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LARGE RESIDENTIAL AREA LIGHT POLLUTION MODELLING

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Abstract

The article explains approaches to modelling classic outdoor lighting systems, such as road lighting, but also new approaches to implementing the radiating characteristics of vertical light sources such as windows and advertisements. All these lighting systems are subsequently implemented in the residential area model with the specification of individual obstacles and their reflective surfaces. A light-technical model is calculated on the points located on the sphere surface named "virtual" software goniophotometer. The output is a lighting calculating model made from available sources simulating the most faithful copy of the residential area with regarding radiation into the upper hemisphere. All lighting systems that radiate at night into the outdoor space are included in the model (public lighting, windows, advertisements and cars). The performed calculations determine both the direct and total radiation of individual lighting systems into the upper hemisphere and thus enable a comparison of their influence on light pollution.

Keywords: Light Pollution; Residential Area; Software Goniophotometer; Luminous Intensity Distribution Curve (LIDC); Lighting Model

1 Introduction

The aim of the paper was to propose a lighting model of an urban district. Specifically, the area selected for a case study was Výškovice in Ostrava (see Figure 1), with a high proportion of blocks of flats without other relevant infrastructure such as commercial or cultural centres, sports facilities, industrial areas and transportation hubs. For this study, it was also necessary to carry out a number of analyses, such as counting the number of light emitting windows in all houses, calculating the maximum number of light emitting windows, determining the method of calculating the number of vehicles passing through the area in a given period of time, measuring the size of the radiating areas in the form of vertical advertisements and, above all, modelling the road lighting with regard to the exact placement, direction and height of the luminaires.

The model is designed for the best possible situation in terms of luminous flux radiation. This means that the calculations will work with new lighting installations in the worst-case scenario. From this point of view, the model provides a basis not only for assessing the impact of individual light sources and the application of other large outdoor light sources (shopping areas, industry, sports facilities, transport hubs, ...), but also for discussing the luminous flux emitted by the designed surfaces. This model is also an important basis for solving the effect of individual light sources.

Different lighting systems can be compared with each other and the effect of luminous flux on the upper hemisphere of new lighting systems can be compared at the design stage by modelling the worst-case situation for a given space.

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Figure 1 – Map of Výškovice Urban Area

2 Description of the Lighting Systems in the Urban Residential Area

Lighting system in the residential area under investigation in Výškovice consists of 4 parts (see Figure 2). Inside of residential area are light sources such as road lighting, light emitting windows, advertisements and low beam car headlamps lighting systems.

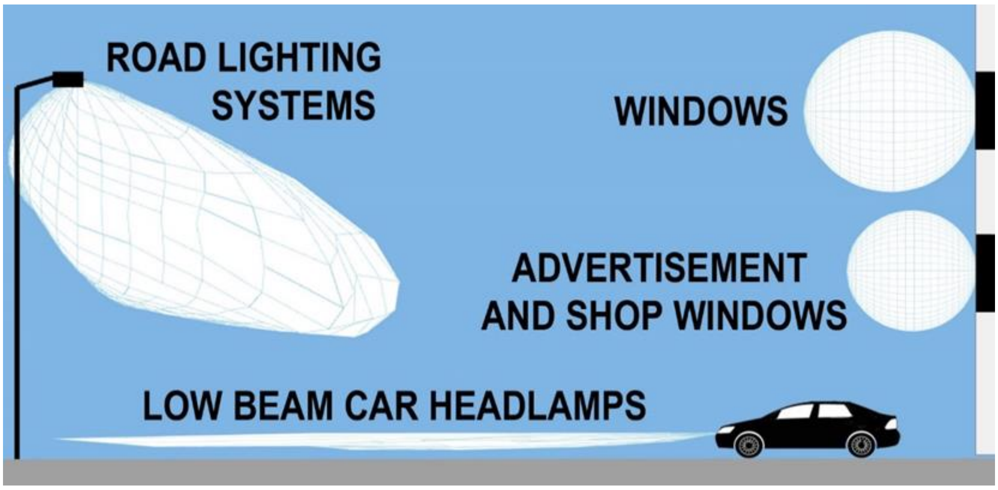


Figure 2 – Graphical Illustration of Lighting Systems in the considered Residential Area

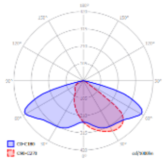
As this part of the city is predominantly residential, it consists mainly of high-rise blocks of flats, where approximately 18,000 inhabitants live. The transportation infrastructure also corresponds to this number of inhabitants. De facto, only road lighting is subject to the normative requirements [1]. Illumination of advertisements is respecting the requirements of the standard too [2]. More detailed requirements are not specified.

