Modeling and the Use of Simulation Methods for the Design of Lighting Systems

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Abstract: The article deals with designing internal artificial lighting as part of the work on the environment, which is subject to certain rules, derived from the nature of lighting. Good lighting exerts an impact on visual comfort – which contributes to overall psychological well-being, and indirectly also to the quality and productivity of performance, to reliability, and to visual performance – and which must be maintained, especially in long-term operations and in adverse conditions, to ensure quality of work and safety. One of the most frequently raised requirements for project design nowadays is speed; therefore a successful project cannot be done without good application software. The result is hundreds of drawings and various other outputs, which, without good software, cannot be handled within a short period of time. Modeling and simulation technologies are tools to streamline the presentation and assess the risks for the implementation.

Keywords: working environment; light; lighting microclimate; simulation

1 Introduction

The lighting of workplaces puts on light-technical solution the following requirements:

1) sufficient horizontal and vertical lighting value for a particular type of the work performed,
2) appropriate distribution of brightness in the area,
3) suppressing the creation of glare and protecting against it,
4) satisfactory psychological impact of the colour of the light and colour of the administration premises,
5) appropriate colour change in the environment,
6) stabile lighting,
7) reasonable uniformity,
8) suitable orientation of the impact of light on the desktop. [1]

In compliance with all the quantitative and qualitative parameters of illumination, we must design a lighting system based on the principles of maximum performance. By selecting a new generation of lamps, i.e. long life and high efficiency ones, we can economise on electricity. Lighting systems with streamlined operation, regulation and management of lighting may also significantly contribute to energy savings. [10]

2 Methodological Procedure of Light-Technical Design

The project of a lighting system is a complex and laborious task that requires not only technical knowledge, but also knowledge of architecture, production, and the physiology of vision. The role of the designer is not only to select the type of solution; this task is often complex and might be of a research character, leading to the development and manufacture of the lighting systems testing, analysis, and finding the optimum lighting conditions of the workplace and the area as a whole.

To develop a quality project of the lighting system, we should have construction in hand, technological and health technical drawings of the lighting the object, and we should also be familiar with the technology or the purpose of the premises. In addition to the quantitative and qualitative parameters of the workplace, the lighting area or the surrounding area should maintain well-observed and fault-free lighting system functions, the possibility of comfortable handling the luminaries and lighting efficiency. [12] The design of the lighting system is divided into light-technical, electric, and budget sections. The light-technical part of the interior lighting consists basically of two main parts: technical reports and the drawing section.

The technical report includes:

- description of the area to be lighted,
- demands on visual activity according to the category and work class,
- lighting values,
- qualitative lighting indicators (brightness distribution, direction of light, flare, lighting, durability, colour and colour submissions, etc.),
- draft operation and maintenance of the lighting system, choice of lamps, etc.,
- computational methods employed and specific calculations of lighting,
- colour adjustment of the immediate surroundings,
- assistant addressing, security, and replacement of emergency lighting,
- proposal for economic recovery.

The drawing section contains:

- footprints and cuts of lighting facilities,
- prescribed value of lighting on certain points and value quality parameters,
- electrical distribution, involvement and control of lighting systems,
- deployment of lamps, their specifications and type of the light resources,
- isoline diagrams and marking control points by which the agent glare was assessed.

In addition to the documents belonging to the base set of the project documentation, it is also necessary to produce drawings of the various elements of installation illumination, drawings of complete assembly nodes, drawings of connections and typical control components and drawings needed for the implementation of the proposed lighting.

3 Modelling of Light-Technical Parameters

In the past, there existed three basic types of light-technical models:

- calculation (without taking into account the actual dimensions, by means of tables),
- accurate (in models in the 1:1 scale),
- mock-ups that generate a display similar to visual perception of the lighting system designed.

Currently, a different approach is applied in the light-technical modeling, which is based on computer visualization of the spatial scenes of the lighting system designed. With computer visualization, whose goal is photo-realistic imagining, the propagation of light in space is often described in detail and simulated. Modern visualization programs can reproduce brightness, colour and surface structures of complex three-dimensional spaces in a quite realistic way, since the calculations include inter-reflection of light between various surfaces in space and quite a number of optical effects arising in daylight, in artificial or joint lighting. Simulation methods are based on classical optical, thermodynamic, or light-technical models of the spread of radiation [14].

