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A design-oriented approach for managing colored light sources in lighting design software

Maurizio Rossi

Department of Design, Politecnico di Milano, Milan, Italy

Correspondence
Maurizio Rossi, Department of Design, Politecnico di Milano, Milan, Italy.
Email: maurizio.rossi@polimi.it

Abstract

In the last decade, the extensive introduction of LED lighting sources has brought elements of innovation to interior lighting design in terms of color. Besides the new tunable white LED source, lighting is no longer exclusively white; indeed, colored lighting has entered the design practice thanks to the positive effects on people's health and mood. Unfortunately, this element of lighting innovation, color, cannot be computed correctly in commercial lighting design software. These computations are based on the assumption that light is only white or defined in terms of RGB triplets in the relative digital color space of computer graphics, which does not have a physically correct relationship with the actual spectral power distribution (SPD) of luminaires. In this paper, attention is focused on a practical design-oriented approach for describing luminaires in lighting design software that also considers the real SPD and the luminous intensity distribution. The focus is on information available to lighting designers who do not have a laboratory to measure light sources and luminaires. This information could be available in online datasheets or as a Cartesian graph from luminaires and light sources manufacturers. Following this approach, a set of functions is proposed that can be easily implemented in lighting design software to improve light sources' color management and allow lighting designers to add SPD data to luminaires.

KEYWORDS

light source, lighting design software, luminous intensity distribution, spectral power distribution

JEL CLASSIFICATION

C0

1 | INTRODUCTION

In the context of lighting design software, the research describing light-matter interaction in the pipeline from luminaires to lighting analysis and rendering has a long history of exciting developments that collide with the need to represent digital images on output devices: RGB displays and CMYK printers. One of the critical points of multispectral research is: how many samples are necessary to describe the simulated spectral physical phenomenon correctly? At the beginning of computer graphics research, a first attempt to determine a reasonable

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sampling of the wavelengths was introduced by Meyer.[1] In his method, the choice of the wavelengths is made to minimize the computational errors regarding the selected tristimulus values. Meyer defined the AC_1C_2 color space to determine how many samples and wavelengths to use. This technique has been successfully used to generate image synthesis colorimetrically more correctly, knowing the spectral reflectance of materials. As far as the description of the materials is concerned other researchers have tried to explore how many chromatic dimensions are necessary to describe the reflectance carefully.[2] Some argued that the reflectance of most natural materials does not contain high-frequency information[3]; therefore, it should be enough to use a limited number of dimensions.

Nevertheless, the spectral distribution of light originates from light sources, so it is not only an issue regarding material spectral reflectance. Deville[4] shows that using a few spectral power distribution (SPD) samples is applicable without errors only for light sources with continuous linear SPD. We know that discharge lamps and some white and colored LEDs have SPD with spikes and discontinuities (Figure 1).

In the adaptive method proposed by Deville, the wavelengths domain is partitioned in intervals. The intervals depend upon the reflectance specter of the materials and the light source's SPD analyzed in a pre-processing phase. The partitions are determined algorithmically to satisfy two conditions: every interval must contain only continuous portions of the SPD, and possible specter peaks are placed in single intervals of at least 5-nm width. Then the single partitions are numerically integrated with the

