Andrzej PAWLAK[1], Krzysztof ZAREMBA[2]

Central Institute for Labour Protection - National Research Institute (1), Bialystok University of Technology (2)

A Monte-Carlo simulation of an indirect lighting installation using light emitting diodes (LEDs)

***Abstract**. For selected lighting installations, we compare results of calculations made using our custom-design software relying on a Monte-Carlo method with results obtained using two internationally-available lighting installation design software packages. We examine differences in average illumination and lighting uniformity.*

Streszczenie**. Dla wybranych instalacji oświetleniowych porównano wyniki symulacji komputerowych wykonanych z użyciem autorskiego oprogramowania wykorzystującym metodę Monte Carlo oraz otrzymanych za pomocą dwóch międzynarodowych programów oświetleniowych. Na tej podstawie dokonano analizy w różnicach średniej wartości natężenia oświetlenia i równomierności oświetlenia. (**Symulacja oświetlenia pośredniego z diodami świecącymi (LED) z wykorzystaniem metody Monte Carlo).

Keywords: Monte-Carlo method, indirect lighting, lighting installation design software, light emitting diodes (LEDs).
Słowa kluczowe: metoda Monte Carlo, oświetlenie pośrednie, programy oświetleniowe, diody świecące (LED).

Introduction

The research conducted up to date by the authors of this paper indicate that computer-aided simulations of indirect lighting installations made using two most popular international software packages available in Poland, i.e., Dialux (www.dial.de) and Relux (www.relux.biz) exhibit substantial differences [1]. In terms of meeting the requirements of the standard PN-EN 12464-1:2012 - „Light and lighting. Illumination of work places. Part 1. Indoor work places", the same lighting installation can be evaluated as good or bad, depending on which of the aforementioned software package was used for simulations. Since details about calculation algorithms in both software packages are unknown, the authors decided to design our custom-made software relying on a commonly used Monte-Carlo method for lighting calculations [2, 3, 4]. The results obtained for selected lighting installations were then compared with results obtained with the other two software packages.

Monte-Carlo method for calculation of illumination

In the Monte-Carlo method, the isometric solid of the light source is modelled with elementary light rays emitted in a random fashion from the surface of the light source. In case of a Lambertian light source in the polar coordinate system (see Fig. 1), in order to guarantee the same luminous flux attributed to each light ray, angles α and β need to be calculated based on the following formulae:

$$\alpha = \arcsin\sqrt{\xi_\alpha} \qquad \beta = 2\pi\cdot\xi_\beta \tag{1}$$

where: ξ_α, ξ_β - random numbers in the range $\langle 0,1 \rangle$.

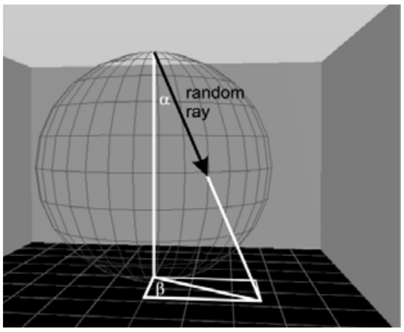

Fig. 1. Designation of angles α and β of the emission direction for a random light ray from a Lambertian light source

Next, the path of the selected light ray is examined, evaluating whether this light ray reaches the target working area (in Fig. 1 – the floor), or any other surface in the room. In the latter case, a new emission direction is randomly selected for a reflected light ray. Assuming uniform scattering of luminous flux on reflective surfaces, the new random emission direction is calculated using the method presented before (1). However, it is necessary to account for the fact that the luminous flux attributed to this light ray decreases proportionally to the reflection coefficient ρ_j for j^{th} reflective surface. This calculation process is repeated until the light ray reaches the target working area or when the associated luminous flux decreases below a pre-defined threshold value. The conducted studies indicate that even for very high value of the reflection coefficient ρ_j for examined room surfaces, it is sufficient to account for at most 10 subsequent reflections. Having examined the path of all test light rays, the illumination E_{MC} can be calculated based on the Monte-Carlo method using the following formula:

$$E_{MC} = \frac{\sum_{i=1}^{n_{xy}}\left(\prod_{j=1}^{10}\rho_j\right)}{n_T}\cdot\frac{\Phi_z}{\Delta x\cdot\Delta y} \tag{2}$$

where: n_{xy} - number of test light rays reaching the target work surface with dimensions Δx, Δy, n_T - the total number of test light rays, Φ_z - luminous flux emitted by the light source.

