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Application of Radiosity Simulation Methods for Lighting Researches

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1. Introduction

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

- sufficient horizontal and vertical lighting value for a particular type of the work performed,
- appropriate distribution of brightness in the area,
- suppressing the creation of glare and protecting against it,
- satisfactory psychological impact of the colour of the light and colour of the administration premises,
- appropriate colour change in the environment,
- stabile lighting,
- reasonable uniformity,
- suitable orientation of the impact of light on the desktop. (Smola, 2003)

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. (Silion & Puech 1994)

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. (Smola et al., 2005) 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.

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.

The technical report includes:

- description of the illuminating area,
- demands on visual activity, and thus the determination of the category and work class,
- lighting values,
- qualitative lighting indicators (brightness distribution, direction of light, glare, lighting, durability, color and color submissions, etc.),
- draft operation and maintenance of the lighting system, choice of lamps, etc.,
- computational methods employed and specific calculations of lighting,
- color adjustment 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 certain value quality parameters,
- electrical distribution, involvement and control of lighting systems,
- deployment 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, drawing 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 (Budak et al., 2006):

- 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 imaging, 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 (Tilinger & Madár, 2008).

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 specular 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 (Rybár, et al. 2001). 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.

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 (Smola et al., 2005). It is therefore a frequently used method of tracing rays 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.

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 (Rybár, et al. 2001).

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

where:

θ - polar angle 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 (as is the area's primary source of radiation) [$\text{W} \cdot \text{sr}^{-1} \cdot \text{m}^{-2}$],

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

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

$\rho_{bd}(\theta_i, \varphi_i, \theta_r, \varphi_r)$ - 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 refractive 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 attempts to remove this shortcoming. (Baum & Winget, 1990).

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 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 (Sillion & Puech, 1989).

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):

$$B_i = E_i + p_i \sum_{1 \leq j \leq n} B_j F_{j-i} \frac{A_j}{A_i} \quad (2)$$

where:

- B_i, B_j - intensity of radiation areas i and j measured in units of energy per unit of surface (W.m^{-2})
- E_i - 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. $B_j F_{j-i}$ is the amount of light leaving the unit content of the surface A_i area and incident on the entire surface of A_i . It is therefore necessary to multiply the equation by the ratio of A_i/A_i for the determination of light leaving the entire surface A_i and incident on the entire surface A_i . (Cohen, Greenberg, 1985). A simple relationship is valid between the configuration factors in the diffuse medium:

$$A_i F_{i-j} = A_j F_{j-i} \quad (3)$$

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

$$B_i = E_i + p_i \sum_{1 \leq j \leq n} B_j F_{i-j} \quad (4)$$

By subsequent treatment we get the equation in the form:

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

Interaction of light between the surfaces may be expressed in the matrix form (Sillion & Puech, 1989):

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

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 p_i and E_i 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.

Cohen and Greenberg proposed the following method for the distribution of intensities of emission peaks. If the point is internal to the surface, he is assigned the average radiation from the radiation spots, which are divided on this point. If the point on the edge, then find the nearest internal point v . Top marginal radiation when averaged with BV should be the average radiation spots, sharing the top edge.

Consider the flats Fig.1. Radiation to the internal edge e $B_e = (B_1 + B_2 + B_3 + B_4) / 4$. Radiation to the top edge b is calculated by finding the nearest internal peak e taking into account that b is the shared areas and a second Therefore, the calculation will use the following definition $(B_b + B_e) / 2 = (B_1 + B_2) / 2$.

The solution to get B_b is $B_b = B_1 + B_2 - B_e$. Internal peak closest to the peak and the peak is also e a very top and the first part of the area Therefore, since $(B + B_e) / 2 = B_1$, we get for $B = 2B_1 - B_e$. Radiation for other peaks are calculated similarly (Cohen et al., 1985).

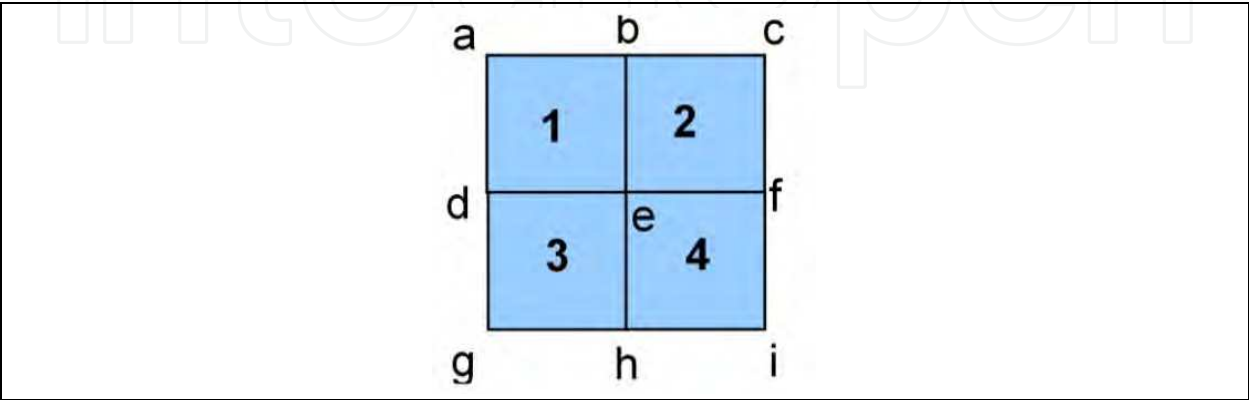


Fig. 1. Elementary surface area of the object

The first radiation method was used by Goral (Goral et al., 1984), who used the contour integrals to calculate the form factor for the environment without absorbed convex surfaces.

In the picture (see Figure 2) you can see the effects of "color bleeding", caused by diffuse reflection between adjacent surfaces, visible in the model in image rendering. Diffuse surface impurities are colors that are reflected by other diffuse surfaces. To become a partial radiological methods, they had to start form factors to calculate absorbed surfaces.

