Light & Engineering
Vol. 26, No. 1, pp. 144-152, 2018

Svetotekhnika
No. 2, 2018

METHODS OF CALCULATION OF FLOODLIGHTING UTILISATION FACTOR AT THE DESIGN STAGE

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ABSTRACT

The main aim of this work is to present different methods of calculation of these new parameters: floodlighting utilisation factor, useful luminous flux, loss of luminous flux and coefficient of floodlighting utilization factor. Each method is carefully described. There is also a general analysis of the assumptions and restrictions used in the calculations. The results of the calculations are presented and broadly discussed with reference to a very simple and a more complex floodlighting design. It was found that these parameters are very helpful and convenient in the assessment of the quality of floodlighting at the design level.

Keywords: floodlighting, energy efficiency, light pollution, floodlighting utilisation factor

1. INTRODUCTION

When we look from the perspective of time, we could say that the day when humans invented fire and used it to light up the dark night, was one of the most significant days in our history. The time for work became longer because of this invention. It has also had an impact on the evolution of technology through the ages. Artificial sources of light were developed in parallel to the development of technologies whose main aim was to make work much easier and more effective. The development proceeded from fire to torch, to oil lamp and finally, at the end of 19th century, to electrical light sources. The incandescent lamp, the discharge lamp and the LED are evidence of this technological growth. They are also a sign that our need to search for and find more refined solutions is infinite. However, the last few years have shown that universal access to this technology and the frequent usage of modern lighting equipment (generally LED lamps [1]), as well as the very low cost of manufacturing, has caused many different problems and threats, which form the opportunities of research for a large number of scientists.

1.1. The issue of energy efficiency

20th century was definitely the most effective period in the development of light sources. The usage of electrical energy became much more common due to the fact that people began to illuminate more frequently. The need to pay attention to the issue of the energy efficiency of lighting began to be realised, both in developed and in developing countries [2,3]. The matter of saving electrical energy has become a problem, which is now widely commented on in terms of its effect on the future of our planet [4]. Many experts consider 20th century as the "Century of Energy Efficiency". The latest research shows that there is a great energy-saving potential in lighting [5]. Nowadays, standards and legal regulations, aimed at the reduction in use of electricity for lighting purposes, have been created [6]. A new and interesting issue is that of Nearly Zero Energy Buildings (nZEB). This is also the basis of many engineering analyses [7,8,9].

1.2. The issue of glare

The phenomenon of glare is one of the main concerns in the area of lighting technology [10]. It is very important not only for interior lighting but also for exteriors. In the case of road and road lighting, there are some consequences related to traffic safety regulations. The analysis of this phenomenon is based on a theoretical calculation [11,12], or luminance measurement, which is quite problematic, even allowing for the contemporary possibility of using imaging luminance measuring devices (ILMD) [13].

1.3. The issue of light pollution

Light pollution is quite a recent problem. It is connected with many negative occurrences, such as skyglow, light trespass, and the lack of proper visibility of the stars [14, 15]. The requirements and regulations are not definite in this area. There are some guidelines [16, 17]; however, only a few countries e.g. Taiwan [18], have legal regulations associated with the reduction of light pollution. Scientists are also trying to measure light pollution and floodlighting utilisation factor in a quantitative way [19,20,21]. Calculation models of skyglow are created as well [22]. There are some attempts at analyses in order to improve the usage of luminous flux emitted from luminaires, which can lead to energy saving and a decrease in light pollution [23,24].

1.4. The photobiological threat issue

The development of light sources creates the need for the analysis of the influence of type of lighting and lighting parameters on plants and living organisms [25,26]. "Bad lighting" or, more specifically, spectral power distribution (especially at high energy in the range of wavelength (420–560) nm) can have a great impact on circadian rhythms, not only in humans, but also in animals and plants.

We need to search for methods that allow us to design lighting in a very considered way, in order to counteract the above problems and threats. These methods should allow us to eliminate potential threats or to let us have conscious control over them.