Lighting installation with a single LED emitting light downwards

The comparison of calculation results obtained using the presented Monte-Carlo method and using commonly available lighting calculation software packages was started with a simple lighting installation with a single LED emitting light downwards. In such a lighting installation, it is theoretically possible to calculate the distribution of the direct illumination. The LED emitting light downwards was placed at the height of 3 meters over the center of the room with the following dimensions (4 x 5 x 3.2 meters; width x length x height). The reflection coefficient for the ceiling was assumed to be 0.9. Then the illumination distribution for the floor was calculated, which was assumed to have the reflection coefficient of zero (0). The floor surface was further subdivided into 11 by 9 elements, with the elemental calculation area of 0.455 m × 0.444 m. The adopted division was driven by the desire to have elemental calculation areas as close to 0.5 m × 0.5 m as possible. Moreover, in both directions the light source surface was divided into an odd number of elements in such a way that the center of the light source matched the middle of the elemental calculation area located in the middle of the examined room. With such room geometry, systematic calculation errors associated with averaging effects range from -0.17% for the room edges to 0.74% for the center. For the examined lighting installation it is therefore possible to directly compare results obtained using the Monte-Carlo method and using the available lighting calculation software packages.

Next, we examined calculation results obtained for various values of the reflection coefficient ρ_w for walls. If assumed to be equal to zero (0), together with the assumed zero reflection coefficient for the floor, the setup allows to establish the direct illumination distribution. In the next step, the reflection coefficient for the walls was increased to 0.8.

The calculation results presented below exhibit the results obtained using the Monte-Carlo method, and the number n_T of randomly selected light rays was equal to 10^7. With such a large number of examined light rays, error distribution associated with the application of the Monte-Carlo method in the developed software were smaller than ±3% and were primarily limited to edges of the examined room.

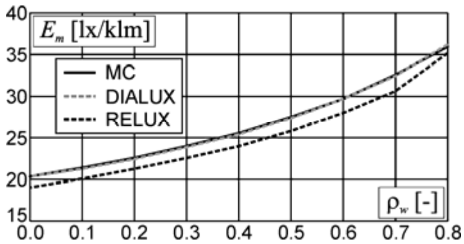

Fig. 2. Calculation results for the average illumination E_m for a lighting installation with single LED emitting light downwards, for various reflection coefficient ρ_w for walls

The two primary normative values were then compared, i.e., the average illumination E_m (see Fig. 2) and lighting uniformity E_{min}/E_m (see Fig. 3). The average illumination E_m values obtained using the custom-designed software corresponded practically to the values obtained using Dialux software package. The observed differences are bounded by ±0.7%, and can be considered negligible. The results obtained in the Relux software package are always smaller by approximately 6.5%, including calculations for the direct illumination.

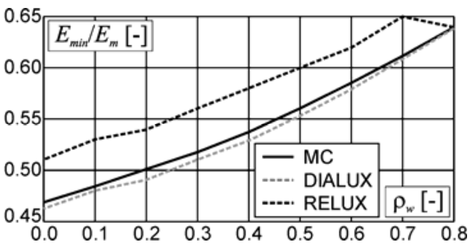

Fig. 3. Calculation results for lighting uniformity E_{min}/E_m for a lighting installation with single LED emitting light downwards, for various reflection coefficient ρ_w for walls

Similar differences were observed for lighting uniformity (see Fig. 3). The results obtained using the custom-designed software relying on the Monte-Carlo method exhibit the maximum difference of 0.01 when compared with results obtained with the Dialux software package. The results obtained using the Relux software package are always greater than results obtained using two other packages, with the maximum error as high as 0.05. Moreover, results obtained using the Relux software package feature an interesting dip in the curve for the reflection coefficient ρ_w of walls equal or greater than 0.8.