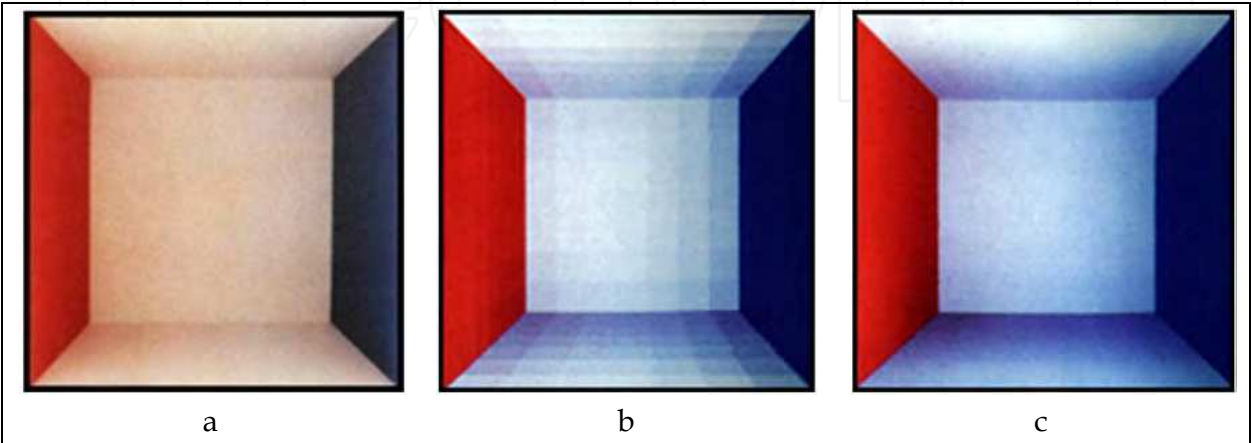


Fig. 2. a-original cube with six sides (front, not shown), we want to model, b-rendered image with 49 flats, using the constant shadow, c-rendered image with 49 flats, using the interpolation shading

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. 3.

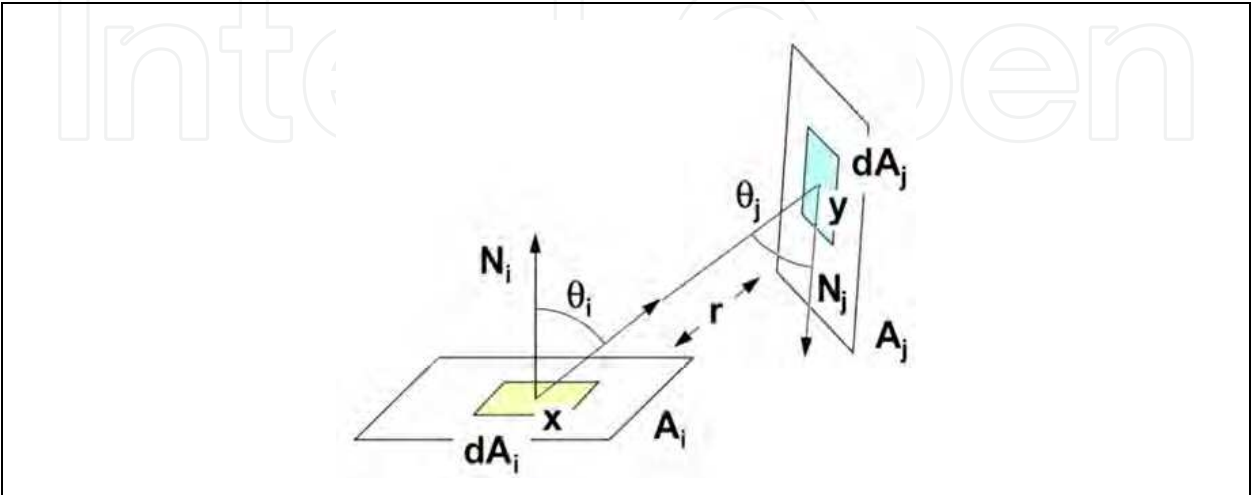


Fig. 3. Form-factor geometry

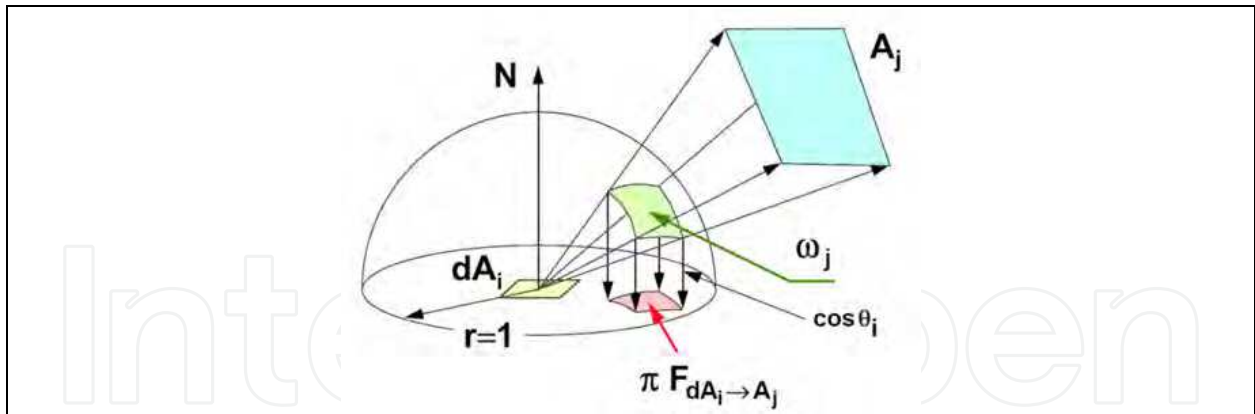


Fig. 4. Projected area onto the hemisphere

If we look at Fig. 4, we see that the area A is related to the projected area, A_p , by $A_p = A \cdot \cos \theta_i$, and the contribution of the projected area A_p is related to the solid angle by (7):

$$\omega = \frac{A_p}{r^2} \quad (7)$$

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

$$F_{dA_i-dA_j} = \frac{\cos \phi_i \cdot \cos \phi_j \cdot dA_j}{\pi \cdot r^2} \quad (8)$$

