

Simulation of Luminaires in Radiance: Verification Method

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Abstract. The aim of this paper is to propose a method for evaluation of the error introduced by lighting simulation of indoor artificial light sources – luminaires. Paper defines verification procedures for comparison of luminaire simulation results against results obtained from standard lighting calculation methods. Defined procedures are used to verify luminaire simulation in Radiance lighting software.¹

1 Introduction

In the process of architectural design architects can use different software tools for modelling and simulation. These programs allow them to simulate imaginary buildings, and verify their intentions, preferences and respect of norms, in order to bring the resulting ambience closer to architects intentions [1]. On the other hand, programs follow strictly defined geometrical and physical laws, which give quantitative accuracy to the project.

For modelling and simulation in architecture there is a great number of different computer programs available on the market, such as AutoCAD, 3DStudio Max, PovRay, Radiance, etc. All these programs offer similar possibilities for modeling of geometrical primitives, but their capability to simulate *luminous ambience* of the building is different. Definition of luminous ambience is rather complex, and it involves description of artificial (luminaires) and natural (sun, sky) light sources, building position and environment, and materials used for building interior and exterior. *Lighting design programs* are software tools for calculation and visualization of luminous ambience. Due to the complex nature of light, all lighting design programs, in the process of light modelling, involve some simplifying assumptions, which lead to some amount of calculation inaccuracy.

The aim of this paper is to propose a method for evaluation of the error introduced by computer simulation of luminaires. The method compares luminaire simulation results from Radiance² software against results obtained from lighting calculation methods proposed by “Illuminating Engineering Society of North America” - IESNA.

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² Radiance software can be downloaded from <http://radsite.lbl.gov/radiance>

2 Lighting Design Programs

Lighting design programs provide tools for luminous ambiance definition, visualization and lighting calculations. They rely on physical principles to predict how light will be reflected between and absorbed by surfaces in arbitrarily complex physical environments [2].

Two common methods are used for modelling of light behavior: radiosity (radiative flux transfer) and ray tracing. *Radiosity* simulates the diffuse propagation of light starting at the light sources and considers only the interaction of light with surfaces in the environment. These surfaces are assumed to be perfect (Lambertian) diffusers, reflectors, or emitters, which reflect incident light in all directions with equal intensity. *Ray tracing* approach assumes that light follows geometric ray paths between surfaces. It follows all rays from the light sources to the observers' eye (camera). Light is represented as a set of one-dimensional rays, defined with an origin point and a vector direction. This method accurately models specular surfaces, but it becomes time and space consuming for diffuse surfaces calculations.

The ray tracing approach is generally slower than radiosity, especially for complex environments with many light sources. However, it has the ability to generate more realistic images, which is an advantage for architectural visualization and glare analysis studies. Most lighting design programs use some kind of combination of these two approaches, to obtain accurate lighting calculation and visualisation.

The brute force ray tracing approach described above needs to trace trillions of rays to ensure that enough rays will be seen by the camera. To overcome this problem, rays can be traced backward from the camera into the environment, until they reach light sources. Only those rays that will be seen are considered in calculation. The advantage of *backward ray tracing* is that it correctly and efficiently models any type of surface, including those with specular and semi-specular reflectance properties. Tracing of finite number of rays introduces some calculation error in the resulting images, which could be irrelevant for 3D art applications, but should not be overlooked in lighting design and analysis. To evaluate the error introduced by ray-tracing, simulation results are compared against results obtained from standard lighting calculation methods.

Radiance. Radiance [3] is open source software for accurate lighting simulation and visualization based on backward ray-tracing algorithm. It consists of over 50 tools, for scenes description, import and export scene descriptions from/to different file formats, rendering and post processing images. Specific attributes of Radiance are:

- Accurate calculation of luminance/radiance. Each pixel in Radiance picture is value of radiance in that point in wats/steradians/m² stored in compact 4-byte/pixel, run-length encoded format. The pictures are both photorealistic and accurate.
- Modelling of artificial and natural light sources. Modelling of electric light is based on measured or calculated luminaires output distribution data; and daylight modelling is based on sky models, and simulation of sky and sun behavior.
- Simulation of light interaction with surfaces made of different materials, is based on different reflectance models. Radiance includes 25 surface material types, and possibility to define different functional or data textures and/or patterns on them.

3 Lighting Calculation Methods

3.1 Luminaire description

Due to [4] luminaire and lamp are defined as follows:

Luminaire (light fixture) – a complete lighting unit consisting of a lamp or lamps and ballasting, together with the parts designed to distribute the light, to position and protect the lamps and to connect the lamps to the power supply.

