance, and provides visual comfort [2]. Besides, a properly-designed lighting system helps to balance the lighting, heating and cooling loads by decreasing the energy consumption. Energy consumption of workspaces is taken into consideration because a significant amount of buildings' energy consumption is due to artificial lighting [3]. The planning of artificial lighting systems involves consideration of the metrics of lighting quality and quantity [1]. The basic metric for the quantity of lighting design is illuminance. Illuminance depends on the features of visual tasks, room surfaces, photometric data of the lighting sources (the lamp/and the luminaire) and their location [4]. It is necessary to distribute illuminance uniformly in the indoor environment, since non-uniform light distribution causes glare. One metric to determine the uniformity is the light distribution curve of the luminaire which is unique for each of them [5]. The light distribution curve of the luminaire consist of information about the power of the light source on different angles of x, y and z plane. Illuminance is calculated according to this information. The other metric is the location of luminaires. It is necessary to determine the correct position of the luminaire to avoid unbalanced illuminance distribution while selecting the accurate light source.

Lighting designers select and decide on the types of lamps and luminaires according to these metrics. Simulations are the assisting tools in their decision process. They present many design alternatives. However, they do not have the power to show the most accurate or optimum position of light sources according to candle power distributions [6]. Simulation tools are helpful in proposing lighting design decisions in general; however, they are not the decision maker to propose the best solution. Potential solutions/designers' assumptions for better performance cannot be confirmed or rejected through effective search mechanism.

Lighting design alternatives may present some bright or dark regions in the horizontal plane due to the overlap or gap of the candle power distribution curve. Non-uniform light distribution results in glare when one region in the interior space is brighter than the general brightness [5]. Thus, it is necessary to determine the correct position of the lighting fixture. The effective and dynamic search mechanism to find optimum solutions should be integrated in the lighting design process. It is worth to study optimization techniques in this sense.

Although optimization techniques have been widely used in the field of engineering [7], [8], [9] i.e. chemical, industrial, and mechanical engineering etc., they are not a well-known technique in the field of architecture. It is necessary to make a contribution to literature in this sense.

Lighting designers make decisions about the locations of luminaires by estimating illuminance levels through simulations. However, by employing optimization techniques, combinations of different design (layout, lamp and luminaire selection) alternatives would be tested together in one model to obtain the most accurate locations of light sources according to defined comfort and efficiency constraints. That optimum solution provides the optimal illuminance on the work plane and of the luminous power.

Thus, it is necessary to find the optimal solution for lighting design which may be achieved by maximizing comfort conditions, and minimizing the energy-consumption of the lighting scheme.

METHOD

The main objective of this study is to estimate the most accurate locations of light sources according to visual comfort conditions by proposing a mathematical model. The other objective is to validate the model by a simulation tool; DIALux [10]. In this section, the procedure of the research is introduced to achieve these objectives.

Firstly, a problem case has been selected to build the phases and to practice the mathematical model. The room was intended to represent a small cellular office and measured 5.80 m in the x-direction and 4.20m in the y-direction. The ceiling height was 3.3 m. The measurement plane was 0.80 m above the floor. Calculation points were placed at least 0.5m away from the surface of the walls. There were 81 calculation points by giving spaces 0.6 m between them in the x-direction and 0.4 m in the y-direction (Figure 1). Locations of light source were constructed out based on ceiling tiles of size 600x600 mm. Recessed mounted modular luminaires have been selected according to architectural qualities of the space. There were 54 different points to estimate location of light source (Figure 1). Location points of luminaires and calculation points are not aligned to capture the distribution angles of the luminaire extensively and to obtain dissimilar illuminance levels at each calculation points. Non-aligned location grids were used in previous studies [6,13].