In the examined lighting installation, the minimum illumination was observed at the corners of the room. The system was symmetric, allowing for additional control of the obtained results. The results obtained using the Dialux software package were symmetric. The results obtained using the Relux software package were symmetric only when the size of the calculation grid was decreased substantially. In the results obtained using the custom-designed software, the maximum observed difference between room edges was equal to ±1%. For calculation purposes, we used the average illumination value for four elemental calculation areas located in the corners of the room.

Lighting installation with a single LED emitting light upwards

The second examined lighting installation had the geometry identical to the first installation, with the only difference being that the LED diode emits light upwards, towards the ceiling. This particular installation does not feature any direct lighting element, therefore impendent from the calculation method, the results obtained using any available software packages should be the same. The values of the average illumination E_m obtained with the custom-signed software relying on the Monte-Carlo method again coincided closely with the values obtained using the Dialux software package (see Fig. 4). The results obtained using the Relux software package featured larger discrepancies, with the maximum difference as large as 9.5%.

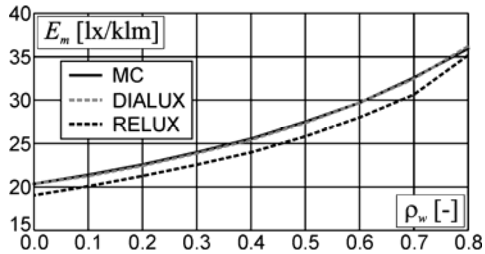

Fig. 4. Calculation results for the average illumination E_m for a lighting installation with single LED emitting light upwards, for various reflection coefficient ρ_w for walls

In the case of lighting uniformity E_{min}/E_m, the results obtained using the Monte-Carlo method featured the maximum difference of 0.01 when compared with the results obtained using the Dialux software package (see Fig. 5), while results obtained using the Relux software package featured the maximum difference of 0.07 and exhibit non-uniform characteristics, clearly indicating problems with the calculation algorithm.

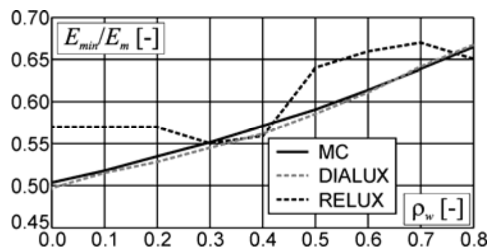

Fig. 5. Calculation results for lighting uniformity E_{min}/E_m for a lighting installation with single LED emitting light upwards, for various reflection coefficient ρ_w for walls

Indirect lighting installation with multiple LEDs

The last examined lighting installation featured a single row of 100 LEDs emitting light upwards, located in a symmetric fashion in the room. A diaphragm of a width d_p

(see Fig. 6) was placed in a symmetric fashion under the row of LEDs. In this study, we examined the effect of the width of the diaphragm on the lighting parameters of the examined lighting installation. The concluded calculations featured the diaphragm width vary between 0 (lack of diaphragm) to 40 cm, with the step of 5 cm. All diaphragm surfaces were assumed to have the reflection coefficient of 0.9 and the reflection coefficient for the walls was assumed to be equal to 0.7.

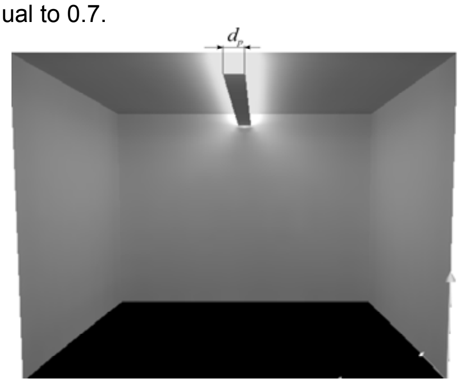

Fig. 6. Visualization of the examined indirect lighting installation with LED, equipped with diaphragm of 20 cm, as generated in the Dialux software package.

