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OPTICAL UTILIZATION FACTOR FOR ARCHITECTURAL LIGHTING

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ABSTRACT

Optical utilization factor (OUF) is applied to architectural lighting, searching to obtain low light pollution. It is demonstrated that OUF could not be used for the assessment of light pollution, because the inter-reflections could not be neglected. DIALUX simulations and MATLAB original functions are used. Onsite measurements for illuminance and luminance are performed. It is demonstrated that OUF could be greater than one for the facade. For the small scale inter-reflections, a luminance gain is demonstrated. Due to this, the floodlighting could be reduced. The understanding about the light pollution assessment is changed, which is a major achievement. It means that a greater OUF don't represent a lower light pollution, and also a facade could be more "visible" on lower level of floodlighting.

Keywords: luminance gain, concave inter-reflections, luminance measurements, mesh generation

1. INTRODUCTION

The traditional light pollution approach is based on visual comfort and saving energy. Light pollution is seen as an individual comfort criterion, and not at global scale as today, when one finds "studies for limiting the impact of light pollution on human health, environment and stellar visibility, the effects of light pollution on ecosystem and countermeasures or even focusing on society's disregard for the loss of a cultural asset that has been a part of art, science, and culture for as long as these things have existed" [1]. One direction of the researchers is to measure the global light pollution, observing the sky glow [2]. Other approach is focus on the sources of Light pollution. Obviously, the main source of light pollution is the street lighting, but the architectural lighting has also an important weight factor [3, 4]. Leaders in the fight of reducing the light pollution are astronomers, but with a wider approach [5]. Other interesting example is STARS4ALL network, a project funded by the European Union H2020 Program. This project is based on a comprehensive definition: "Light pollution is excessive, poorly directed or unnecessary artificial light at night" [6]. This definition is very clear with the terms excessive and poorly directed, but unnecessary could generate a special discussion, especially in context of facade lighting. The paradigm of this paper consists in the acceptance of hypothesis that the light is necessary for the beautification of the facade, with non-excessive level and perfectly directed, but the light pollution level could be different. This aspect could optimize through the Optical utilization factor (OUF). A supplementary example about the necessity of this study one find in [7], where light pollution is seen only like obtrusive lighting, sky glow, disability glare and trespass lighting are mentioned.

Optical Utilization Factor (OUF) demonstrates his relevance also in [8], where the real dimension of the problem can be found: "The dominant part of the light source luminous flux (70–80) % misses the building and is emitted towards the sky. This fact is much more important for determining light pollution than the fact when light reflected from even a too brightly illuminated facade" [8]. This estimation enhances the importance of OUF, more than traditional approach [9], where utilization factor (UF) was used as an indicator for energy efficiency of road lighting. From [10] one could take more similarity between facade lighting and road lighting, considering "the road lighting energy efficiency evaluation based on the normalized power density including the impacts of the applied lighting equipment, the reflection properties of the road surface (facade!), and the maintenance factor. The road lighting energy efficiency evaluation based on the installed power density permits including, in addition, any over sizing of lighting arising from too high (irrational) levels of road surface luminance compared to the required levels (or facade!)".

2. THE RELEVANCE OF OPTICAL UTILIZATION FACTOR (OUF)

OUF is a classical indicator in designing interior artificial lighting or street lighting. OUF is still used in recent papers [6].

OUF is the ratio of the lumens actually received by a particular surface to the total lumens emitted by a luminous source.

A specific definition, adapted to floodlighting is given below:

$$FUF = \frac{\varnothing_u}{\varnothing_t}, \tag{1}$$

where:

FUF – floodlighting utilization factor, similar to OUF,

$\varnothing_u$ – useful luminous flux

$\varnothing_t$ – rated luminous flux of the light source

The light output ratio (*LOR*) of luminaire is also very important parameter as the total loss of light energy including transmission through fittings is also taken into account.

The following expression (2) is used.

$$LOR = \frac{Output\ of\ Luminaire}{Output\ of\ luminous\ source} \ . \tag{2}$$

This convention could be accepted (FUF is equivalent to OUF), but the next affirmation, in equation (3) from [10], must be analyzed carefully:

$$FUF \le LOR \tag{3}$$

Any attempt to deny equation (3) seems to deny energy conservation law. Contrary this, one demonstrate that equation (3) is not true. The argument is based on inter-reflections (The illumination of an object by reflected light from other objects that are not light sources), which generates an effect of "multiplying" the luminous flux. After the demonstration of this, one uses the results to obtain the maximum visual effect with minimum luminous flux, equivalent with a reduction of light pollution.