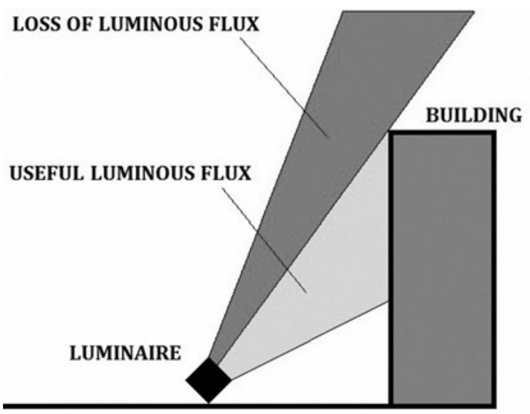

Fig. 1. The schematic approach to luminous flux analysis in floodlighting

2. NEW PARAMETERS AND CALCULATION METHODS

At present, there are no requirements or regulations in the literature connected with floodlighting design. However, there are some general recommendations [27, 28] and publications, which have been prepared by specialists with good practice in this field [29]. The problems of energy efficiency and light pollution have not been presented yet in the context of floodlighting. Contemporary assessment is done only at an aesthetic level and is rather subjective. However, there is the possibility of using some parameters, whose main aim is to assess floodlighting designs at the technical and engineering level. These parameters are shown by the formulae (1–7). The precise definitions are described in the literature [20,24].

$$FUF = \frac{\varphi_u}{\varphi_t} \cdot 100 \ [\%], \quad (1)$$

$$\varphi_t = \sum_{i=1}^{n} \varphi_{0_i} \ [lm], \quad (2)$$

$$FUF_{\max} = \frac{\varphi_t}{\varphi_{tlum}} \cdot 100 \ [\%], \quad (3)$$

$$\varphi_{tlum} = \sum_{i=1}^{n} \varphi_{lum_i} \ [lm], \quad (4)$$

$$\varphi_{loss} = \sum_{i=1}^{n} LOR_i \cdot \varphi_{0_i} - \varphi_u \ [lm], \quad (5)$$

$$\varphi'_{loss} = \frac{\varphi_{loss}}{\sum_{i=1}^{n} LOR_i \cdot \varphi_{0_i}} \cdot 100 \ [\%], \quad (6)$$

$$CFUF = \frac{FUF}{FUF_{\max}} \cdot 100[\%], \qquad (7)$$

where:

FUF is the floodlighting utilisation factor,

LOR is the luminaire output ratio,

$FUF_{\max}$ is the maximum value of floodlighting utilisation factor,

φ_u is the useful luminous flux,

φ_{loss} is the loss of luminous flux,

φ'_{loss} is the relative loss of luminous flux,

φ_t is the total luminous flux (of all light sources),

φ_0 is the rated luminous flux (of a light source),

φ_{tlum} is the total luminous flux (of all luminaires),

φ_{lum} is the rated luminous flux (of a luminaire),

$CFUF$ is the coefficient of floodlighting utilisation factor.

These formulae allow the calculation of the floodlighting utilisation factor, useful luminous flux, loss of luminous flux and coefficient of floodlighting utilisation factor. It has to be remembered that floodlighting has, until recently, focused only on visual effects and on ensuring lighting consistency and other aesthetic features. This fact confirms the need to determine what proportion of luminous flux emitted from the light sources used in the floodlighting project is actually being aimed at the designated surfaces. The Floodlighting Utilisation Factor (FUF) can be a useful parameter to enable this to be done [20]. It is defined as a ratio of useful luminous flux, which is aimed at the surface of a floodlit object and which causes a specific visual effect (such as luminance), to the total luminous flux, coming from all the light sources used in that lighting solution. By contrast, the part of the luminous flux, which is not aimed at the object, can be called the loss of luminous flux [20], Fig.1. It is exactly this part of the luminous flux, scattered around the floodlit object, which causes light pollution (provided that the luminaires are directed to the upper hemisphere) [20].