2.1 Road Lighting

The road lighting system is designed to ensure safe passage through the city. This lighting system operates throughout the night. For this reason, LED road lighting luminaires are predominantly used. As part of this district, the roads are classified from M2 to P4 [1].

930 road lighting luminaires are used with a total power of 50.5 kW. Of these, the LED luminaires emitting only to the lower hemisphere consist of 726 units with a total power of 26.9 kW. The luminaires equipped with high-pressure sodium lamps consist of 204 pieces with a total power of 23.6 kW. It should be noted that there are 3.5 times more LED luminaires. This situation is changing even more in favour of LED luminaires.

Table 1 – Description of Road Lighting

Luminaire type	Light source	LIDC example	Total luminaire power	Total luminous flux	Amount of luminaires
Road and asymmetrical luminaires	LED/HPS		50.5 kW	6,266 klm	930 pcs

Based on the evaluation of all LIDCs, it can be concluded that the lighting system formed by the road lighting luminaires can emit a maximum luminous flux of 6,266 klm.

2.2 Light emitting windows

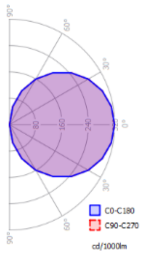
The presence of blocks of flats or detached houses is an integral component of any given neighbourhood. The light emitting window counts from the local survey were utilised in the modelling process. In order to obtain information about the number of light emitting windows, the residents were approached at the times of day when they were most likely to be at home and therefore most likely to have lights on.

As illustrated in Figure 3, the image shows the apartment building and the number of windows and light emitting windows. Utilising this example and additional measurements, the maximum number of light emitting windows in buildings was established at 50 %. Consequently, the maximum number of light emitting windows in the designated study area was set at 9,331. This amount was implemented in the calculation software uniformly on the vertical surfaces of the residential buildings.

Figure 3 – Example of Block of Flats with Light Emitting Windows

The prevailing tradition of using curtains and drapes in windows leads to the assumption that the average window in a block of flats should be modelled as a Lambertian surface, i.e. as a cosine radiator. The luminance of light emitting windows were measured. The average luminance of a light emitting window in a block of flats was found to be 6 cd·m^{-2}. This value was then converted into the LIDC with the average surface of the light emitting window (1.44 m^{2}) and the assumption of cosine distribution [7].

Table 2 – Description of Light Emitting Window

Luminaire type	Light source	LIDC example	Light emitting window luminous flux	Amount of Light emitting window
Light emitting window	Miscellaneous		27 lm	9,331 pcs

2.3 Advertisements

Advertisements constitute an integral component of urban development. These can be categorised as dynamic, static, or various shop windows. In this particular instance, a field survey was conducted within the urban area of Výškovice. Specifically, the field survey encompassed illuminated names of retail chains, their shop windows, restaurants with advertising space indicating the type of beer, petrol stations, news kiosks, etc. The actual dimensions of each real advertising space were assigned. The total area of active vertical advertisements in the study area was found to be 1,613 m^{2}.

The average luminance of the advertisements was determined from local and previous [7] measurements to be 50 cd·m^{-2}. As with the light emitting windows, this value was taken into account with the luminous area of the advertisements and the assumption of cosine radiation and converted into the LIDC a discrete luminaire (see Table 3). For the purpose of modelling

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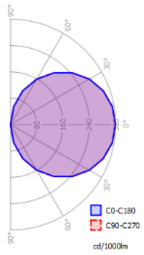
the radiation to the upper hemisphere, the total area of the active advertisements was divided into 35 units, corresponding to a 9.6 m by 4.8 m.