A discussion is necessary, because ϕ_u (useful luminous flux) is not a theoretical parameter. Also in [10] it is determined using the luminance measurement of the facade, which includes, finally, the inter-reflections!

Following the same author, in [11] discovered details about how useful luminous flux is measured, based on field luminance measurements: "When the average level of luminance of the facade, its surface *S* and reflectance factor ρ of its materials are known, it is possible to calculate the useful luminous flux … (assuming that there are no inter-reflections)". But this last hypothesis was not studied at all in [10], and for a large number of facades (different from a flat surface) it is difficult to be accepted that the inter-reflections are absent.

3. THE FLUX AMPLIFICATION FACTOR OF CONCAVE INTER-REFLECTIONS

The idea of flux amplification factor is based on the well-known expression of illuminance in an integrating sphere [12]:

$$E_{fin} = E_1 \frac{\rho}{1-\rho} \ , \tag{4}$$

where

E_{fin} is the final (after inter-reflections) illumination in interior of the sphere,

E_1 is the initial (direct) illumination in interior of the sphere (lx),

ρ is the reflectance factor of the interior surface.

Obvious, affecting the equation (4) with the interior surface of the sphere (*S*), one obtains the expression of useful luminous flux:

$$\varnothing_u = \varnothing_t \frac{\rho}{1-\rho}, \tag{5}$$

Table1. Luminous Intensity for the Lighting Fixture Used In DIALUX Model

Angle	0°	1°	2°	3°	4°	5°	6°	7°	8°	9°
cd/1000 lm	8000	7900	7800	7700	7500	7200	6800	6300	5700	0

Table2. The Results Obtained from DIALUX Simulation (see Fig.1.)
(S_{facade} is the target surface, M_f is maintenance factor, and E_{med} is average illuminance)

	Entry				Results		
Symbol	$\varnothing_t$	S_{facade}	M_f	LOR	E_{med}	$\varnothing_u$	OUF
Units	lm	m^2	-	%	lx	lm	%
Values	2700	1.2x4	0.85	46.7	223	2696	99.8

Notice: the value for OUF is practically 100 % but its calculated value is 99.8. It is due to error as there is lack of sufficient decimals in DIALUX.

whence follows equation (6):

$$OUF = \frac{\varnothing_u}{\varnothing_t} \cdot 100\ \% = \frac{\rho}{1-\rho} \cdot 100\% > 100\%. \quad (6)$$

Off course, OUF is greater than one for an integrating sphere due to a maximum inter reflections phenomena. It can be concluded that for other facade configurations the OUF will be in different proportion. To observe this, one should start from simple hypothesis to more complexes one.

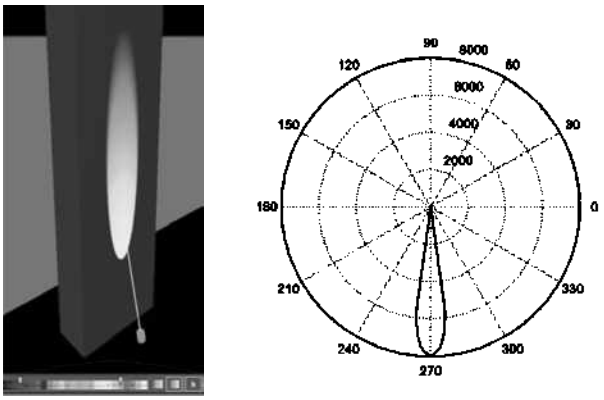
3.1. The Perfect Planar Facade

This is the most common situation, considered to represent a reference for the next configurations.