The definitions of these parameters are not new but the application is definitely innovative (in the floodlighting area). These calculations can be obtained by using Autodesk 3dS Max [30]. This software was chosen because of its usefulness during the process of floodlighting design by the method of computer visualisation [31] and because of the precision of the calculations [32]. The values of illuminance (illuminance distribution) can be obtained by using the calculation plane Light Meter. The user has the opportunity of changing the accuracy of the calculation by modifying the amount of calculation points. The Light Meter can be of any arbitrary size and the user can bend it freely or set it in any position. This allows for the possibility of creating a number of different calculation types. The basis of these methods is the illuminance distribution or luminance distribution on each plane. When the area S of this plane is known, the luminous flux φ, which reaches the plane, can be calculated by (8).

$$\varphi = \int_S E ds [lm]. \qquad (8)$$

Useful luminous flux or loss of luminous flux can be calculated, depending on how the planes are positioned with respect to the illuminated object. Therefore, the calculation methods can be divided into methods for the calculation of useful luminous flux and methods for the calculation of loss of luminous flux. Each of these methods has some special variants, and some advantages and disadvantages. Whichever method is chosen, all these parameters (1–7) can be calculated.

3. METHODS FOR THE CALCULATION OF USEFUL LUMINOUS FLUX

3.1. The method of evaluation of luminance by eye

This is the only method where using the Light Meter is not necessary. It is based on the assessment by eye of the average luminance on the pseudo colours diagram, Fig. 2. a, generated by the 3dS MAX. When the average luminance and area are

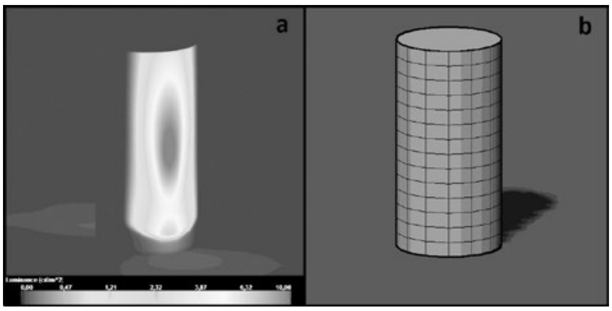

Fig. 2. Methods for the calculation of useful luminous flux: a – the method of evaluation of luminance by eye (luminance distribution on surface in pseudocolors scale), b – calculation grid on the surface of the object (object-surface method)

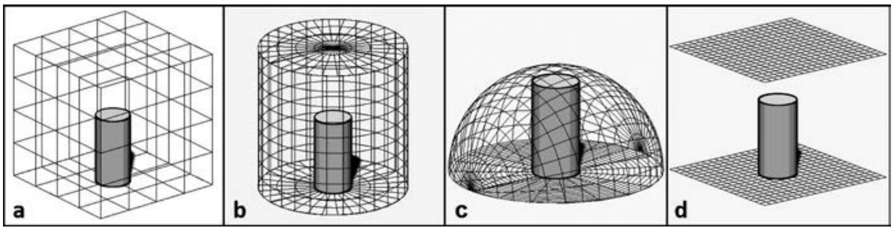

Fig. 3. Schemes of methods for the calculation of the loss of luminous flux: a – the cuboid method, b – the cylinder method, c – the hemisphere method, d – the parallel planes method

known, the useful luminous flux can be calculated by (9).

$$\varphi_u = \frac{\pi L_{avg} S}{\rho}[lm], \qquad (9)$$

where:
L_{avg} is an average value of luminance,
S is an area,
ρ is the reflectance factor.

This method is very quick to use. However, it has a very low accuracy. The values of average luminance are subjectively evaluated. Moreover, there is a problem connected with the proper value of the reflectance factor. Even small changes in it can cause a large discrepancy in the results. Therefore, this method will not be discussed any longer. In order to increase the accuracy and reliability of the results, methods based on the distribution of illuminance on the plane Light Meter should be used.