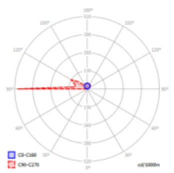
Table 3 – Description of Advertisements

Luminaire type	Light source	LIDC example	Luminaire luminous flux	Amount of billboards
Advertisement	Miscellaneous		7,365 lm	35 pcs

2.4 Low Beam Car Headlamps

There are several major problems in specifying the radiation caused by the lamps of cars passing through the study area. The first problem is to provide valid LIDCs that can then be implemented into the lighting model. The second problem comes from the need to specify the number of cars that are currently on the roads in the study area. It was possible to use publicly available traffic counts to determine the number of cars on the road. To calculate the maximum amount of cars, the traffic intensity between 18:00 and 22:00 o'clock was used. Based on the length of the roads and the maximum speed allowed, it is possible to calculate how many cars may be driving in a given area. For our study area and traffic density, 50 cars were calculated. For the lighting model, the LIDCs of the low beam car headlamps with a halogen lamps H7 (obtained directly from the automotive industry), were used (see Table 4). Based on the evaluation of the behaviour of the cars in the lighting model, it can be concluded that they are able to produce a luminous flux of 57.3 klm from their low beam car headlamps. The cars in the model were uniformly placed on the roads.

Table 4 – Description of Low Beam Car Headlamps

Luminaire type	Light source	LIDC	Luminaire power	Low beam car headlamps luminous flux	Amount of cars
Low beam car headlamps	2 pcs of halogen lamp H7		2 · 55 W	1,147 lm	50 pcs

3 Lighting Model Description

Lighting model of the residential area is based on the real documentation. It is made on the area 1 km by 1.5 km of the urban district Výškovice. The final 3D model of radiation with all described lighting systems is shown in the Figure 4. By implementing the overall lighting model of the residential area into the software goniophotometer [3, 4, 5], the behaviour of both the direct and the total (direct and reflected) component of the luminous flux, which is generated from the individual lighting systems and from the complex model, can be solved. The modelled results are compared from all possible points of view and their influence on radiation to the upper hemisphere (light pollution) will be determined.

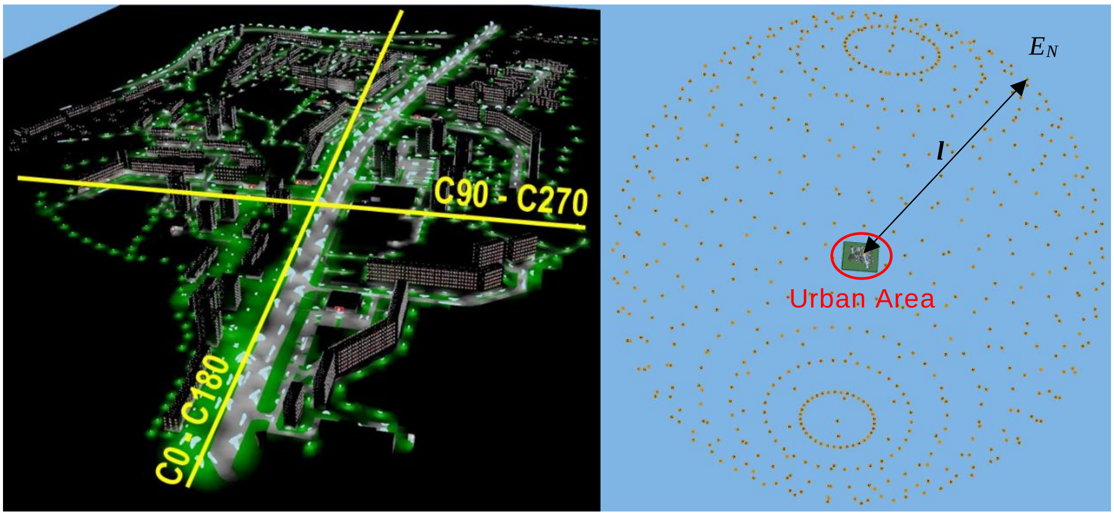


Figure 4 – Zoomed Model of Light System Installed in Residential Area on the Left Side [11] and the Same Model Installed in Software Goniophotometer on the Right Side

4 Materials and Methods

The model used for calculating the components of luminous flux radiated to the upper hemisphere emitted by individual lighting systems described in introduction of this article is based on the concept of a theoretical far-field goniophotometer [3]. This approach, detailed in a previously published article, applies fundamental principles of photometry, specifically the inverse square law, where the residential area is considered as a point light source [6, 7, 8]. The partial components of luminous flux are calculated from lighting systems described above.