The DIALUX model is based on a vertical facade, dimensions 1.2 m x 4 m (surface area) implemented with a cuboid with 0.5 m thickness, positioned at (0, 4, 0) and rotation (0°, 0°, 180°). The dimensions give the possibility to replicate the model in DIALux. A floodlight is orientated from a distance of 0.3 m to the facade, respectively from the point in DIALux coordinates (0; 3.4; 0.1) and an angle of 165° from horizontal, respectively (0°; 165°; –90°). The floodlight has a source of 2700 lm, with *LOR* = 46.7 %. This extremely low value is calculated in LDT Editor Software (by DIAL), after the original file of the luminaire was modified, in order to eliminate the luminous intensity emitted over 9° from optical axis. The purpose of this constraint is to impose an OUF equal with 100 %, based on a total control of light. Considering a punctual rotational-symmetrical lighting fixture, the values imposed for this luminous intensity are presented in Fig.1. and Table 1.

The results (Table 2) are predictable, but useful for the next considerations.

We anticipate that OUF equal with 100 % is not the ideal situation, in the sense that no spilling light is generated by the luminaire. A fast estima-



a) b)

Fig. 1. The DIALUX model for a planar facade (a), and the polar curves for luminous intensity *(cd/1000lm)* of the luminaire (b)

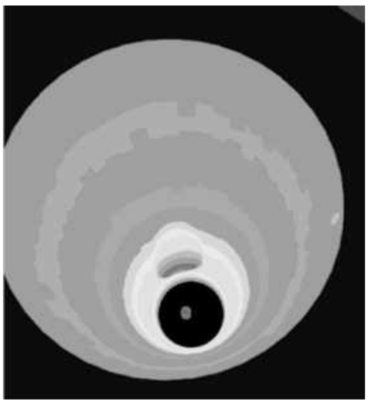


Fig. 2. The interreflections in an interior of a cylinder

Table 3. Optical Utilization Factor for the Cylinder Used in DIALUX Model

Wall reflectance	0.0	0.10	0.50	0.86
$\varnothing_u$ – useful luminous flux (lm)	2715	3110	23885	30340
$\varnothing_t$ – total luminous flux (lm)	2700	2700	2700	2700
OUF	1	1.152	8.846	11.237

The OUF for an integrating sphere.

Wall reflectance factor (ρ)	0.0	0.10	0.50	0.86
$OUF = \frac{\rho}{1-\rho} + 1$	1	1.11	2.0	7.14

tion can be done with (5), considering a white painting ($\rho = 0.86$) for that the flux amplification value results greater than six!

3.2. The Useful Flux Amplification from a Complete Cylinder

The inter-reflections on the usual facades are generated by cylindrical shape, in a small scale (window framing) or in a larger scale (on soffit or arches). In order to estimate the possible values, the limit of the useful flux amplification will be generated by a close cylinder by similarity with the integrating sphere as shown in Fig.2.

For a better understanding, Fig.2 was obtained by maintaining the lamp in the same position as in Fig.1.The wall is replaced by a cylinder with 0.3 m radius and positioned at (0, 3.4; 0.1). The height of the cylinder is the same 4 m, and the number of elementary surfaces used to approximate the cylinder was 44 (dimensions 42.84 mm x 4 m, equivalent to surface equal to 0.17136 m^2). For every individual surface in Fig.3, an average illuminance (lx) was calculated, giving the possibility to compare the direct illumination (available for reflection factor $\rho = 0.0$) with the other situation, where inter-reflections are presented with $\rho = 0.10$; $\rho = 0.50$ and $\rho = 0.86$. Result shows that $\rho = 0.10$ is very close to direct illumination and $\rho = 0.86$ gives maximum inter-reflections.

A technical observation is necessary: due to specific export of the results from DIALUX, all the data must be extracted individually, especially because in DIALUX the cylinder is solved like a collection of disconnected elements with particular values, not as a specific vector. Even with those difficulties, one obtains the balance between total flux of the lamp $\varnothing_t$ and useful luminous flux $\varnothing_u$ on the cylindrical wall:

Once again, OUF indicates that the total luminous flux will be amplified by the interreflections. Due to the specific method of computing of DIALux (photon method) and the difficulties in setting the calculus points for the cylindrical elements, a certain uncertainty over the results from Table 3 must be avoided. The main source of uncertainty is the comparison with the integrating sphere, where