3.1 Simulation Methods

There exist two basic methods employed in computer simulations of the light environment, namely the Monte Carlo method, which applies the technology of tracing the light rays (ray tracing is the name used for the follow-up of rays; one also uses the term of "ray casting" - sending the light ray when a ray of light comes from the light source), and the radiation method (also radiosity). From a physical point of view, both of the methods are similar; the difference lies in algorithmization.

3.1.1 The Monte Carlo Simulation Method and the Calculation of Direct and Indirect Lighting

We have initially considered only spectacular reflections of light in a manner of subsequently applied probability calculations and other components of illumination. The stochastic (probability) method of light calculation, often referred to as the Monte Carlo method, is conveniently applied in furnished rooms with surfaces that have different optical properties. In general, this method is one of the operational methods of research used for the simulation of technical, economic, and social situations [8]. There exists a number of variants of this method.

In general, these methods employ a large number of randomly cast light rays or energy bearing particles. Their movement in the area is subject to physical laws and is monitored. A completely accurate calculation can only be made if the path of each photon can be followed, which, of course, is impractical for a number of reasons. However, if a sufficient number of rays (particles), e.g. 50 million, is accidentally sent out, the calculation of the lighting capacity will also correspond to high demands for accuracy. If the propagation of light is monitored from the source to the environment, one usually talks about the method of monitoring the particles (Fig. 1).

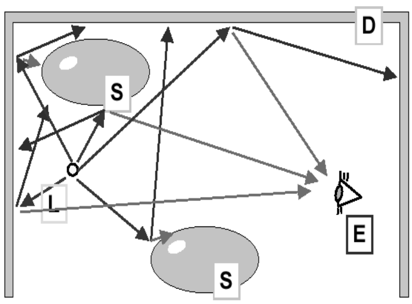

Figure 1

Behaviour of light rays in the Monte Carlo simulation method of ray casting

D - Wall space S - lighting operator, L - light source, E - Observer

In terms of computer graphics, ray tracing in the direction of the light source to the observer's eye or camera lens is onerous. Quantity rays are "lost" before the eye reaches the observer. [12] It is therefore a frequently used method of tracing rays (Fig. 2) when the monitor path of light rays is in the direction of the observer to the light source.

In this way, the algorithms take into account the particles that are mostly involved in the lighting of the scene as seen by observers. In this case, lighting of a place is proportionately dependent on the number of light particles which hit it, and on the density of luminous flux carried by each of these particles.

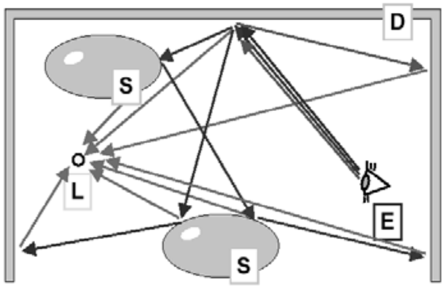

Figure 2

Behaviour of light rays in the Monte Carlo simulation method of ray tracing

D - space walls S – object being lighted, L - light source, E - observer

In the method of back tracing the rays, a virtual ray of light is cast in the direction of the observer through each of the imagining points on the display screen (pixels), and its intersection is tested along with all the objects in that space. Rays are cast in the direction of the light source to determine whether a visible place is overshadowed by an object. If the object surface is shiny, it mirrors the reflection of the primary ray. If the surface is transparent, rays are created, representing light reflection and refraction according to optical properties of the transparent material. If the surface is non-transparent, rays are generated (often more than 100) mimicking the light reflection from the surface concerned.

In the case that the location of the intersection of the primary ray with a certain object in space is illuminated by any of the light sources (or a mirror reflection of a certain material), its lighting or brightness is calculated. The term of direct lighting is employed in computer graphics for this lighting in contrast to the overall lighting containing the contribution of the reflected light, which in this field of science is called global lighting.