The shape of the LIDC for different luminaires depends on particular lighting application and the target exterior area to be lit [1] comprising the task area and other associated areas that should be illuminated according to the relevant lighting standards. From the LIDC, it is possible to calculate the total luminous flux of a luminaire using the Formula (1).

$$\Phi = \int_{\gamma=0}^{\pi} \int_{C=0}^{2\pi} I(C,\gamma) sin\gamma d\gamma dC \text{ (lm)} \quad (1)$$

where

Φ is the total luminous flux in all directions;

$sin\gamma$ is the geometric factor accounting for the curvature of the surface during integration over the sphere;

$\gamma \in [0, \pi]$;

$C \in [0,2\pi]$.

The normal illuminance E_N which is determined in each calculation point of a software goniophotometer can be expressed by Formula (2),

$$E_N = \frac{I_\gamma}{l^2} \text{ (lx)} \quad (2)$$

Where

E_N is the Normal Illuminance on the software goniophotometer (see Figure 4);

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I_γ is the calculated luminous intensity;

l is the distance between the modelled object and the grid of calculation points (see Figure 4).

The software goniophotometer then by calculation transforms the normal illuminance in individual calculation points into the luminous intensity I_γ coming out from the centre of the model (point source). Usual lighting calculation software, which can work with measured LIDC in the form of photometric files of real luminaires, can work only with Lambertian surfaces. In real surroundings the mirror reflection is negligible, and all surfaces are very close to the Lambertian surface.

This model assumes that the luminous flux and LIDC of individual lighting system can be represented as point light sources [4]. Results represented by LIDCs of individually used lighting system enabling evaluations of their contribution to light pollution. The use of a software far-field goniophotometer made possible a detailed analysis of luminous flux distribution while considering the specific characteristics of each lighting system. These instructions, previously outlined in, should be a basic reference for further calculations and analyses in this context [7, 8, 9].

The total luminous flux radiated to the upper hemisphere comprises two main components. First part is the luminous flux radiated directly to the upper hemisphere. Second part is the luminous flux reflected from the terrain and other outdoor surfaces in the evaluated residential area. In addition to the already described advantage of this model, which contains individual lighting sources of light pollutions, the results can also be used to simulate worst-case scenarios. It should serve as a base for analysing the distribution of luminous flux in the upper hemisphere through atmospheric scattering, considering various meteorological conditions as well as the level of atmospheric pollution specific to the given area. Additionally, by dividing the luminous flux radiated to the upper hemisphere directly and reflected components and categorizing the individual lighting systems (such as building windows, road lighting systems, and others) it is possible to assign and describe their LIDCs using a polar coordinates.

For a correct calculation, in addition to the already described lighting systems, it is necessary to define the boundary conditions. Minimally is necessary to set maintenance factor and reflectance factors for all surfaces. For new lighting systems is radiation and that is why light pollutions highest. Because of it the maintenance factor [10] was set 1. Reflectance factors are defined not only on roads and other horizontal surfaces, but also on vertical surfaces that are represented by buildings [8]. All these surfaces are behaved as diffuse in the lighting model. For modelled surfaces were chosen next reflectance factors (grass and vegetation – 10 %, roads – 10 %, building facades – 30 %, concrete sidewalk – 25 %).

5 Results

The results of this model study can be found in the comparative images with 3D models of individual LIDCs and in following Table 5. The most dominant lighting system is road lighting, which radiates 6,266 klm. It is 91.7 % of the total luminous flux emitted from the investigated residential area. Due to the fact that the optical systems of road luminaires are highly sophisticated, this dominance is greatly reduced from the point of view of the direct radiation of luminous flux to the upper hemisphere. In our case, road lighting system radiate directly to the upper hemisphere only 12.5 klm, which is 0.2 % of the overall emitted luminous flux of these lighting systems. If we consider luminous flux directly radiated to the upper hemisphere from other lighting systems, we can see (Figure 5) that windows with luminous flux 113 klm and advertisements with luminous flux 94.8 klm are much bigger than road light system. It is because of their vertical placement.