Lamp (light source) is a surface that emits light.

Set of characteristics required for lighting calculation and simulation are:

- Geometrical characteristics – shape, length, width, height.
- Candlepower distribution - distribution of luminous intensity. These values are given either by luminaire polar-curves or by intensity tables that contain values of luminous intensity as a function of vertical and horizontal angles. While polar-curves are better for by-hand calculations and estimations, intensity tables are more useful for accurate luminaire simulation and calculation.
- Total flux of lamps in the luminaire (in lumens).

It is advisable to have some additional data, but even without them it is possible to perform accurate calculations. Different illuminating engineering societies and luminaire manufacturers define specific photometric file formats for storing this data.

For the simulation method described in this paper, IESNA candlepower distribution file format (IES format) [5], is used because it is widespread and it can be used as luminaire input description in lightning design programs. It is an ASCII text file format for description of luminaires characteristics. It contains various luminaire data such as: manufacturer data, luminaire catalogue number, description of luminaire and lamp(s) used inside of it, electrical and photometric data about luminaire etc. The most important data in an IES files are candlepower distribution values.

3.2 IESNA calculating methods

This section describes lighting calculation methods defined by IESNA, which are used in the verification procedures defined in Section 5.

Inverse-Square Method. Inverse-square method is method for calculation of direct illuminance at a point on a horizontal or vertical plane [4]. Direct component of illuminance is contributed by luminous flux coming directly from the luminaire to a point. Due to its simplicity and fundamental character, this method is present in one form or another in most methods of calculating direct illumination.

The method is limited to *point light sources*. A source is categorized as a point source when calculations are made for distances greater than five times the maximum source dimension. All calculations made in this domain are accurate within one or two percent. This is not a significant limitation for typical use.

Zonal Cavity Method (ZCM). ZCM, as defined in [4], is a procedure for calculating Coefficients of Utilization (CU), Wall Exitance Coefficients (WEC), and Cavity Exitance Coefficients (CECC) [4]. It is based on flux transfer theory, which includes:

luminaire candlepower distribution, room size and shape (cavity ratio concept) and room surface reflectances into calculation. This method is used widespread because it can be applied in most real-world lighting calculations. When the coefficients are calculated, they can be used for further calculation of *indirect plane illuminance*.

ZCM model assumes that luminaires are uniformly distributed throughout the empty room with ideally diffuse, spectrally neutral surfaces, and that incident flux is uniformly distributed over the room surfaces. If the luminaire has rotationally asymmetric candlepower distribution, during the ZCM calculations luminous intensity values for a vertical angle are averaged. As the deviation between assumed mathematical model and the physical system increases, the difference between the calculated and actual or simulated values will increase to some extent.

Infinite Plane - Exitance Difference Method (IP-ED). This method is used for calculation of indirect illuminance, contributed by light reflected within a space [6]. ZCM coefficients are used as input variables; due to it the method inherits ZCM limitations.

In general, indirect illuminance calculation methods are less accurate than methods for direct illuminance, due to the complex nature of light propagation and interreflections. If ZCM coefficients calculation is accurate within 2%, accuracies within 10% are reasonable to expect for indirect illuminance in real environments [6].

Total Illuminance Value. Total illuminance at a point is a sum of direct and indirect illuminance component. The accuracy of calculated values depends on accuracy of components. If the direct component dominates, total illuminance value is closer to real value. If direct and indirect component ratio is rather small, e.g. indirect lighting applications, total illuminance value is less accurate [4].

4 Simulation of Luminaires in Radiance

In luminaire simulation two goals should be achieved: simulated luminaire should have the same candlepower distribution as real luminaire and its appearance should be as close as possible to real luminaire appearance. When simulating luminaires with complex optics (louvers, diffusers, reflectors), it is difficult to respect both requests, due to approximations that are included within simulation algorithms.

Radiance default method for luminaire simulation is based on *ies2rad* program, which represents the luminaire as simple emitting surface (polygon, disk or sphere), made of *light* material, with an appropriate candlepower distribution mapped on it as a pattern. This method lacks ability to accurately represent appearance of the complex luminaires and luminaires with direct/indirect light distribution.

To overcome this limitation an “impostor” object that encloses real luminaire geometry could be used [3]. Impostor object would have appropriate candlepower distribution, obtained from IES file, but it should be invisible when viewed directly. Precise luminaire geometry, from manufacturer specification sheet, should be put inside this impostor object. The resulting object will have proper candlepower distribution, due to impostor, and appearance, due to luminaire geometry description. In Radiance *illum* material is used for definition of impostor objects.