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

$$F_{dA_i-A_j} = \int_{A_j} \frac{\cos \phi_i \cdot \cos \phi_j \cdot dA_j}{\pi \cdot r^2} \quad (9)$$

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

$$F_{A_i-A_j} = \frac{1}{A_i} \iint_{A_i A_j} \frac{\cos \phi_i \cdot \cos \phi_j \cdot dA_j}{\pi \cdot r^2} \quad (10)$$

There are several different methods for evaluating this integral. The contour integral is found by transforming the double integral by Stoke's Theorem (Goral, et. al, 1984):

$$F_{A_i-A_j} = \frac{1}{A_i} \iint_{A_i A_j} (\ln(r) dx_i \cdot dy_j + \ln(r) dy_i \cdot dx_j + \ln(r) dz_i \cdot dz_j) \quad (11)$$

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 (Baum & Winget, 1990) 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, from Fig. 5.

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

(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 in Fig.3 and direction given by the cross product of vectors R_g and R_{g+1}

Baum use this approach when evaluation by the more efficient hemi-cube method of evaluation described in the following sub-section is geometrically inappropriate for form factor evaluation. They also incorporate an extra term to account for the visibility between surfaces (Baum et al., 1990).

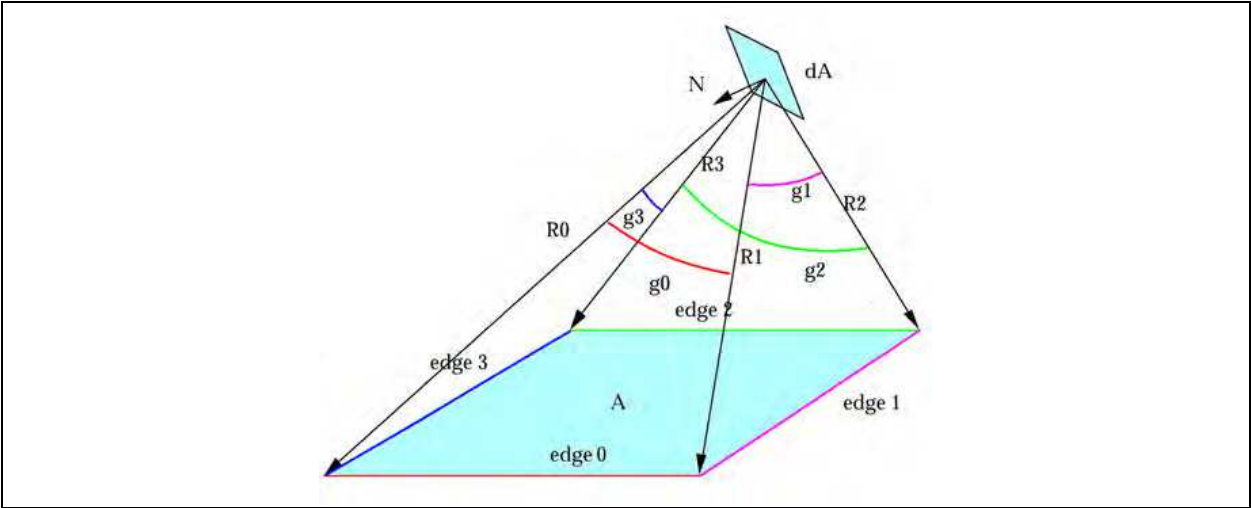


Fig. 5. Geometry for contour integral

3.3 Hemi-cube evaluation

The hemi-cube approach for evaluating form factors was introduced by Cohen (Cohen et al., 1985). It is motivated by examining the geometry in Nusselt’s Analog shown in Fig. 6. First, a patch is projected onto the hemisphere surrounding a patch. This projection accounts for the cosine of the angle between the normal of the projected patch and the hemisphere as well as one 1/ r term. This projected patch is now projected onto the base of the hemisphere accounting for another 1/r and cosine term. The area at the base is equivalent to the form factor. Many areas are identical to the projected area on the hemisphere, and several of these lend themselves to calculation in a more straightforward fashion. See Fig. 7.

Instead of projecting the environment onto a hemisphere, a cube is placed with the receiving patch at the center (see Fig. 8) and each surface of the cube is divided into a set number of pixels. The contribution of each pixel on the cube’s surface to the form factor value can be