The nearest intersection is determined for each secondary ray, and the process is repeated until the ray leaves the space, or until the amount of light (or brightness) represented by the imaginary ray falls below the selected value. In some of the algorithms, the ray is monitored until it is returned in the eye of the virtual observer, or only a specified number of reflections is considered. In this way, the geometry of the space is modelled simultaneously with its synthetic (colour) imagining. Maps of direct and overall lighting are stored in the computer memory, which are further processed to achieve a smooth transition of shadows, in order to describe optical phenomena, among other things. In principle, the ray tracing technique solves the following integral equation (1) for the energy balance of each nearly the same surfaces in space [8].

$$L_r(\theta_r,\varphi_r)=L_e(\theta_r,\varphi_r)+\iint L_i(\theta_i,\varphi_i).\rho_{bd}(\theta_i,\varphi_i,\theta_r,\varphi_r).|\cos\theta_i|.\sin\theta_i.d\theta_i.d\varphi_i \quad (1)$$

where: θ - polar angle as measured from the surface at normal levels,

φ - azimuthal angle of the surface at normal levels,

$L_e(\theta_r,\varphi_r)$ - its own radiation [$W.sr^{-1}.m^{-2}$]

$L_r(\theta_r,\varphi_r)$ - the total radiation [$W.sr^{-1}.m^{-2}$]

$L_i(\theta_i,\varphi_i)$ - incident radiation [$W.sr^{-1}.m^{-2}$]

$\rho_{bd}(\theta_i,\varphi_i,\theta_r,\varphi_r)$ - two-way function of the reflectivity distribution [sr^1].

3.1.2 Radiation Methods and Radiation Equation

Although the ray tracing algorithm produces perfect results in modeling the mirror reflectivity and undispersional refractional transparency, the algorithm has a shortcoming; specifically, it does not take into account the physical laws of some of the important visual effects, for example shade staining by the influence of the reflection of light from another object. It is due to the fact that ray tracing only monitors the final number of rays emanating from the observer's eye. The radiation method is attempts to remove this shortcoming. [2]

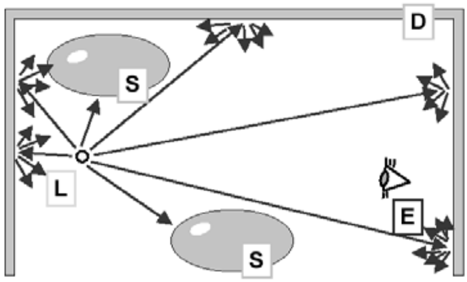

Figure 3
Behaviour of light rays in the radiation method
D - space walls S – object lighted, L - light source, E - observer

The radiation method may be seen as a certain generalization of the method of monitoring the ray. This method assumes that all the surfaces are ideal diffuse primary or secondary light sources (Fig. 3) or a combination of the given types of sources. The advantage of this method in terms of visualization and algorithm development is that the surfaces lighting is calculated independently from the direction of view on the simulated scene [9].

The radiation method is based on the principles of the spread of light energy and the energy balance. Unlike conventional rendering algorithms, this method first determines all the mutual light interactions in space from various independent perspectives. Then one or more perspectives are calculated by defining a visible surface and interpolation shading.

In the algorithm of shading, the light sources have always been considered independently from the surfaces that are lighted. In contrast to the above, the radiation method allows any surface to emit light, i.e., all the light sources are modeled naturally as an active surface. Consider the distribution of the environment as a final number of *n* discrete surfaces (patches), each of which has its final respective size and emits and reflects light evenly across its surface. The scene then consists of surfaces acting both as light sources and reflective surfaces creating a closed system. If we consider each of the surfaces as an opaque Lambertian diffuse emitter and reflector, then the following equation applies for the surface due to energy conservation (2):

$$B_i = E_i + p_i \sum_{1 \le j \le n} B_j F_{j-i} \frac{A_j}{A_i} \tag{2}$$

where:

B_i, B_j - intensity of radiation areas *i* and *j* measured in units of energy per unit of surface (W.m^{-2})

Ei - power of light radiated from the surface *i* and has the same dimension as radiation,

p_i - the reflection coefficient (reflectivity) of the surface *i* and is dimensionless,

F_{j-i} - dimensionless configuration factor (form-factor), which specifies the energy leaving the surface *i* and the energy incoming to the surface and taking into account the shape, relative orientation of both of the surfaces, as well as the presence of any areas that could create an obstacle. The configuration factor takes its values from the interval <0,1>, while for the fully covered surfaces it takes the value of 0,

A_i, A_j - surface levels *i* and *j*.