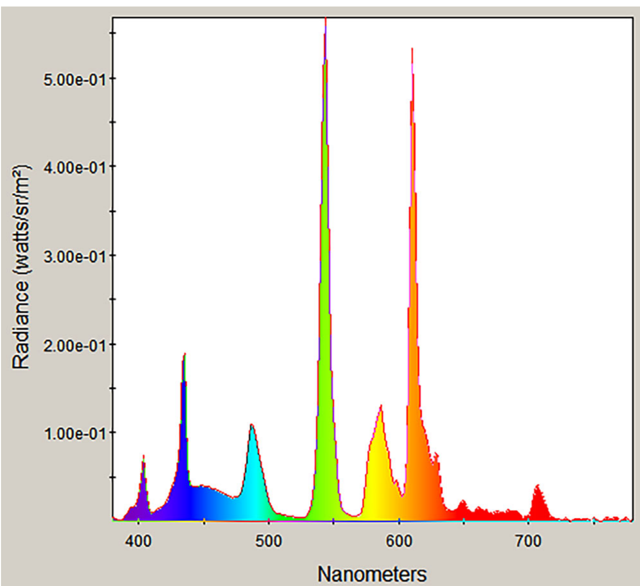

FIGURE 1 The radiance spectral power distribution (SPD) of a linear fluorescent light with CCT = 3843 K measured with a Spectrascan PR701s

trapezoids method only for 5-nm intervals or with the Gaussian method in the other cases. The choice of the wavelengths depends on all those selected for the numerical integrations in the various integration intervals. In the following years, many studies focused on the sampling methods for multispectral rendering.[5–10] The goal was to determine the minimum number of samples needed to contain calculation errors. Nevertheless, these researches have not been implemented in lighting design software.

Verifying a lighting project is based on the analysis of some photometric requirements: illuminances, luminances, uniformity factors, contrast yield, and UGR evaluation.[11,12] In the modern lighting design methodology, lighting design software has supported the designer's experience for some time for white lighting quantitative verification. However, this software has limitations when the chromatic component is also evaluated in the lighting project. Although there has been software for some time with multispectral unbiased rendering,[13,14] these calculation methods are not applied in worldwide used lighting design software. In commercially available software, the color of light and surfaces is approximated by RGB triplets. This method, at best, respects the digital sRGB standard[15] and does not have a physically correct relationship with the spectral quantities defined in radiometry. This simplification of the spectral and chromatic aspects in lighting design software is due to the difficulty, or almost impossibility, for lighting designers to find the spectral information concerning light sources and materials in design practice.

For the multispectral calculation, the idea followed in this paper is not to focus on the SPD sampling method, instead to propose a practical approach that allows lighting designers, and lighting design software developers, to obtain the SPD of light sources, starting from the data available in the manufacturers' online datasheets.[16] In very few cases, goniometric spectral data is available online, as a file, in the recent North American standard TM-27-20.[17] This situation occurs because only very few laboratories in the lighting sector are equipped with goniophotometers capable of measuring the spectral radiant intensity instead of the luminous intensity of luminaries.[18]

2 | LUMINAIRES: AVAILABLE ONLINE DATA

In the following text, we distinguish the radiometric (e subscript) and photometric (v subscript), and the total values to spectral functions where the dependence by wavelength λ is always explicit.

What is usually available online by the manufacturers is the light intensity distribution (LID) of the luminaire. The LID describes the intensity variation as a function of

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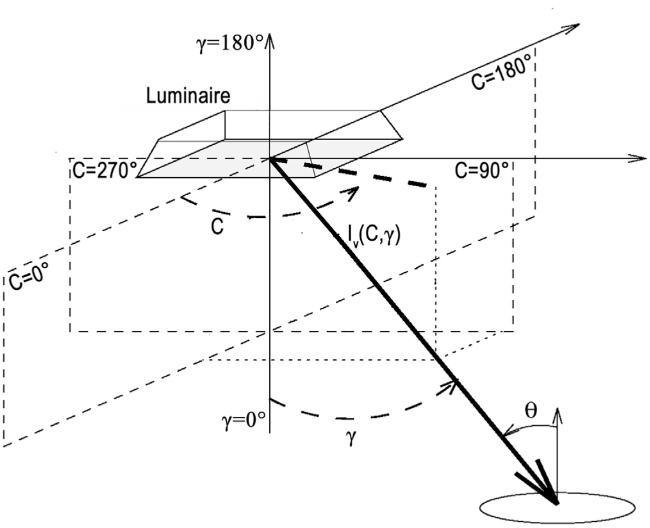