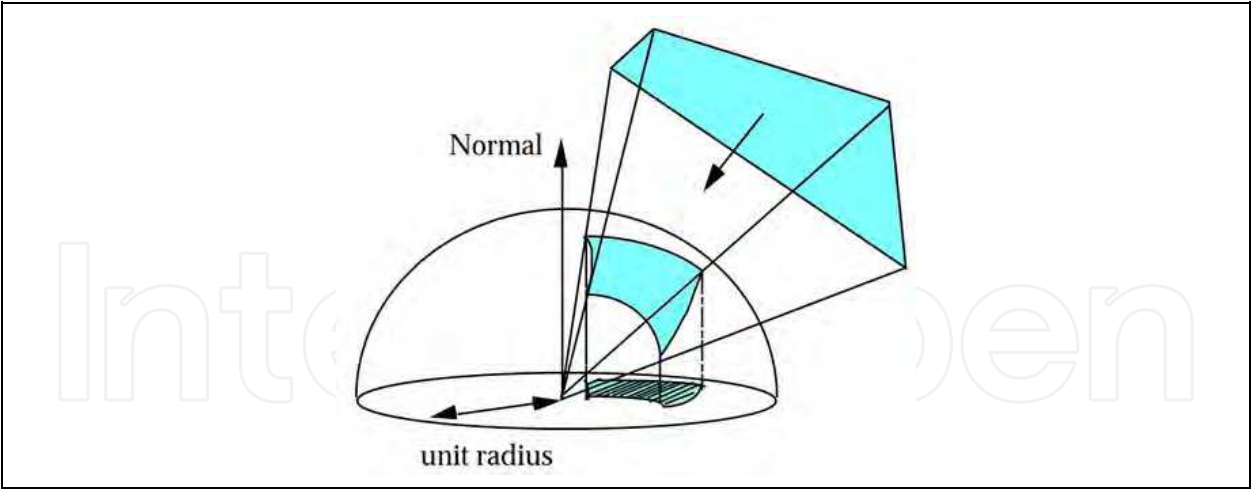


Fig. 6. Nusselt’s Analog

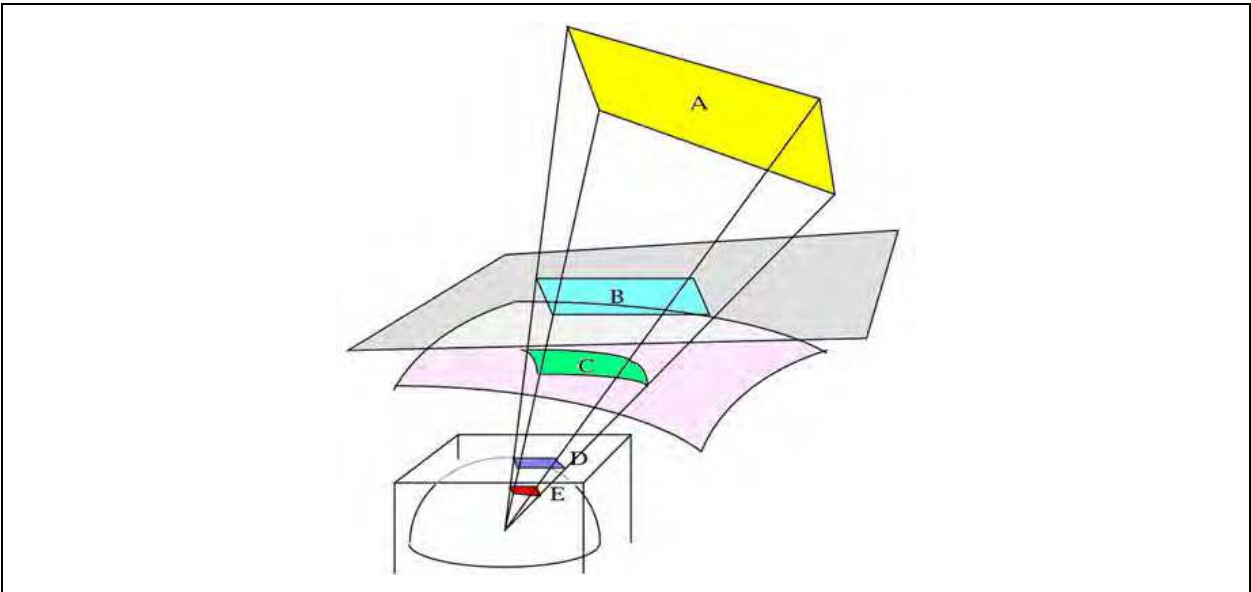


Fig. 7. A, B, C, D & E all have same form factor

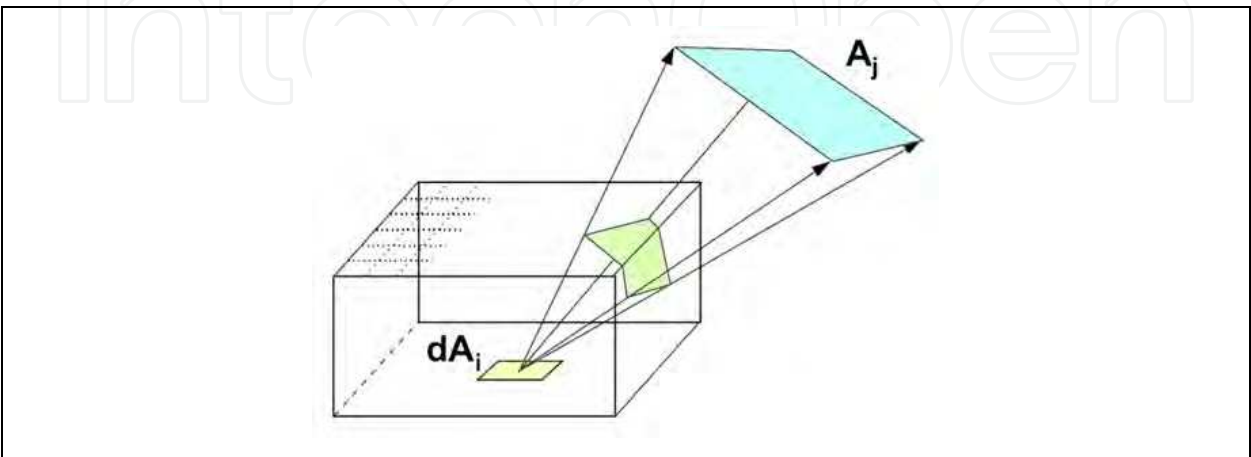


Fig. 8. The hemi-cube project

recalculated since it is only dependent on the pixel location and orientation. The environment is then projected onto the faces of the cube (and half faces). Object visibility can be determined by using simple z-buffer techniques.

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 parameters of lighting systems, which would reflect light effects that arise in artificial and day lighting.

The computer programs will be able to calculate and visualize the daylight, lighting scenes, plan the color and intensity of the lights, position on the project the emergency lighting, with the right legal number of luminaires, prepare photo realistic visualizations of light planning. The furniture, surfaces and luminaires can be placed simple dragging and dropping elements from the provided libraries. For a better realism, the programs can use different textures and furniture, and it uses an integrated ray tracing or radiosity module. In consequence, the market appeared to be several light-technical programs with different purposes and uses. In principle, computer programs can be divided into two basic groups (Smola et al., 2005):

- calculation programs - the result include lighting parameters (Dialux, Relux, Europic, Calculux, WinLuxus, Wils a pod.),
- visualization programs - the result include visualization - the figures of lighting (3D Studio, Catia, AutoCAD, LightScape, Corel Photo-Paint a i.).