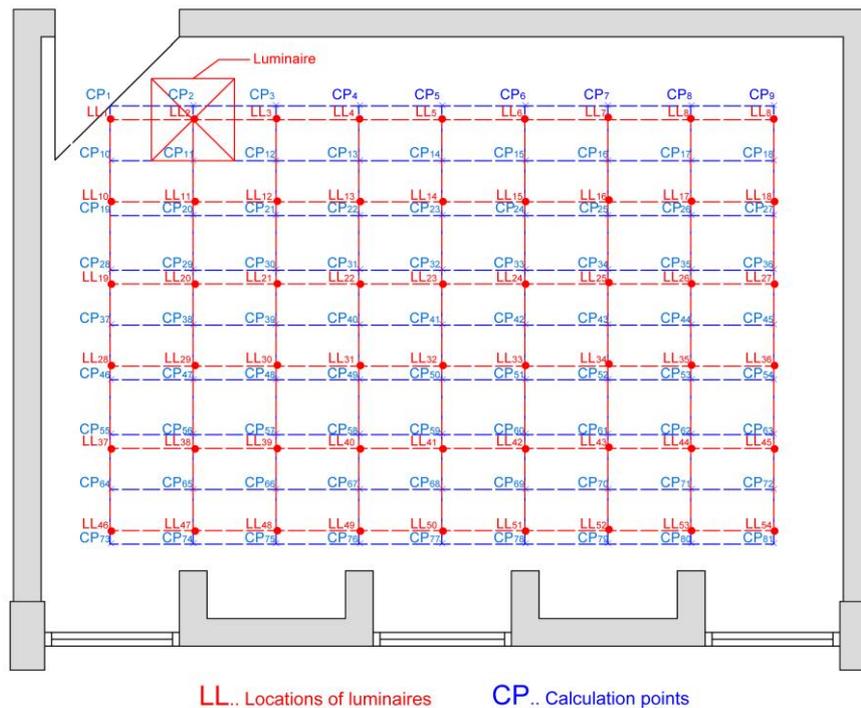


Figure 1. Location points of luminaire in model case and calculation points.

Spreadsheet Steps

A mathematical model was created and developed for this optimization problem. An Excel spreadsheet was used as a base of the model because of its simpler and transparent approach to modelling. This spreadsheet included 5 steps.

Step 1. The first step of this model was the construction of the locations of points on the working plane and ceiling. Their co-ordinates on x, y and z plane were entered to the model according to point of 0, 0, 0 on left and bottom side of the room. C and gamma angles between calculation points of model case and location points of light source were calculated. C angle is the resulting angle on horizontal plane. Likely, Gamma angle is the resulting angle on vertical plane.

Step2. Luminous intensity of luminaires which varies according to C and Gamma angles composes photometric data. DIALux provided such data to be imported in this model.

Step 3. This step included composing information about total luminous flux of selected luminaire, data about room dimensions (height, width and length), and reflectance of wall, ceiling and floor. This type of data is interchangeable easily to create different lighting scenarios for the same room. For this reference room reflectance of wall, ceiling and floor are 0.50, 0.70 and 0.20 respectively.

Step 4. This step is the calculation process. The model calculates total illuminance of the points (the summation of reflected and direct illuminance), which varies according to the light source location scenario. The point method has been used to calculate illuminance at calculation points on the working plane.

Step 5. Based on recommendations about working places, the average illuminance level is 300-500 lx. According to the illuminance level at calculation points, the average illuminance level on the working plane was calculated by the division of total illuminance by the number of points. On the other hand, the main goal of the study, after having desired light intensity, is to provide uniform illuminance on the working plane. The mean relative deviation (MRD)

was used for this problem to calculate relative deviation of illuminance level at the point from average level of whole space [11].

The validation process involves the formulation of a linear regression line to compare the simulation and mathematical model illuminance levels at each calculation points for two luminaire locations and observe the strength of their relationship. Coefficient of determination (R^2), root mean square error (RMSE), normalized root mean square error (NRMSE) and coefficient of variation (CV) are calculated for two luminaire locations. A scatter diagram is developed to figure out whether the mathematical model fits the simulation model or not.