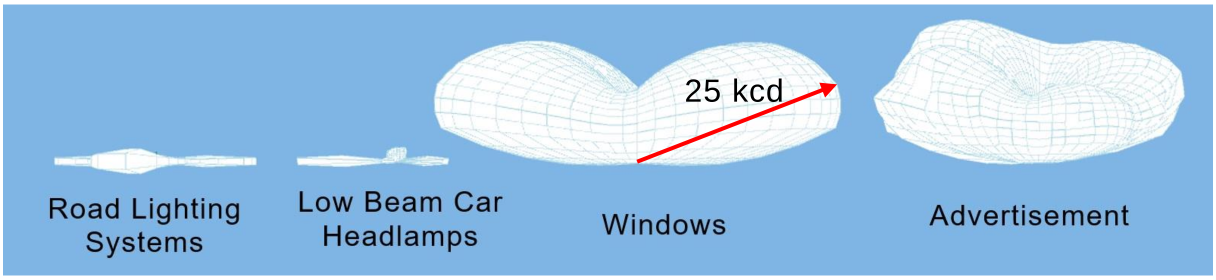

Figure 5 – 3D LIDCs of Direct Radiation from Particular Outdoor Lighting Systems to the Upper Hemisphere in the Same Scale [11]

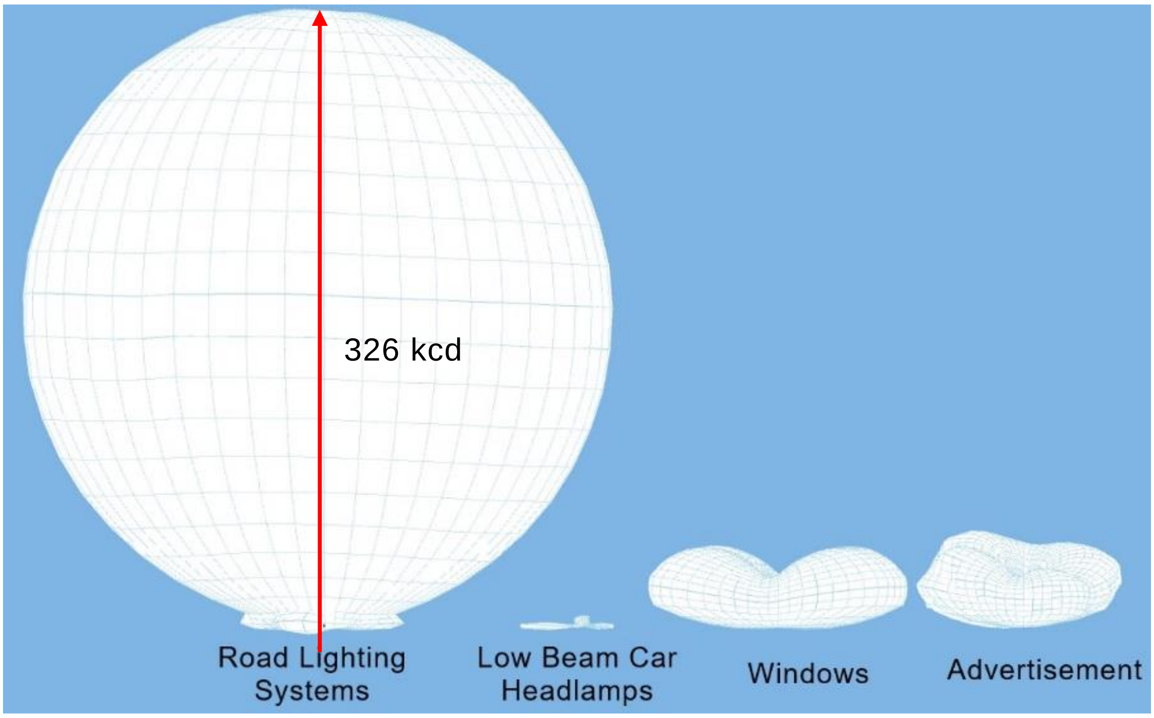

Figure 6 – 3D LIDCs of Total Radiation from Particular Outdoor Lighting Systems to the Upper Hemisphere in the Same Scale [11]

When we take together direct and reflected total luminous flux, the LIDCs will change. Because of big total luminous flux of road lighting system, it is total luminous flux radiated to the upper hemisphere increase rapidly to level 382 klm (Figure 6). From this point of view is very interesting to compare total influence of radiation to the upper hemisphere from light emitting windows which is 122 klm and advertisements which is 107 klm. Both are not dominant but comparable with road lighting system and its total radiation to the upper hemisphere.