3.2. The object-surface method

This method is based on the positioning of the Light Meter on the surface of the illuminated object, Fig. 2b. By obtaining the illuminance distribution on the illuminated object and when the main dimensions of the surface are known, the useful luminous flux can be calculated by (10). This method is easier to use for an object with quite simply geometry, because of the difficulty in manipulating the Light Meter.

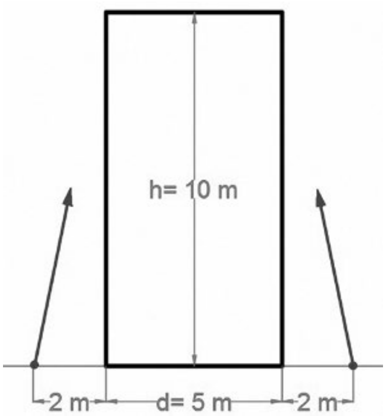

Fig. 4. The main dimensions and method of illumination of the cylinder

$$\varphi_u = ES = Eab \ [lm], \qquad (10)$$

where:
E is an average value of illuminance, a and b are the main dimensions of the surface.

4. METHODS FOR THE CALCULATION OF LOSS OF LUMINOUS FLUX

The methods for the calculation of loss of luminous flux are very helpful, especially when the geometry of the illuminated object is more complex and there is no possibility of positioning the Light Meter on the surface of the object.

4.1. The cuboid method

The cuboid method is based on the enclosure of an illuminated building by six Light Meters, forming a cuboid (or a cube, depending on the geometry of the inside object), Fig. 3a. By summing the luminous flux from every wall of the cuboid, we can obtain the loss of luminous flux (11).

4.2. The cylinder and hemisphere methods

In a similar way to the previous method, the loss of luminous flux can be obtained when the illuminated object is inserted into Light Meters that are bent into the form of a cylinder or hemisphere, Fig. 3. b, c. The value of loss of luminous flux can be obtained based simply on the geometrical formulae, which represent the area of a cylinder or hemisphere with a circular-shaped base (12–13).

Fig. 5. Computer visualisation of the concept of floodlighting of the Rector's Palace of WUT

Fig. 6. Luminance distribution of the concept of floodlighting of the Rector's Palace of WUT

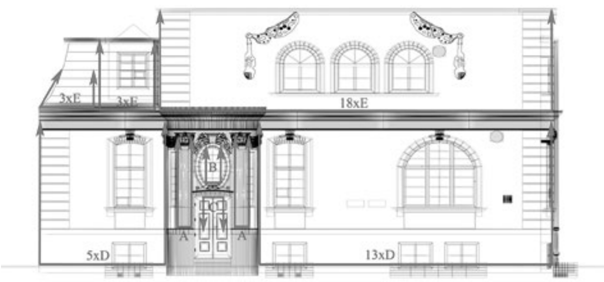

Fig. 7. Scheme of location and angle of direction of the lighting equipment (south wall)

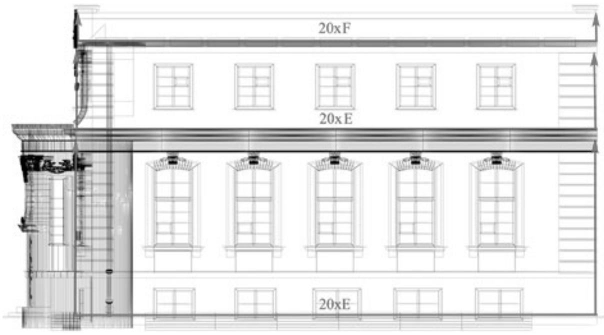

Fig. 8. Scheme of location and angle of direction of the lighting equipment (east wall)

For a cube:

$$\varphi_{nu} = \sum_{i=1}^{6}(E_i S) = \sum_{i=1}^{6}(E_i ab)\ [lm], \tag{11}$$