Problem Formulation

The design variables of the study were the positions of selected luminaires on the x plane. The luminaire is recessed mounted type (4 x 14 W – 64.6W) which is 600 x 600 mm in dimension. The problem involves two scenarios; one including two luminaires and the other including three luminaires. There are a total of 54 different positions to locate the luminaires and 81 horizontal calculation points which are on the working plane. The illuminance levels resulting from these two scenarios were analysed to define their optimal positions.

The primary objective of the research is to get illuminance uniformity (1) on the working plane with two constraints (2, 3). I_{avg} is the average illuminance level of working place. I_i is the illuminance level at one calculation point, and I_m is the mean of illuminance level at all these points.

$$\text{Minimize: } MRD = \frac{\sum_{i=1}^N |I_i - I_m|}{NI} \quad (1) \text{ [11]. Subject to: } I_{avg} \geq 300 \quad (2), I_{avg} \leq 500 \quad (3)$$

To solve this optimization problem, Evolver 6 was used as optimizer in this study. Evolver applies genetic algorithm-based optimization techniques to find optimal solutions for standard linear and non-linear problems. This program is used as an add-in to Microsoft Excel spreadsheet program to solve problems set up in spreadsheets (Evolver 6) [12].

RESULTS

Before the optimization process, the mathematical model was evaluated due to DIALux findings. Considering the photometric data, the luminous intensity of luminaire is 4264 lm. Model was performed at two different specific luminaire locations. The illuminance level at calculation points on the work plane was calculated for one luminaire at LL₂₃ and LL₃₂. The luminaire was located at similar positions in the DIALux model. Outputs of the mathematical model were higher than the ones in the simulation. To compare them quantitatively, R^2 was almost 88 % at for all results, showing the high accuracy of the mathematical model. This meant that knowing the illuminance at points by the mathematical model gives an almost 88% chance of predicting their values on the simulation model (Figure 2). To observe differences between outputs and model results at two luminaire locations, RMSE was 42.82 and 43.09 respectively. NRMSE and CV were 0.14 and 0.26.

After the validation step, the optimizer tool employs to solve this optimization problem while using the same luminaires. According to results of the first scenario, which was to identify the best position of these two luminaires meeting recommended horizontal illuminance requirements, the average illuminance (E_{avg}) is 306.71 lx and uniformity (MRD) is 0.31. Locations of this optimization problem were simulated in DIALux and their average illuminance is 224 lx and E_{min}/E_{avg} is 0.28(Figure 3). The second scenario, which was to identify the best position of three luminaires, resulted in better uniformity with higher illuminance level. E_{avg} is 363.87 lx and uniformity (MRD) is 0.13. By conducting the

simulation for the second scenario, E_{avg} increased to 283 lx and better uniformity with E_{min}/E_m is 0.436 was obtained (Figure 3)

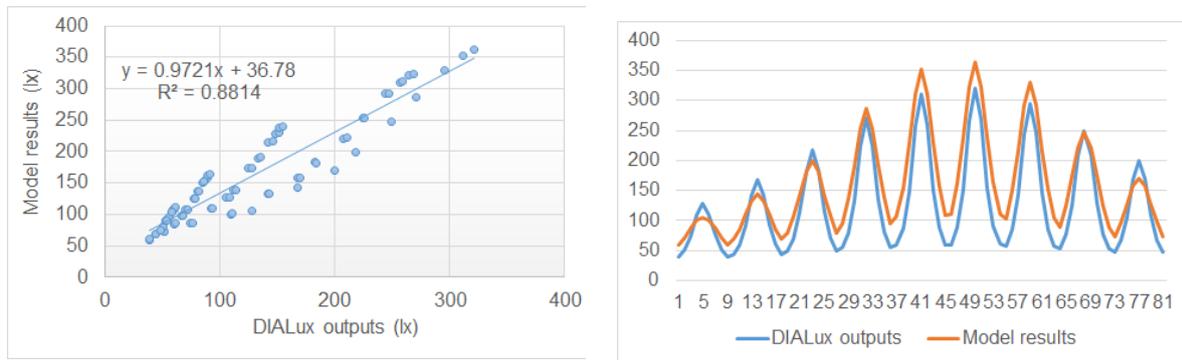


Figure 2. Scatter diagram and comparison of illuminance distribution at calculation points.