FIGURE 2 The C-γ angle format for the luminous intensity distribution (LID) of a Luminaire

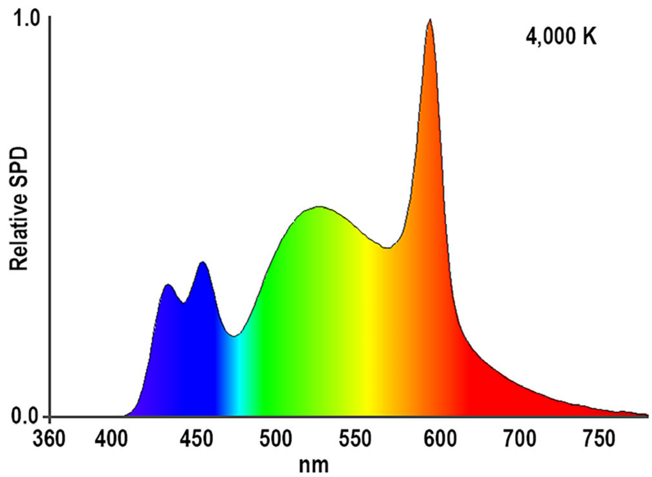

FIGURE 3 The relative spectral power distribution (SPD) of a 4000 K light source, made using LEDs of different colors. The tabular data were acquired from a Cartesian graph available in an online datasheet, using Engauge Digitizer[20]

its direction. The LID is defined through $I_v(\theta,\phi)$, where θ and ϕ are two angles in polar coordinates measured from the center of the luminaire emitting surface or volume. Within the LID, the luminous intensity I_v has SI candles (cd) as tabular functions of polar angles (θ,ϕ), in the C-γ angle format for general lighting (Figure 2) or V-H angle format for projectors. Other data available are the luminaire $\Phi_{v,\text{luminaire}}$, and/or lamp $\Phi_{v,\text{lamp}}$ luminous flux in lumens (lm) and the efficiency η_a of the luminaire.

The manufacturers generally make available the LID, normalized with respect to the conventional flux of 1000 lm:

$$I_{v,1\text{Klm}}(\theta,\phi) = 1000 \cdot I_v(\theta,\phi)/\Phi_{v,\text{lamp}} \left(\text{cd Klm}^{-1}\right) \tag{1}$$

Anyway, the type of standardization applied may change in different countries. Today, more often, in the case of products that integrate non-detachable LED sources, the absolute value $I_v(\theta,\phi)$ of the LID is provided directly. The relation between the luminous flux of the lamp and the fixture is:

$$\Phi_{v,\text{lamp}} = \Phi_{v,\text{luminaire}}/\eta_a\ (\text{lm}) \tag{2}$$

Also available is the relative SPD: $S_e(\lambda)$. This is given by the ratio between the SPD, $\Phi_{e,\lambda}$ and the SPD value for $\lambda = 560$ nm percent:

$$S_e(\lambda) = 100 \cdot \Phi_{e,\lambda}/\Phi_{e,560\times10^{-9}}\ \left(\text{m}^{-1}\right) \tag{3}$$

The definitions of standard illuminants use, for this definition, the normalization to $\lambda = 560$ nm.[19] Other texts report this for $\lambda = 555$ nm, the wavelength of the photopic luminous function $V(\lambda)$ reaches its maximum. The increasing use of sources with discontinuous SPD has brought other kinds of normalization. For example, compared to the maximum value of the SPD, $\Phi_{e,\max} = \Phi_{e,\lambda\text{m}}$ at a generic wavelength $\lambda_\text{m} \neq 560$ nm. This way, the graph of the relative SPD reaches its maximum with a unitary value for $\lambda = \lambda_\text{m}$:

$$\Phi_{e,\lambda,\bar{1}} = \Phi_{e,\lambda}/\Phi_{e,\lambda_\text{m}}\ \left(\text{m}^{-1}\right) \tag{4}$$