Table 5 – Description of Modelled Radiation to the Upper Hemisphere from Výškovice Urban Area

	Road lighting	Light emitting windows	Advertisements	Low beam car headlamps	Total amount
Direct luminous flux	12.5 klm	113.4 klm	94.8 klm	7.9 klm	228.7 klm
Reflected luminous flux	369.7 klm	9.3 klm	12.1 klm	4.9 klm	396 klm
Total luminous flux	382.3 klm	122.7 klm	107 klm	12.7 klm	624.7 klm

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6 Discussion – Comparison of Outdoor Light Radiations from Different Light Sources

A comparison of the results with respect to the total luminous flux indicates that road lighting is the most dominant component, followed by advertisements, light emitting windows, and finally, low beam car headlamps. However, it is important to note that the largest outdoor light sources, such as railways, shopping centres, industry and sport stadiums, have not been included in the model design. In the event of the inclusion of these influences in a given design (influences which will be incorporated in other models due to the more general description of all light sources), it is evident that road lighting would be comparatively negligible in proportion to these sources of radiation to the upper hemisphere [12]. Although the levels of cars radiation may appear negligible, it is important to consider that these measurements are typically taken on relatively uncongested roads. In larger urban areas, these levels can often be several times higher.

If we look at direct luminous flux radiated to the upper hemisphere produced by advertisements and windows, it is evident that those are dominant radiators on the base of CIE recommendations and European technical standards. Even though the rules say that the maximum levels of direct radiation to the upper hemisphere should not be more than a certain amount, these levels were still exceeded many times in these cases. Advertisements are of particular concern, given that they frequently working throughout the night, even in the absence of observers. Another component of direct radiation to the upper hemisphere is road lighting system, which meets the limits set by the standard. The value of the radiation to the upper hemisphere from modelled road lighting system is only 0.2 %. This value is specific to high pressure sodium lamps, primarily attributable to their LIDCs. It is probable that this type of light source will be replaced by LEDs soon, resulting in the direct luminous efficacy of road lighting being zero. Considering the above, it is imperative to pose the following question for future consideration: does the necessity to restrict the direct luminous flux to the upper hemisphere hold rationality, and does the advancement of luminaires ultimately constrain their evolution to optics with flat cover glass, thus impeding the overall efficiency of these devices? The final source modelled is that of cars and their low beam headlamps. The necessity for direct radiation to the upper hemisphere has been implemented for two reasons: firstly, in order to see vertical obstacles, and secondly, in order to see vertical road signs.

The reflected component is determined by the physical properties of the surfaces. The predominant component is road lighting. Advertisements and light emitting windows have been identified as a further source of outdoor light. It is evident that the radiated component from advertisements exhibits a greater proportion compared to that from light emitting windows.

It is crucial to acknowledge that the proposed model is constructed as a worst-case scenario, with the maintenance factor fixed at 1. This stipulation signifies that the lighting system is to be operated as if it were new. Additionally, the design cannot take into account shading caused by trees, shrubs, and similar foliage. It is evident that these factors have a detrimental effect on the luminous flux radiating to the upper hemisphere. In reality, the results of radiating to the upper hemisphere should be reduced. From this standpoint, it is worthwhile to pose the question of how the so-called “ALAN – Artificial Light at Night” [13], caused by, for instance, urban agglomerations, can proportionally affect the surroundings in relation to the so-called "NLAN - Natural Light at Night". It is imperative to consider the total luminous flux modelled for the worst-case situation of 624.7 klm relative to the area of the urban area under investigation to obtain a luminous exitance value of 0.41 $lm{\cdot}m^{-2}$. A comparison of this value with the maximum value of the luminous flux generated by the Moon on all areas of the Earth, and not only on the bounded cities and towns, reveals a value of 0.25 lx ($lm{\cdot}m^{-2}$). This is half the value, but as previously stated, it is the radiation generated towards the surface of the Earth, and not the other way around, and within the whole area of the Earth. As demonstrated above, it is imperative to continue reflecting on the radiation to the upper hemisphere from the perspective that there are pressures to eliminate outdoor light, particularly in the area of the road lighting systems, even at the cost of reducing safety, for example by not complying with the normative parameters. Furthermore, it is crucial to determine whether these steps are essential to reduce ALAN.

Acknowledgement

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