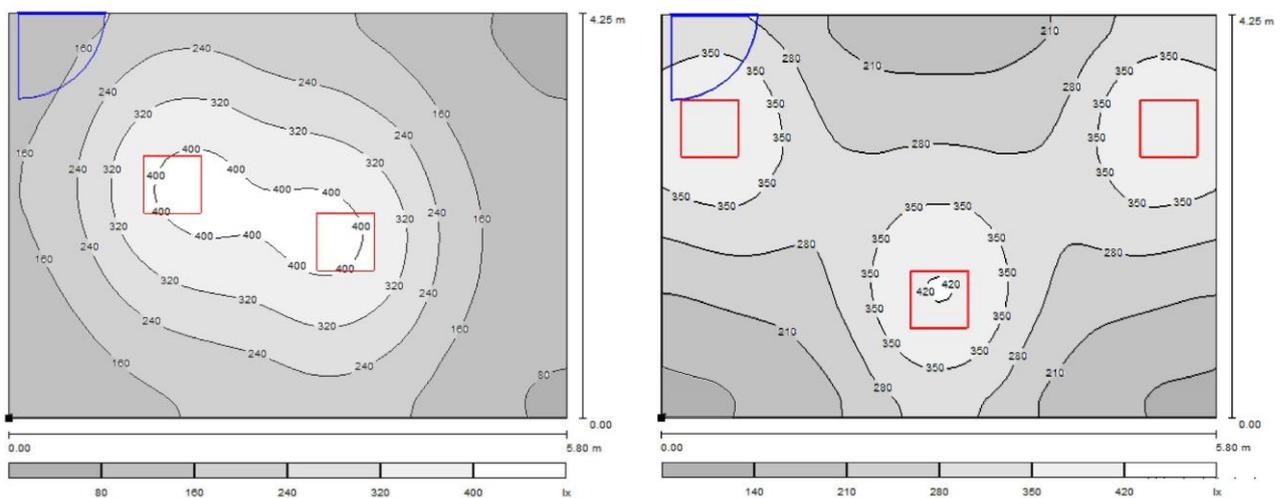


Figure 3. Illuminance distribution and location of luminaires in the first scenario and second scenario.

DISCUSSION AND CONCLUSION

This study proposes a mathematical model to find the optimum position for luminaires by providing visual comfort requirements. Two different scenarios for a selected test case were conducted to obtain sufficient illuminance levels by using different numbers of luminaires. At the same time, by minimizing the differences between illuminance of calculation points and the average illuminance level, maximum uniformity of light distribution was tried to achieve.

This proposed method is a new and alternative approach of applying a mathematical model with an optimization process in architectural research. It is considered that this model would be beneficial, less time consuming, effective and dynamic if integrated in the early design phase. In an earlier study [14], researchers tried to find optimum positions for two different luminaires in two identified and smaller/limited areas. Apart from that study, the optimization study focused on finding the optimum positions of two luminaires in Scenario 1 and three luminaires in Scenario 2 in one identified and determinate area. Thus, their mutual impact while calculating the illuminance and uniformity is integrated in the optimization model. The optimization model in this case performs well in locating and determining the luminaire positions. It presents a high accuracy with the outputs of the DIALux model.

As this is an ongoing research, this model can be developed by integrating different objectives to achieve best positions for luminaires by regarding energy efficiency in further steps. For instance, adding constraints about distances between luminaires would be a good solution to reduce glare on walls and darker spaces between luminaires. Since the simulation, bright spots on walls were observed in Scenario 2 (with three luminaires). To add the distance constraint in the optimization problem, this inefficient and unbalanced light distribution will be eliminated. Also, the problem could be developed by integrating different types of luminaires with different luminous flux and distribution. Luminance efficacy (lumens per watt) would be a good objective for this problem to consider energy consumption. Such objectives would be helpful to estimate positions and numbers of different types of luminaire in designing energy efficient luminaire layout.

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