Another normalization uses the SPD to produce a total luminous flux of 1 lm or 1 Klm. Given Φ_v, the luminous flux of a lamp and $\Phi_{e,\lambda}$ its spectral radiant power:

$$\begin{aligned} \Phi_{e,\lambda,\bar{1}\text{lm}} &= \Phi_{e,\lambda}/\Phi_v\ \left(\text{W lm}^{-1}\ \text{m}^{-1}\right); \\ \Phi_{e,\lambda,\bar{1}\text{Klm}} &= 1000 \cdot \Phi_{e,\lambda}/\Phi_v\ \left(\text{W Klm}^{-1}\ \text{m}^{-1}\right) \end{aligned} \tag{5}$$

The sampling step of this relative SPD, usually available as a table or Cartesian graph, should never be smaller than 5 nm. Often the only data available is a Cartesian graph in which the units of measurement are not specified. In this graphic representation, we are interested in the spectrum's shape. Fortunately, in these cases, the lighting designer can use free software such as Engauge Digitizer[20] or WebPlotDigitizer[21] to quickly obtain the table of $S_e(\lambda)$ from the graph (Figure 3).

A database of some lamp spectral power distributions is also available online.[22] As a last chance, if the source is incandescent light, the only information available is usually the correlated color temperature (CCT). In these cases, we may compute the spectral radiant exitance $M_{e,\lambda}$ by Plank's law:

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$$M_{e,\lambda} = \left[\varepsilon(\lambda)\cdot 2\pi\cdot h\cdot c^2\right]/\left[\lambda^5\left(e^{hc/\lambda kT}-1\right)\right]\ (\mathrm{W\ m^{-3}}) \quad (6)$$

where T is the CCT in Kelvin degree, $h = 66\,262 \times 10^{-34}$ is the Plank's constant, $k = 13\,805 \times 10^{-23}$ is the Boltzmann's constant, and c is the light speed. The function $\varepsilon(\lambda)$ is the spectral emissivity characteristic of the material. Materials with constant emissivity for every wavelength are called gray bodies. For tungsten filament lamps ($\varepsilon = 0.3$), the T of these lamps can vary from 2800 to 3100 K. For halogen lamps, the T is from 3000 to 3400 K. In this case, however, the transparent material's spectral transmittance, including the light source, should also be considered. If this data is unavailable, the only alternative is to measure the spectrum of the light source; unfortunately this is an activity that is not economically sustainable for a lighting designer.

3 | COMPUTING THE SPECTRAL INTENSITY DISTRIBUTION

In lighting design software, the key information for computing illuminance E_v on the surfaces is the LID, $I_v(C,\gamma)$, of luminaires, usually downloadable as .IES or .LDT file format. In a desirable future multispectral lighting design software, the data we need for the light sources is the spectral intensity distribution (SID) $I_{e,\lambda}(C,\gamma)$ with SI units (W sr^{-1} m^{-1}). This is the spectral radiant intensity emitted by the luminaire in its surrounding space as a function of three variables, the two polar angles C,γ and the wavelength λ. We need to obtain this from the manufacturers' available online data: $I_v(C,\gamma)$ and $S_e(\lambda)$. Usually, the normalized photometric LID $I_{v,1\mathrm{Klm}}(C,\gamma)$ is available, so the absolute photometric LID can be determined recalling Equation (1):

$$I_v(C,\gamma) = 10^{-3}\cdot I_{v,1\mathrm{Klm}}(C,\gamma)\cdot \Phi_{v,\mathrm{lamp}} \quad (7)$$