These programs are designed for light-technical parameters calculation and on the presentation of projects and usually offers the following program modules for lighting design:

- Interior lighting, utilisation factor method,
- Interior lighting, point by point calculation,
- Interior lighting, direct glare (UGR calculation),
- Interior lighting, glare by reflection on visual display terminals,
- Exterior lighting, area lighting,
- Exterior lighting, street lighting.

For purposes of this contribution to the possibilities of simulation outputs in the DIALux 4.7 (Fig. 9) and Relux (Fig. 10). This simulation programs offers the following options selected lighting system and various options for presentation of results as graph values, isolines maps, light maps - colour scale, false colour rendering, summary tables of lighting respectively brightness, three-dimensional model lighting respectively, brightness economic evaluation of the lighting project in terms of energy consumption, visualization of sunshine and so on (Krupa, 2005).

Figure 11 shows isoline maps, which display equal values of illuminance measured in the vicinity of a luminaire. With DIALux the user has the option to display the 3D rendering in a false colour rendering presentation (Fig. 12). The presentation of illuminance and luminance with freely scalable value ranges and definable colour gradients is now available.

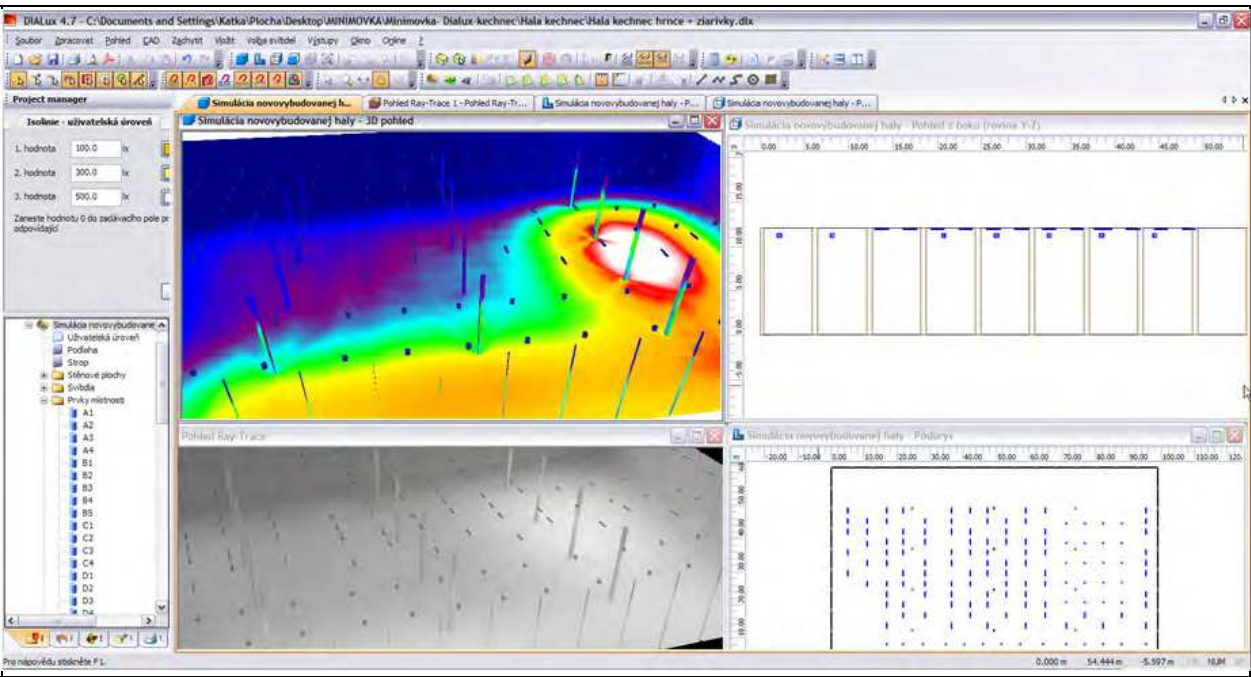


Fig. 9. Display of Dialux

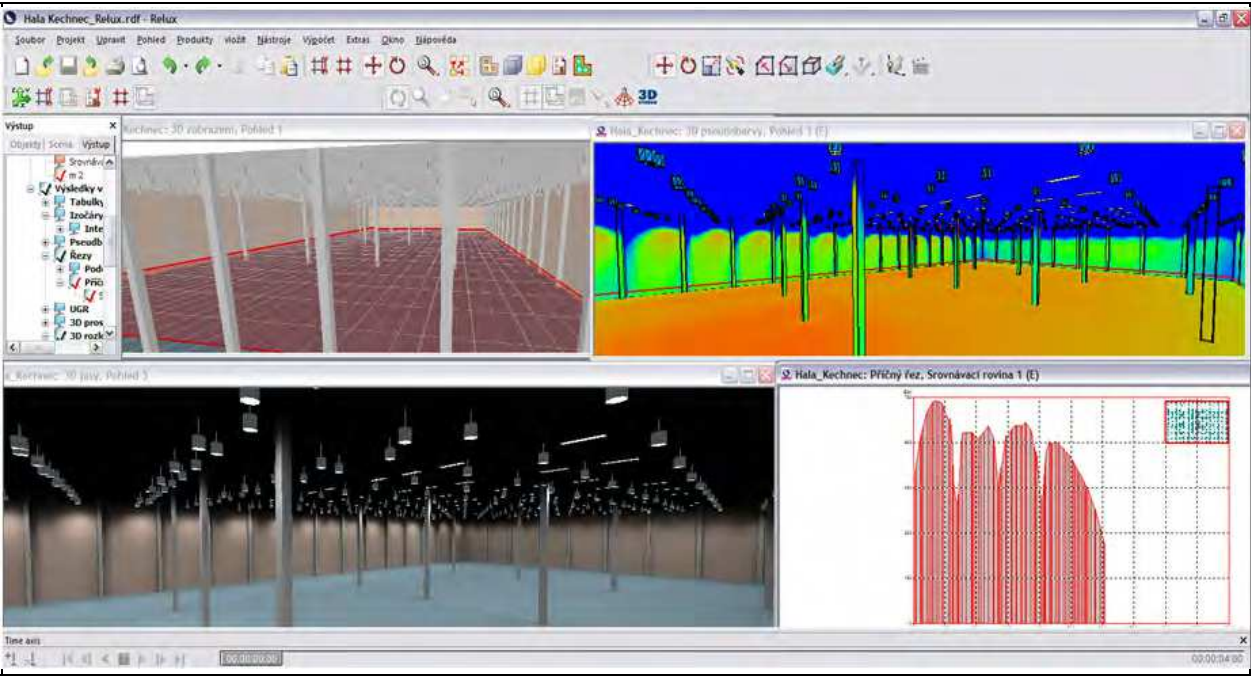


Fig. 10. Display of Relux

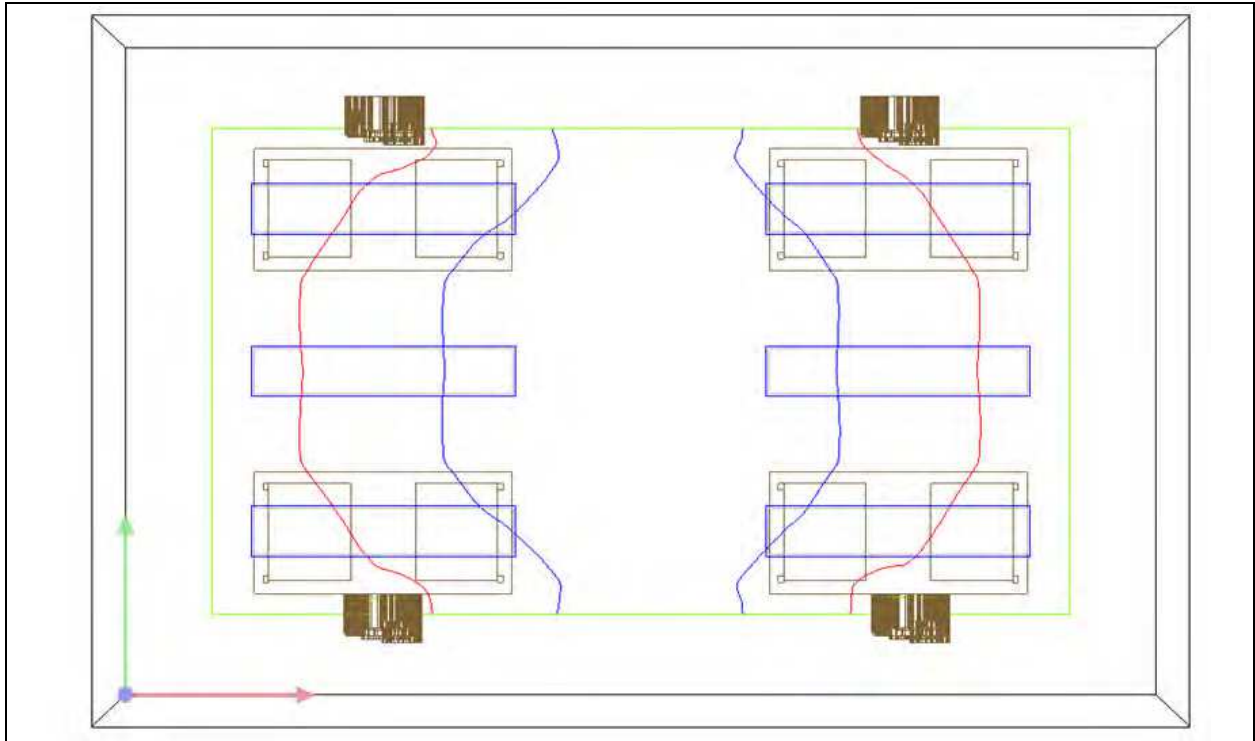


Fig. 11. Isoline map (Dialux)