In the case of a lighting installation with multiple identical LEDs placed in a symmetric fashion, the first step in the Monte-Carlo method features selection of the LED element to emit the test ray. The next steps of the method are identical to the method used to examine the lighting installations with a single LED.

The calculations results for this simple indirect lighting installation with multiple LEDs featured much larger variations when compared with the lighting installation with a single LED. Along with the increase in the diaphragm width d_p, the average illumination E_m using the custom-design software decreased in a monotonic fashion (see Fig. 7). The results obtained using the Dialux software package feature differences varying between -2.4% and +2.0%, while the results with the highest variability were obtained using the Relux software package, ranging from -9.3% to +4.8%. The observed large difference in the case of diaphragm-free installation (see Fig. 7, d_p = 0 cm) is very hard to comprehend.

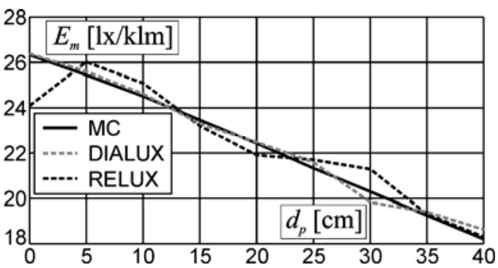

Fig. 7. Calculation results for the average illumination E_m for an indirect lighting installation with multiple LEDs emitting light upwards, for varying diaphragm width d_p.

The lighting uniformity is influenced by not only the average illumination E_m, but also its minimum value E_{min}. Along with the increase in the diaphragm width d_p, the minimum illumination value E_{min} (in the corners of the room) decreased in a fashion different than the average illumination E_m. That is the reason why the lighting uniformity E_{min}/E_m first grows and then decreases (see Fig. 8). In this case, the smoothest curve was again obtained using the custom-designed software. The results obtained using the Dialux software package featured difference ranging from -0.025 to +0.028. Results with the highest variation were again obtained using the Relux software package, where almost all calculated values were larger (by at most 0.053) than the values obtained using the custom-designed software.

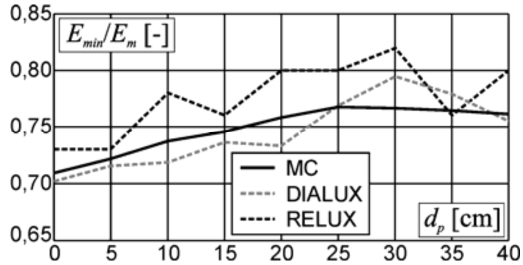

Fig. 8. Calculation results for lighting uniformity E_{min}/E_m for an indirect lighting installation with multiple LEDs emitting light upwards, for varying diaphragm width d_p

Conclusions

In this study, we compared calculation results for selected lighting installations obtained using the custom-designed software relying on the Monte-Carlo method and two international lighting software packages, i.e., Dialux and Relux. The conducted simulations indicate that the results obtained using the custom-designed software and Dialux software package coincide very closely, especially in the case of a lighting installation with a single light source. The results obtained using the Relux software package featured substantial variations, both in the average illumination as well as lighting uniformity. Results obtained for more complex lighting installations with multiple LEDs featured more accentuated variations, especially in terms of lighting uniformity.

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Authors: *Andrzej Pawlak, M.Sc. (E.Eng.), Central Institute for Labour Protection - National Research Institute, ul. Czerniakowska 16, 00-701 Warszawa, Poland; phone 48 22 623-46-75, fax 48 22 623-3695, anpaw@ciop.pl*

Krzysztof Zaremba, D.Sc. (E.Eng), Bialystok University of Technology, Faculty of Electrical Engineering, ul. Wiejska 45D, 15-351 Białystok, Poland; k.zaremba@pb.edu.pl