The problem here is that the LID contains only information on directional photometric intensities. Instead, the relative SPD $S_e(\lambda)$ contains normalized information of radiant spectral. However, it does not have a total energy value and SI unit (m^{-1}). To get the SID one cannot simply multiply $I_v(C,\gamma)$ and $S_e(\lambda)$ since the product has dimensional value (cd) (m^{-1}) $\neq$ (W sr^{-1} m^{-1}) that is physically not compatible with $I_{e,\lambda}(C,\gamma)$. For the calculation of $I_{e,\lambda}(C,\gamma)$, it should also be considered the human photopic spectral efficacy function $K(\lambda) = V(\lambda)\cdot 683.002$, which has SI unity (lm W^{-1}). We want to find how to justify this affirmation analytically. Remembering the definition of spectral radiant intensity $I_{e,\lambda}$, the definition (3) can be rewritten in the following way:

$$S_e(\lambda) = 100\cdot\frac{d\Phi_\lambda}{d\omega}\Big/\frac{d\Phi_{560\times10^{-9}}}{d\omega} = 100\frac{I_{e,\lambda}(C,\gamma)}{I_{e,560\times10^{-9}}(C,\gamma)} \quad (8)$$

where the differential solid angle $d\omega$ is along the direction identified by the polar angles (C,γ). We know, from the photometric definition of luminous intensity:

$$I_v = \int_\lambda I_{e,\lambda} K(\lambda)\, d\lambda \quad (9)$$

so if we define a function $I_{v,\lambda}$:

$$I_{v,\lambda} = I_{e,\lambda}\cdot K(\lambda) \quad (10)$$

Equation (8) could be written the following way:

$$S_e(\lambda) = 100\frac{I_{v,\lambda}(C,\gamma)}{K(\lambda)}\frac{K(560\times10^{-9})}{I_{v,560\times10^{-9}}(C,\gamma)} \quad (11)$$

In Equation (11) $K(560 \times 10^{-9}) = 679\,585$ (lm W^{-1}); however, the value $I_{v,\lambda}(C,\gamma)$ is not known for $\lambda = 560 \times 10^{-9}$ nm. Nevertheless, if from Equation (11) we get $I_{v,\lambda}(C,\gamma)$ it results:

$$I_{v,\lambda}(C,\gamma) = \left[\frac{I_{v,560\times10^{-9}}(C,\gamma)}{100\cdot K(560\times10^{-9})}\right]\cdot\left[S_e(\lambda)\cdot K(\lambda)\right] \quad (12)$$

in Equation (12), $I_{v,\lambda}(C,\gamma)$ is given by the product of two factors: the first, unknown, is a function of the polar angles C,γ, while the second is the product of two known spectral functions and depends only on wavelength. To determine the first factor, we can integrate Equation (12) with respect to wavelength:

$$\int_\lambda I_{v,\lambda}(C,\gamma)\, d\lambda = \xi(C,\gamma)\cdot S_v \quad (13)$$

where $S_v = \int_\lambda S_e(\lambda)\cdot K(\lambda)\, d\lambda$ and $\xi(C,\gamma) = \frac{I_{v,560\times10^{-9}}(C,\gamma)}{100\cdot K(560\times10^{-9})}$ could be computed:

$$\xi(C,\gamma) = I_v(C,\gamma)/S_v \quad (14)$$

where $I_v(C,\gamma)$ is the LID known by the manufacturers and defined in Equation (9). From the Equation (12) we could obtain the function $I_{v,\lambda}(C,\gamma)$:

$$I_{v,\lambda}(C,\gamma) = \xi(C,\gamma)\cdot S_e(\lambda)\cdot K(\lambda) \quad (15)$$

and from Equations (10), (14) and (15) we finally obtain the SID:

$$I_{e,\lambda}(C,\gamma) = S_e(\lambda)\cdot I_v(C,\gamma)/S_v\ \left(\mathrm{W\ sr^{-1}\ m^{-1}}\right) \quad (16)$$