Equation (2) shows that the energy leaving the unit part of the surface is the sum total of both light emitted and reflected. The reflected light is calculated as a product of the reflection coefficient and the sum total of the incident light. On the contrary, the incident light is the sum total of the light leaving the whole surface changed in the part of the light which reaches the receiving unit content of the receiving surface. B_jF_{j-i} is the amount of light leaving the unit content of the surface *Ai* area and incident on the entire surface of A_i. It is therefore necessary to multiply the equation by the ratio of *Ai*/*Ai* for the determination of light leaving the entire surface *Ai* and incident on the entire surface A_i. [4]. A simple relationship is valid between the configuration factors in the diffuse medium:

$$A_i F_{i-j} = A_j F_{j-i} \tag{3}$$

By simplifying equation (2) using equation (3) we obtain the equation:

$$B_i = E_i + p_i \sum_{1 \le j \le n} B_j F_{i-j} \tag{4}$$

By subsequent treatment we get the equation in the form:

$$B_i - p_i \sum_{1 \le j \le n} B_j F_{i-j} = E_i \tag{5}$$

Interaction of light between the surfaces may be expressed in the matrix form [9]:

$$\begin{bmatrix} 1-p_1F_{1-1} & -p_1F_{1-2} & \ldots & -p_1F_{1-n} \\ -p_2F_{2-1} & 1-p_2F_{2-2} & \ldots & -p_2F_{2-n} \\ . & . & \ldots & . \\ -p_nF_{n-1} & -p_nF_{n-2} & \ldots & 1-p_nF_{n-n} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ . \\ B_n \end{bmatrix} = \begin{bmatrix} E_1 \\ E_2 \\ . \\ E_n \end{bmatrix} \tag{6}$$

Note that the contribution of a part of the surface to its own reflected energy (which may be hollow, concave) must be taken into account. Thus, in general, each term on the diagonal need not necessarily equal to 1. Equation (6) must be solved for each group of wavelengths of light in the model, since *pi* and *Ei* depend on the wavelength. Form factors are independent of wavelength and are solely a function of geometry; therefore, they need not be recalculated, if the surface reflectivity or illumination changes. Equation (6) may be solved by employing the Gauss-Seidel method obtaining radiation for each area. In order for radiological methods to become partial, one had to start calculating the form factors for absorbed surfaces.

3.2 Form-Factor Calculation

To find the form factor, we must find the fractional contribution that a single patch makes upon another patch. This term is purely geometric, related only to the size, orientation, distance, and visibility between the two patches. The basic geometry for the form factor calculation is shown in Fig. 4.

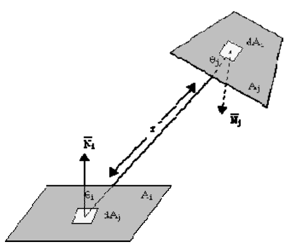

Figure 4
Form-factor geometry

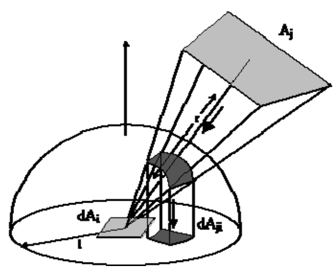

Figure 5
Projected area onto the hemisphere

If we look at Fig. 5, we see that the area A is related to the projected area, A_p, by A_p=A.cos_q, and the contribution of the projected area A_p is related to the solid angle by (7)

$$\omega = \frac{A_p}{r^2} \tag{7}$$

The expression relating the contribution from one infinitesimal area to another is:

$$F_{dA_i - dA_j} = \frac{\cos\phi_i . \cos\phi_j . dA_j}{\pi . r^2} \tag{8}$$

The contribution from the infinitesimal area to the finite area is found by integrating over the receiving area:

$$F_{dA_i - dA_j} = \int_{A_j} \frac{\cos\phi_i . \cos\phi_j . dA_j}{\pi . r^2} \tag{9}$$