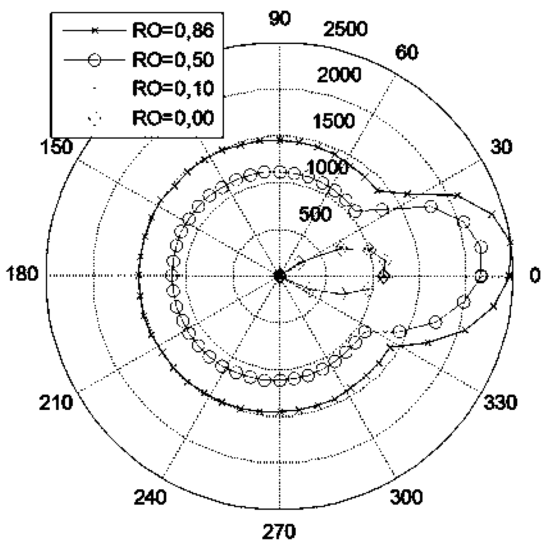


Fig. 3. The average illuminance (*lx*) in the interior of the cylinder, for different reflection factors RO(ρ)

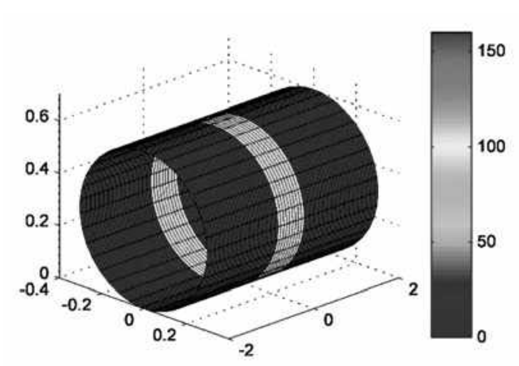


Fig. 4. The MATLAB model for interreflections in a close cylinder (initial illuminance,100 lx)

Table 5. The OUF Calculation After Every Reflection in the Cylindrical Concavity

No.. of reflection	1	2	3	4	5	6
Transmitted Flux (lm)	5679	1587	512	159	50.2	15.7
Attenuation	-	0.279	0.323	0.312	0.314	0.313
Total flux (lm)	5679	7267	7779	7939	7990	8005
OUF	1.000	1.279	1.370	1.398	1.407	1.409

the OUF has a well-known value, calculated starting from the constant of the sphere $\rho/(1-\rho)$ in addition with one (the direct illumination from the source), as in Table 4:

This correction is possible using the exact calculus of the interreflections, developed in MATLAB by the authors.

3.3. The MATLAB Calculation for OUF for a Complete Cylinder

The interior of a similar cylinder as in Fig. 2, with diameter of 0.6 m and length of 4 m was generated in MATLAB. A direct illumination was imposed for a central region, with a constant level of 100 lx. This hypothesis could simplify the analysis of the reflected flux, with contribution to the final value of OUF. The advantage of MATLAB calculation consists in successive evaluation of every reflected flux.

Mesh generation for this cylinder is presented below:

R=0.3m;% Radius of the cylinder used for interior inter-reflections

j=1–59, Number of elements on the generatrix of the cylinder

i=1–36, Number of elements on the directrix of the cylinder

*XCIL(j, i)=R*cos((i-1)*2*pi/35);% domain (–0.5 to 0.4) in Fig.4*

*YCIL(j, i)=2-(j-1)*4/58;% domain (–2 to 2) in Fig.4*

*ZCIL(j, i)=.30-R*sin((i-1)*2*pi/35);% domain (0 to o.6) in Fig.4*

end

end

After the imposing of the direct (initial) illumination level equal to 100 lx (light grey colour in Fig.4), the initial model for inter-reflections in MATLAB was obtained:

The inter-reflections in the deep interior of the cylinder ***follow the model of the integrating sphere*** as in Table 4. It is due the fact that the luminous flux