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From the point of view of the SI units, the result is correct:

$$\left(\mathrm{m}^{-1}\right)(\mathrm{cd})/\left(\mathrm{m}^{-1}\,\mathrm{lm}\,\mathrm{W}^{-1}\,\mathrm{m}\right)=\left(\mathrm{m}^{-1}\right)\left(\mathrm{lm}\,\mathrm{sr}^{-1}\right)/\left(\mathrm{lm}\,\mathrm{W}^{-1}\right) \\ =\left(\mathrm{W}\,\mathrm{sr}^{-1}\,\mathrm{m}^{-1}\right) \tag{17}$$

This definition for the SID is calculated through the data provided by the manufacturers. For lighting design software computing, we observe that Equation (16) is the product of a function that depends only on the wavelength λ with a function that depends only on the polar angles (C,γ). Therefore, it is easier to integrate using numerical methods with respect to the wavelength (to get weighted multispectral values or tristimulus values XYZ) or with respect to the angles to compute the irradiance on surfaces. The value S_v must be determined with numerical integration since the two spectral functions $S_e(\lambda)$ and $K(\lambda)$ are tables not available analytically. Therefore the integration method on the wavelength domain by Meyer[1] must be excluded because of the possible presence of spectral discontinuities. For this kind of integration, the method of Deville[4] may be used. Alternatively, thanks to the computational power reached by today's PC, it is possible to use the more straightforward approach of uniform quadrature with a fixed footstep of 5 nm width for a total of 81 samples. In practice, such calculation must be done only one time in a preprocessing phase for every light source present within the project:

$$S_v=\int_{380}^{780} S_e(\lambda)\cdot K(\lambda)d\lambda \\ =5\times10^{-9}\sum_{i=0}^{80} S_e\left((380+5\cdot i)\times10^{-9}\right) \\ \cdot K\left((380+5\cdot i)\times10^{-9}\right) \tag{18}$$

To use the light source with a SID defined by the Equation (16) in a simplified multispectral computation model, it is also possible to use only three dimensions, the tristimulus values XYZ:

$$I_X(C,\gamma)=\xi(C,\gamma)\int_\lambda S_e(\lambda)\bar{x}(\lambda)d\lambda$$

$$I_Y(C,\gamma)=\xi(C,\gamma)\int_\lambda S_e(\lambda)\bar{y}(\lambda)d\lambda \tag{19}$$

$$I_Z(C,\gamma)=\xi(C,\gamma)\int_\lambda S_e(\lambda)\bar{z}(\lambda)d\lambda$$

4 | DISCUSSION

The proposed method for determining the SID has a limitation: it can be applied only to luminaires where the $S_e(\lambda)$ function does not vary with the polar angles (C,γ). Anyway, this is true for most of the luminaires used in general lighting, but it is not always confirmed with the advent of LEDs for lighting. For example, projectors used in the show have a chromatic emission that can vary according to the direction. However, the use of these products is generally temporary during the show. The stage color and lighting design follow very different methods and rules from general lighting.[23] There are also a few general lighting products with mixed emission today: white light for visual functions and colored light for indirect ceiling and wall lighting. In this case, in the practice of lighting design, it is pretty common to treat the different light sources present in these mixed luminaires as separate luminaires, hoping to have all the necessary data for the various light sources in the product. These applications follow the current of thought of biophilic design,[24] which proposes a reconnection to the lighting variation of the natural environment in the design of artificial human spaces. Another limitation is that when $S_e(\lambda)$ is determined through a reverse data construction process from the Cartesian graph of the spectrum, this operation could generate errors.[20]

In the limited instances where $S_e(\lambda)$ changes with the direction as a design choice of the lighting product, the only possibility to obtain the SID is to measure it. This measurement could be done using the newly available gonioradiometers for luminaires measurement and a suitable file format to store the measured data.[17] Measured SID is also required to be represented in 3D for the benefit of the Lighting Designer to help understand the color performance of the luminaire.[18] Having the SID of a light source available, the lighting design software has the starting point to manage the calculations in a radiometrically correct way. This requires three other fundamental steps, which various studies have already deepened.