For a cylinder:

$$\varphi_{nu} = \pi R\left[R(E_{b1}+E_{b2})+2HE_s\right]\ [lm], \tag{12}$$

For a hemisphere:

$$\varphi_{nu} = \pi R^2 (E_b + 2E_{Sp})\ [lm], \tag{13}$$

where:

E_i is an average illuminance on the particular wall of a cube,

E_{b1}, E_{b2}, E_b are the average illuminance at the base of a cylinder or hemisphere,

E_{Sp}, E_s are the average illuminance on a hemisphere or on the side surface of a cylinder,

a and b are the main dimensions of the calculation of a surface,

R is the radius of a hemisphere or cylinder,

H is the the height of the cylinder.

4.3. The parallel planes method

The last method of calculation is the parallel planes method. The manner of insertion of the Light Meter onto the illuminated object is presented in Fig. 3d. There are two planes in this method: the first of them is located above the illuminated object and the second below the object. The calculation formula is the same as in the case of the object-surface method, but now the formula (10) allows us to calculate the value of the loss of luminous flux (14).

$$\varphi_{nu} = (E_A + E_B)ab\ [lm],\ \text{where} \tag{14}$$

E_A is an average illuminance on the plane which is located above the object,

E_B is an average illuminance on the plane which is located below the object.

5. CALCULATION FOR A SIMPLE DESIGN OF FLOODLIGHTING

All of the above calculation methods were tested on a simple design of floodlighting. This model

Table 1. Technical data of lighting equipment for a simple floodlighting design

Light source	Amount	ϕ_0, lm	*P, W*	LOR, %	φ_{lum}, lm	$\delta_{1/2}$
MH	2	3300	35	67	2211	C0–180: 16 C90–270: 16

Table 2. Results of the calculation for a simple floodlighting design

Method	Type	*E*, lx	*S*, m^2	φ_{loss}, lm	φ_u, lm	FUF, %	CFUF, %
Object surface	object	10,37	157	2794	1628	25	37
The cube 20m × 20m	top	5,25	400	2100	1440	22	33
	bottom	0,01	400	4			
	front	0,71	400	284			
	back	0,71	400	284			
	left	0,39	400	156			
	right	0,40	400	160			
				2984			
The cylinder R=10m H=20m	top	9,53	314	2991	451	7	10
	bottom	0,00	314	0			
	left side	0,78	628	490			
	right side	0,78	628	490			
				3971			
The hemisphere R=11,3m	base	0,00	314	0	2329	35	52
	hemisphere	2,61	802	2093			
				2093			
The parallel planes 100m x 100m	above	0,30	10000	3000	1422	22	32
	below	0,00	10000	0			
				3000			

consisted of an object with very simple "the cylinder" geometry with a height of 10 m and a radius of 2,5 m, Fig. 4. The cylinder was illuminated with two ground-recessed luminaires. The spatial luminous intensity distribution of these luminaires (for metal halide sources) was rationally symmetrical and the power of each of them was 35 W. The basic lighting and electrical parameters are presented in Table 1. The calculations were carried out only in relation to direct illuminance (the reflectance factor for all the materials in this model was zero, $\rho=0$). The computing grid maximum dimensions were 20 cm x 20 cm. The results are presented in Table 2.

6. CALCULATION FOR A COMPLEX DESIGN OF FLOODLIGHTING

Having shown the calculation for a simple model, it is now necessary to show a calculation for a complex design. The object, which formed the basis of this part of the research, was a floodlighting design, which has already been prepared for the Rector's Palace of the Warsaw University of Technology (WUT). The visualisation of floodlighting is presented in Fig. 5, and the luminance distribution of this concept in Fig. 6. The main concept of this floodlighting design is based on the usage of linear LED luminaires. All the facades are illumi-

Table 3. Summary of the lighting equipment for floodlighting of the Rector's Palace of WUT