“Impostor” method for luminaire simulation involves complexity to the scene and prolongs rendering time. When luminaire appearance is not of great importance (luminaire is not visible or it is too distant), classical simulation method is used, which creates accurate image for significantly shorter rendering time.

5 Verification Method

In order to evaluate Radiance simulation results against theoretical values obtained by methods previously described in Section 3, verification method consisting of three procedures is proposed. For simulation and verification purpose luminaire is placed in the testing room with known geometrical and photometric parameters: length, width, height, ceiling, walls and floor reflections.

Procedure 1. This procedure compares input candlepower values from IES file against values measured in simulated environment. Although it seems that IES input values are the same as measured ones, error can be generated in different phases of simulation: during the pattern mapping, during the ray tracing of luminaire light etc.

Procedure is based on calculation of luminous intensity at different vertical angles around the simulated luminaire. Measurement points are placed on an imaginary sphere around the luminaire, and each point corresponds to one vertical angle defined in IES file [8]. If IES file contains more than one horizontal angle, for each horizontal angle one set of coplanar points is defined. Radiance color component values, R_L , G_L and B_L , are calculated using *rtrace* program, and converted to luminance L values using equation suggested in [3]:

$$L = 47.4 * R_L + 120 * G_L + 11.6 * B_L, \quad (1)$$

Using luminance values, luminous intensity is computed:

$$I = L * S * \cos(\theta), \quad (2)$$

where S stands for luminaire opening area, and θ is vertical angle.

If “impostor” method is used for simulation, luminaire has more than one radiate surface, and Eq. (1) is inappropriate. The procedure is adapted for this case and *rtrace* program calculates irradiance values, rather than radiance. Direct plane illuminance at point, E_d is calculated from irradiance value using Eq. (1), where irradiance color components are used instead radiance values. Luminous intensity for vertical angle θ - I_θ , can be calculated using Inverse-square law as:

$$I_\theta = E_d * D^2, \quad (3)$$

where D is the distance between luminaire and the point. Resulting values can be compared with input candlepower distribution file or with luminaire polar curve.

Procedure 2. This procedure compares simulated values of direct illuminance on a plane surface, with values obtained by Inverse-square law. Firstly, measurement points on an arbitrary chosen horizontal plane in the testing room are defined. Then, direct component of irradiance for defined points is computed using *rtrace*; interreflections are excluded from calculation. Resulting irradiance values are

converted to illuminance values using Eq. (1).

Procedure 3. This procedure compares simulated values of indirect illuminance on a plane surface, against values obtained by IP-ED method. Radiance doesn't provide a mechanism for separate calculation of indirect illuminance; rather it calculates total illuminance at a point. Indirect component is calculated as difference between total direct illuminance for the same point, and compared with resulting values from IP-ED method. For the total illuminance calculation same method is used as in Procedure 2, but the interreflectances are taken into account.

For a computer simulation, it is impossible to trace a light ray through infinite number of interreflections, as it is the case in reality. Even for a finite tracing depth, it programs can't to trace an infinite number of rays scattered from a ray that hits a diffuse surface. In Radiance, finite depth and a finite number of ray samples traced away from a diffuse surface is used. This approach introduces some errors that converge to zero as the number of light bounces rises. The number of interreflections that produces acceptable results for most applications is four or five.

6 Results and Discussion

Luminaire and Testing Room Data. For this experiment Ledalite Cachet luminaire (8913H01) is used – Fig 1. Cachet is luminaire with indirect rotationally asymmetric candlepower distribution, and it is used as suspended luminaire. This luminaire is selected for the experiment because the difference between simulated and calculated data could be considered as worst-case analysis.

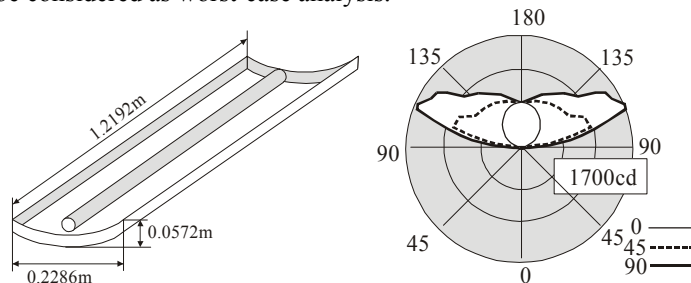


Fig. 1. Ledalite Cachet luminaire (8913H01) dimensions and luminous intensity polar curves for three specific horizontal angles³

Simulated luminaire was positioned in the centre of the cubical testing room 20m wide. Work plane height is 2m. Ceiling, walls and floor are assumed to be ideally diffuse and spectrally neutral - grey. Average reflectances for ceiling, walls and floor are respectably 0.8, 0.5 and 0.2. The room is empty. Room dimensions are adequate for Inverse-square method calculations. All ZCM assumptions, except the incident flux distribution, are respected. This disparity could lead to some difference between simulated and calculated indirect illuminance values. Two test cases are treated:

- *lum1*- luminaire is simulated using default *ies2rad* parameters. Luminaire is represented as a *light* polygon with appropriate candlepower distribution.