And from a finite patch to another finite patch, we take the area average of the previous equation:

$$F_{dA_i - dA_j} = \frac{1}{A_i} \iint_{A_i A_j} \frac{\cos\phi_i . \cos\phi_j . dA_j}{\pi . r^2} \tag{10}$$

There are several different methods for evaluating this integral. The contour integral is found by transforming the double integral by Stoke's Theorem [6]:

$$F_{dA_i - dA_j} = \frac{1}{A_i} \iint_{A_i A_j} \left(\ln(r) dx_i . dy_j + \ln(r) dy_i . dx_j + \ln(r) dz_i dz_j \right) \tag{11}$$

where ln(r) is the intensity for a particular wavelength. One limitation of this algorithm is that it does not take into account the visibility between one patch and another; another limitation is that it is extremely expensive computationally. Baum [1] also uses an analytical approach to find form factors. They integrate the outer integral numerically, while integrating the inner integral analytically by converting it into a contour integral. They then calculate the contour integral by piecewise summation.

$$F_{dA_j A_i} = \frac{1}{2.\pi} \sum_{g \in G_i} N_j . \Gamma_g \tag{12}$$

where:

G_i - is the set of edges in surface *i*,

N_j - is the surface normal for the differential surface *j*,

Γ_g - is a vector with magnitude equal to the angle gamma illustrated.

4 Outputs from the Proposal of Lighting System

Currently, the development of computer graphics software products exist to enable a comprehensive design and calculation of the parameters of lighting systems, which would reflect light effects that arise in artificial and day lighting. In consequence, there are on the market several light-technical programs with different purposes and uses. For the purposes of this paper, as to the possibilities utilisation simulations of light - technical parameters are presented the outputs created in the software DIALux 4.7. The above simulation programme offers the following options of the selected lighting system and various options for the presentation of results as chart values, isofotic lines (Fig. 6), light maps (colour scale) (Fig. 7), false colour rendering, summary tables of lighting or brightness, a three-dimensional model lighting, economic evaluation of brightness of the lighting project in terms of power consumption, visualization of sunshine, and so on. [11]

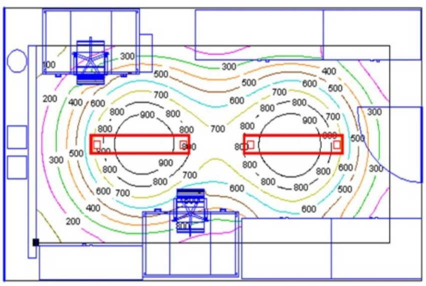

Figure 6
Isofotic lines

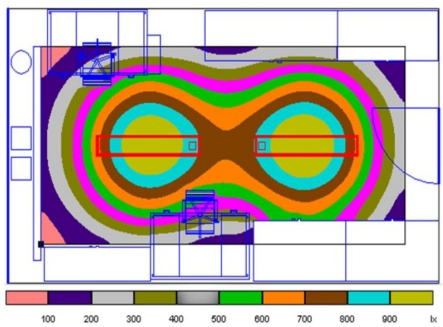

Figure 7
Light maps (colour scale)

Conclusion

In terms of the quantity of information, a person registers 80% to 95% of all the information visually in the work. The primary role in creating the work environment is to ensure optimal conditions of vision and ensure a safe working environment. Visibility must therefore be seen as a precondition for the implementation of high quality, safe, and reliable work operations. It is necessary to pay close attention to this issue. When dealing with light-technical projects, the visualization of lighting parameters is a useful tool by using programmes realistically displaying the lighting parameters.

Despite numerous possibilities that the current software tools offer, in some cases there is a difference between the modelled and actual light-technical parameters. One of the reasons affecting the result of the computer output may be the inadequate definition of certain inputs (the colour shades and quality of the room's surfaces, the lightning effects on the scattering characteristics of light sources, etc.). However, these differences do not affect the overall relevance of computer outputs and may be virtually eliminated by qualified estimation.

Acknowledgement

This contribution was elaborated within the project KEGA No 3/7426/09 “Physical factors of environment - valuation and assessment" and KEGA No 3/7422/09 Creating of research conditions for preparation of modern university text book "Ecodesign in Mechanical engineering".

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