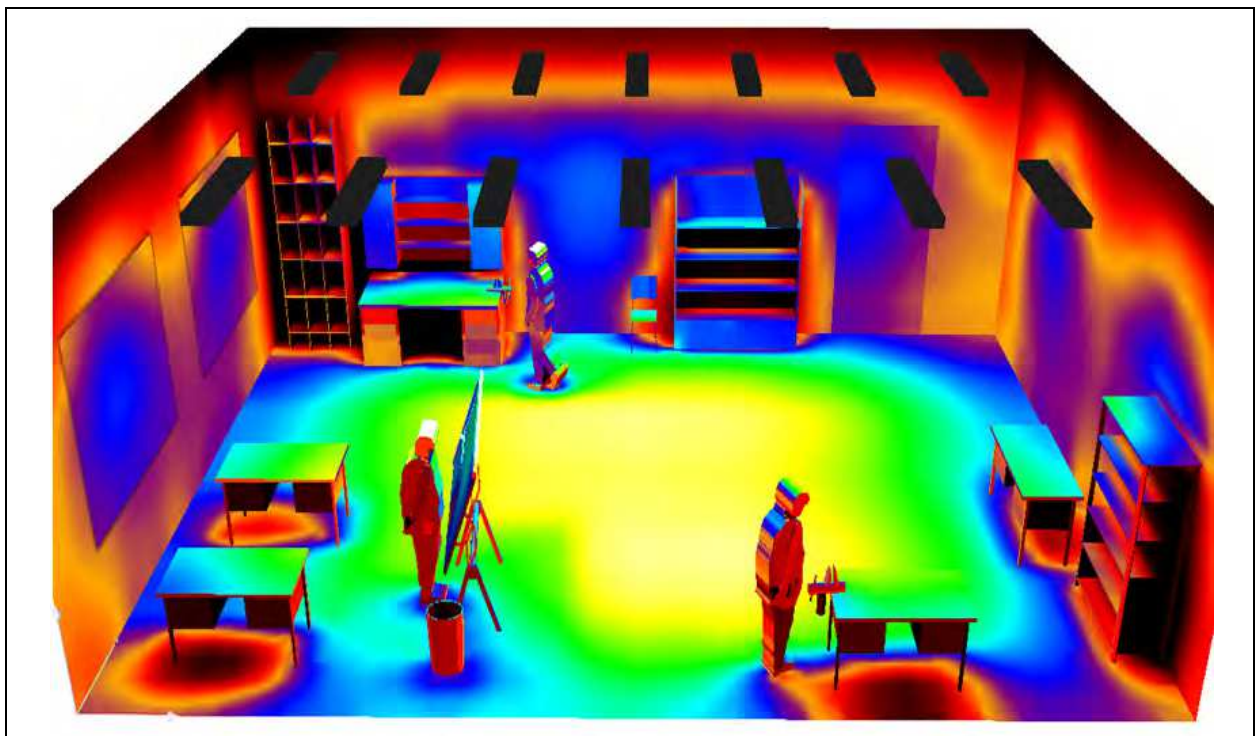


Fig. 12. Layout of false colour rendering (Dialux)

On the Fig. 13 is 3D Light distribution curve, (LDC). This function is useful to check the correct placement of luminaires with asymmetrical distribution. Figure 14 shows layout of false colour rendering and detail of light distribution curve.

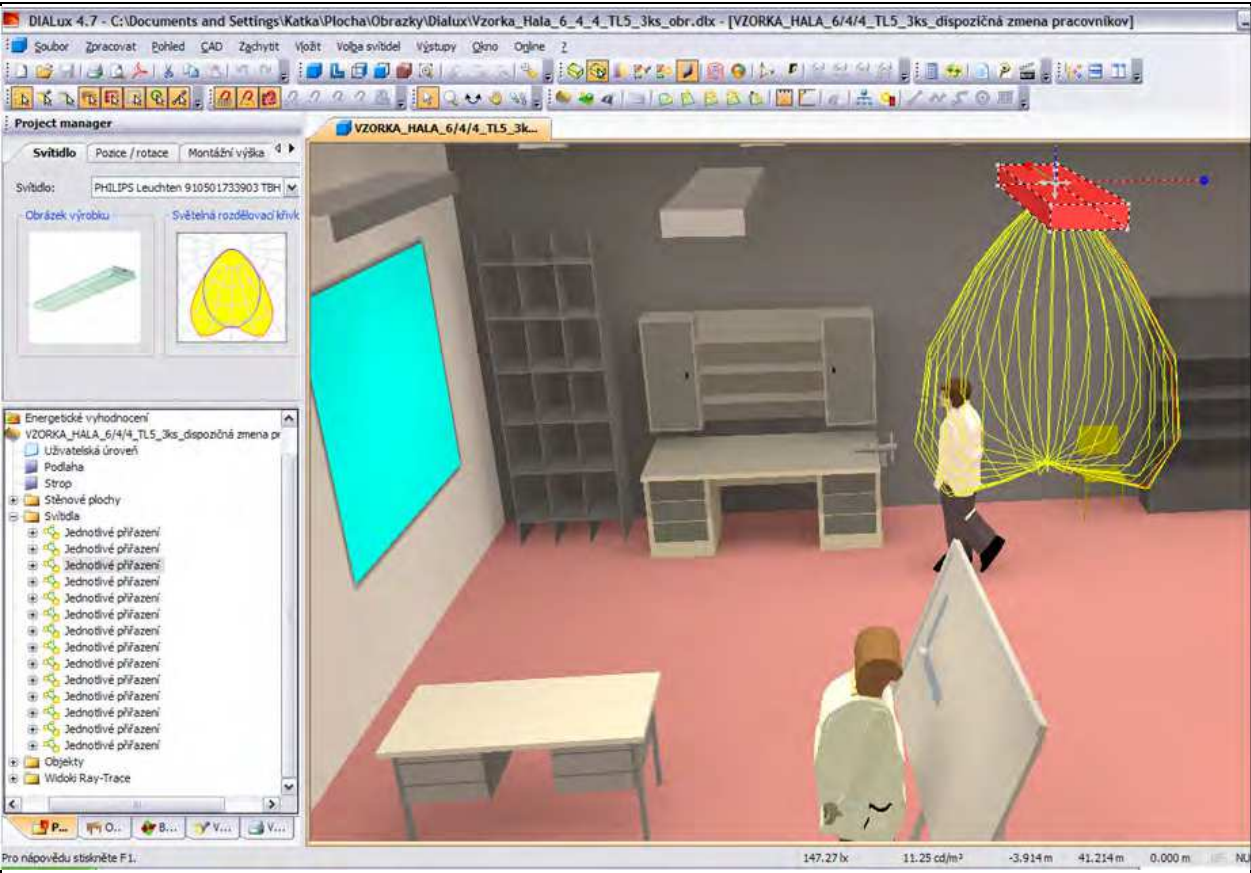


Fig. 13. Detail of light distribution curve (LDC) (Dialux)