³ Detailed luminaire description can be found on www.ledalite.com site

- *lum2* - for luminaire simulation is used *illum* impostor object and detailed luminaire geometry description is placed inside it.

6.2 Simulation results

Procedure 1. Table 1. contains luminous intensity values from IES file and lum1 and lum2 test cases. For *lum1* case, luminaire opening area is rectangular and its value is $S=0.24536 \text{ m}^2$. For *lum2* case Procedure 1 is adapted, as described in Section 5.

Table 1. Candlepower distribution data for Ledalite Cachet luminaire (8913H01). All luminous intensity values correspond to horizontal angle 0.

Angle [°]	IES file [cd]	lum1 [cd]	lum2 [cd]
90	4.5	0	5.10
95	35.7	35.69	37.59
115	218.3	218.29	221.30
135	421.6	421.61	424.83
155	576.4	576.43	579.78
175	662.3	662.34	666.11
180	664.4	664.44	668.28

For *lum1* Radiance simulates Cachet luminaire as rectangle with appropriate candlepower distribution, and due to its two-dimensional nature, it doesn't radiate in the horizontal plane - 90°. Since portion of light radiated in horizontal plane is small, in comparison to total luminaire flux, this error doesn't significantly decrease simulation accuracy. To overcome this inaccuracy *lum2* can be used instead of lum1, since it encloses the luminaire geometry and radiate in all directions. *Lum2* simulation introduces greater error, but the error values do not exceed 3% for all angles, except 90°. For *lum2* the relative error for horizontal plane is 13%. Due to previous results, Radiance simulation of luminaire, both *lum1* and *lum2*, can be used as good starting point for further lighting calculations.

Procedure 2. Direct illuminance values are calculated for the plane placed seven meters above the luminaire. Direct illuminance values for all planes below the luminaire are equal to zero, since the Cachet luminaire has indirect candlepower distribution. Results are represented in Table 2. Deviations from calculated values are lower than 1%, which is acceptable error.

Table 2. Direct illuminance values calculated in four representative points

X	Y	Z	E_d [lux]	Lum1 E_d [lux]	Lum2 E_d [lux]
2	2	17	2.70	2.67	2.69
2	10	17	2.24	2.24	2.27
10	2	17	6.91	6.86	6.90
10	10	17	13.55	13.56	13.67

Procedure 3. In this experiment, indirect horizontal illuminance weren't measured for the plane above the luminaire, since Zonal Cavity Coefficients are not valid for planes above the luminaire. Indirect horizontal illuminance was calculated on the

work plane, positioned two meters above floor height. For indirect illuminance calculation in Radiance seven light bounces are taken into account. Since Cachet has indirect candlepower distribution direct component of illuminance on the work plane is equal to zero, and indirect illuminance component is equal to total illuminance.

Table 3. Indirect illuminance values calculated in four representative points.

X	Y	Z	E _i [lux]	Lum1 E _i [lux]	Lum2 E _i [lux]
2	2	2	2.25	1.98	1.99
2	10	2	2.69	2.48	2.49
10	2	2	2.69	2.45	2.46
10	10	2	3.32	3.06	3.09

Values obtained from Radiance indirect calculation for lum1 and lum2 are similar. The disparity of Radiance and IP-ED method results is between 7% and 12%. Such results can be interpreted by the variation of the simulated environment characteristics from ZCM assumptions described in Section 3.2. According to the IP-ED method accuracy [6], Radiance software can be used as good estimation tool for indirect illuminance calculations.

7 Conclusion

According to verification results presented in the previous section, Radiance software is as accurate as approved lighting calculation procedures used in practice. It can be used for luminaire simulation, visualization and calculations.

The verification procedures proposed by this paper, although related to Radiance software, can be used, with minor modifications, for error evaluation of other lighting design programs. Although simulation method could be program specific, the evaluation criteria for candlepower distribution, direct and indirect plane illuminance should be the same.

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