The materials' colors must not be defined based on digital color models but based on the bidirectional reflectance distribution function (BRDF).[25] The BRDF can be measured with different methods,[26,27] also considering the spectral component,[28] approximated with analytical models based on the parameters of the material,[29,30] or more simply retrieved from online databases.[31–37]

The calculations of direct and indirect lighting must be physically correct. So it must follow the principles of global illumination defined in the integral rendering equation of Kajiya through solutions with path-tracing[38] or photon-mapping methods[39] based on Monte-Carlo methods.[40]

The final step concerns the image calculated using a multispectral global illumination algorithm. This image

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must be converted to digital color to be represented on RGB displays.[41] This poses the problem of chromatic adaptation and tone mapping algorithm that can best simulate the complex effect of visual perception known as perceptual constancy.[42,43]

5 | CONCLUSIONS

The principal characteristics we need to define for luminaires in lighting design software are the geometry of the luminaires, the LID, the variation of the luminous exitance on the source surface, and the SPD of the emitted light.[44] This paper presents a design-oriented approach to reconstructing the goniometric spectral data of luminaires without complex measurements, using the datasheets usually available online on manufacturers' websites. This work is for the benefit of the lighting designer, and above all, for the benefit of the lighting design software developers, to integrate it into a multispectral calculation system. Having multispectral calculations would also allow us, in the future, to design and evaluate the circadian component due to artificial light and indoor colors,[45] for example, by applying a computational model such as that of Rea.[46] However, there are currently no recommendations or standards worldwide for assessing circadian light.

The solid-state lighting revolution has changed the practice of lighting designers. Lighting design is no longer based only on the choice of luminaires taken from manufacturers' catalogs but also on semi-finished light sources products. The availability of LED modules and LED strips allows other professional roles such as makers and interior designers to dematerialize the luminaires with custom installations hidden into the architectural niches or behind large transparent diffusing surfaces. Having large surfaces emitting light generates another problem. The classical method to measure the LID, known as far-field photometry, uses the goniophotometer. This instrument measures the luminous intensity exiting in all directions around the luminaire. The photometer is placed at a distance of ~10 m or more to measure the luminous intensities relative to the center of light exitance. If the emitting surface is small, that is fine. When we have larger luminaires, the center is a conventional point placed in the center of the principal luminous exitance surface of the luminaire, considering it a point source. However, the nature of the known near-field photometry problem resides within this last statement. If a light source is geometrically extended, the LID measure allows to correctly use the LID to calculate the illuminance only at the same distance the measures have been done. In this case, in commercial software for lighting design, the far-field measurement is distributed with a uniform weight on a conventional emitting surface which can be a rectangle, an ellipses, or a spherical surface. So, new products and custom installations based on LEDs can have an emitting surface on which the color of the light emitted also varies according to the position. This means that a complete definition of the SID presupposes a more complex function for the geometrically extended light sources, $I_{e,\lambda}(C,\gamma,u,v)$ in which the emitted SPD also varies as a function of the parametric position on the surface (u,v). The problem, therefore, arises of how to measure and describe the light field surrounding these luminaires. If solutions to this further problem have already been proposed from a theoretical point of view,[47–49] there is still a long way to go for the implementation of lighting design software developers.

AUTHOR CONTRIBUTION

Maurizio Rossi: Conceptualization, formal assessment, writing and editing.

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CONFLICT OF INTEREST

The author wishes to state that no conflicts of interest exist.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

ORCID

Maurizio Rossi https://orcid.org/0000-0003-0480-7912

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AUTHOR BIOGRAPHY

Maurizio Rossi, MSc, PhD, full professor at Politecnico di Milano where is the chair of the Lab. Luce and member of the PhD, Design faculty. He directed 25 research financed projects on topics related to light and color. From 2012 to 2018 he was the President of the GdC-Associazione Italiana Colore, since 2022 is the vice-president of the AIC-International Colour Association and since 2021 he is member of the board of directors of the SID (Società Italiana Design).

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