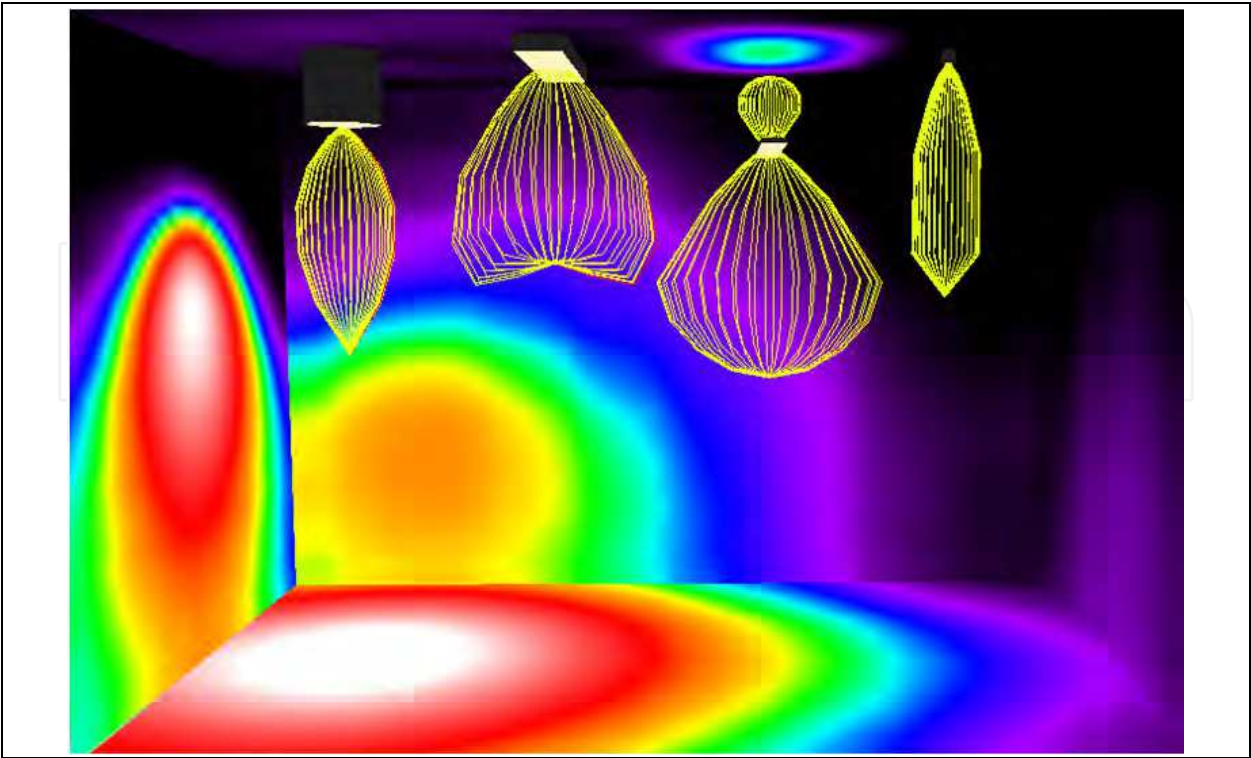


Fig. 14. False colour rendering and LDC (Dialux)

Relux offers the raytracing calculation (fig. 15) which is based on a version of Radiance that has been revised by Relux. This verified method, which has been validated worldwide, is noted for its accurate calculation results.

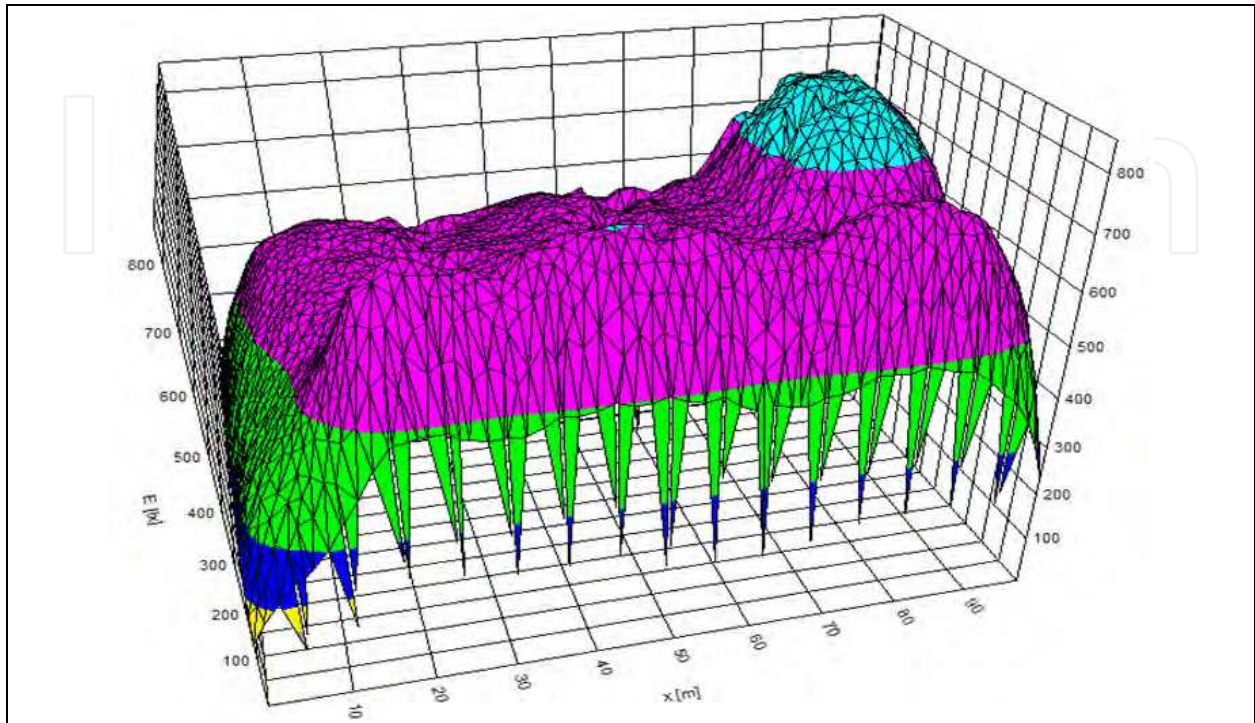


Fig. 15. Raytracing calculation in Relux

5. 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.

Current development of computer technology has influenced also the area of light-technical design. A wide range of computer software, that are available, enable the efficient generation of lighting projects, visualization of photometric parameters, lighting parameters, etc. Calculations of these parameters are becoming commonplace, without

laborious and lengthy calculations as it used to be in the past. These programs based on the point and flow method use several simulation methods to model lightning-technical parameters (described in this paper). They also allow the creation of models of various scenes, by which it is possible to model different variants of each situation and subsequently evaluate them. New trends of research in this area will continue to focus on research into the impact of color of light appearance to man, with emphasis on biological lighting systems, that will positively influence the feeling of a man. In connection with the application of information technology in research of lighting, developments in area of fotorealism, interactivity, dynamic visualizations of illuminance is expected, allowing to monitor the variability of lightning-technical parameters depending on the current environment and time.

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