Symbol	Light source	Number	ϕ_0, lm	P, W	*LOR*%	φ_{lum}, lm	$\delta_{1/2}$
A	LED	2	636	16	67	426	C0–180: 3 C90–270: 3
B	LED	1	636	16	63	401	C0–180: 13 C90–270: 7
C	LED	1	1260	50	39	491	C0–180: 10 C90–270: 27
D	LED	18	1584	50	39	618	C0–180: 10 C90–270: 27
E	LED	64	1584	43	39	618	C0–180: 9 C90–270: 26
F	LED	20	504	14	39	197	C0–180: 9 C90–270: 26

Table 4. Summary of useful information for both a simple and a complex floodlighting design

Type	Number	φ_{tlum}, lm	φ_t, lm	FUF_{max}, %
Simple design	2	2211	6600	67
Complex design	106	56360	143136	39

nated from bottom to top in such a way as to create a highly uniform effect. There are delicate lighting accents on the baroque-style entrance and on the decorations above it. The location, the directionality, and the technical data for the lighting equipment are presented in Figs. 7,8 and Table 3.

7. DISCUSSION AND CONCLUSION

The results show that each particular method is somewhat different from the other one – give different results. However, the main aim of this paper was only to introduce the possibility of the calculation of these new parameters at the design level. The analysis (e.g. of the influence of the size of the computing grid on each particular method) is not discussed in detail.

In the case of a simple floodlighting design, similar values of the floodlighting utilisation factor (22–25)% are obtained in the surface-object method, the cuboid method and in the parallel planes method. The cylinder method and the hemisphere method have divergent results, which could be caused by the need to manipulate the plane of the Light Meter in these two methods or by the low accuracy of the computing grid in this situation.

In the case of a complex floodlighting design, there is a much higher convergence in the results obtained. However, the closest values of the floodlighting utilisation factor (18–20 %) are obtained for the same methods as in the previous case. The results for the cuboid method and hemisphere method are much closer to the others in this case (21 % and 24 %). This seems to be connected with the use of much larger computing planes. In the case where the calculation with extremely high accuracy is required, it is necessary to be aware of the need for a compromise between the size of the computing plane and the density of the computing grid, depending on the parameters of the computer. However, it seems that the use of a sufficiently large computing area, with a highly accurate calculation grid, will unify the calculation results for all methods.

The calculations show that the values of these parameters are relatively small (FUF: (20–30)%; CFUF: < 62 %). There is also a high level of dependence between the floodlighting utilisation factor and the luminaire output ratio. It is necessary to use high quality lighting equipment in order to increase energy efficiency. It has to be ensured that the final result of the floodlighting design is as good as possible from a technical and engineering point of view and from an aesthetic angle. The analysis described

Table 5. Results of the calculation for a complex floodlighting design

Method	Type	*E, lx*	*S, m²*	φ_{loss}, lm	φ_u, lm	FUF, [%]	CFUF, %
Object surface	part 1	199,32	13,2	27162	2631	20	51
	part 2	45,15	30,0		1355		
	part 3	106,48	69,5		7402		
	part 4	40,54	39,4		1599		
	part 5	58,72	70,8		4157		
	part 6	93,86	75,7		7103		
	part 7	47,97	103,2		4951		
					29198		
The cube 30m x 30m	top	18,93	900	17037	26233	18	46
	bottom	0,47	900	423			
	front	3,09	900	2777			
	back	2,05	900	1845			
	left	2,76	900	2484			
	right	6,18	900	556			
				30128			
The cylinder R=15m H=30m	top	13,61	695,6	9467	30373	21	54
	bottom	0,43	695,6	299			
	left side	7,82	1413	11050			
	right side	3,66	1413	5172			
				25987			
The hemisphere R=24 m	base	0,27	1963	530	33983	24	62
	hemisphere	6,04	3617	21847			
				22377			
The parallel planes 100m x 100m	above	0,04	10000	400	26560	19	49
	below	2,94	10000	29400			

in this work could make it easier to apply floodlighting design in the context of a rational use of energy in the form of useful luminous flux, as well as in the reduction of the adverse effects of environmental light pollution in floodlighting.

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