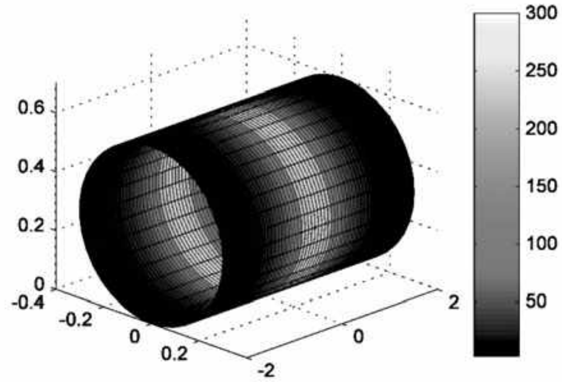


Fig. 5. The interior illuminance (lx) after six inter-reflections

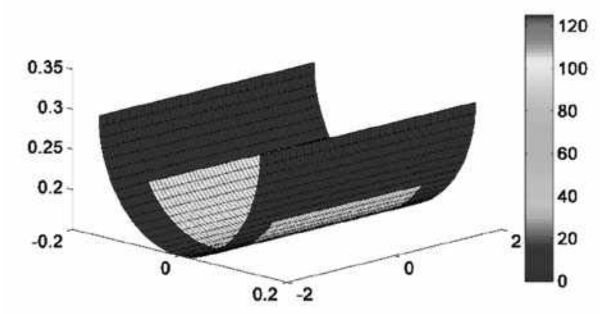


Fig. 6. The cylindrical concavity, with initial direct illuminance (lx)

spill through the extremity of the cylinder could be neglected (as it is 4 m long). In this way a fast confirmation of the precision of our calculation is obtained.

A visual examination indicates that luminous flux, *after six Lambertian reflections*, is located in the central region of the cylinder also, as shown in Fig.5.

3.4. The OUF of a Cylindrical Concavity of a the Facade

After the previous validation of the MATLAB model, a general situation of a cylindrical concavity with a central illuminated zone could be evaluated. This hypothesis is based on the small or medium size concavity in facades, and the purpose is not the

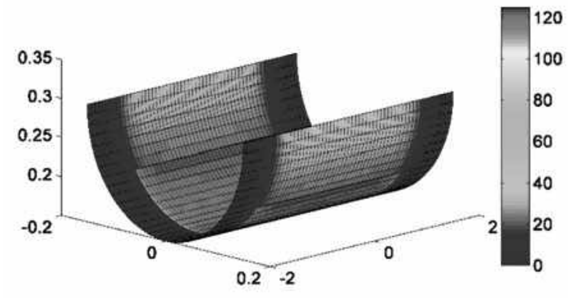
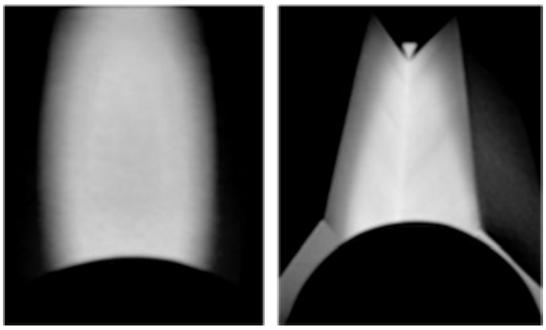
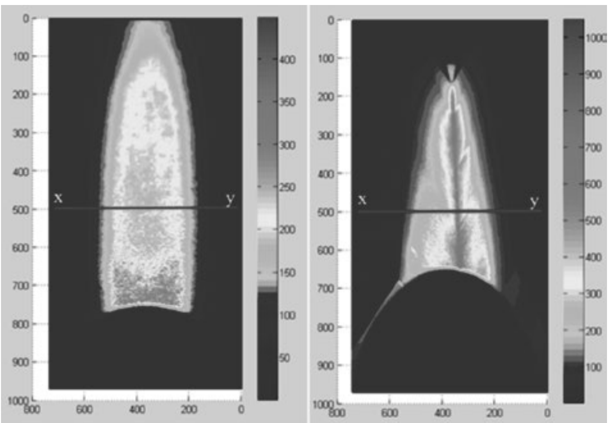


Fig. 7. The cylindrical concavity with final reflected illumination after six steps



a) *b)*

Fig. 8. The image for luminance measurement for (a) the planar surface and (b) prismatic concavity



a) *b)*

Fig. 9 The luminance (cd/m^2) for the planar surface (a) and prismatic concavity (b)

calculation of the OUF, because it depends by random factors. OUF is greater than 100 %, just to illustrate that OUF is not a good indicator for light pollution.

In Fig. 6 the initial configuration is presented with 36 x 56 cylindrical elements, illuminated with 100 lx (from element 9 to 28 on the directrix and from element 9 to 49 on the generatix).

In Fig.7 the total reflected flux after six steps of cflculations can be visualized.

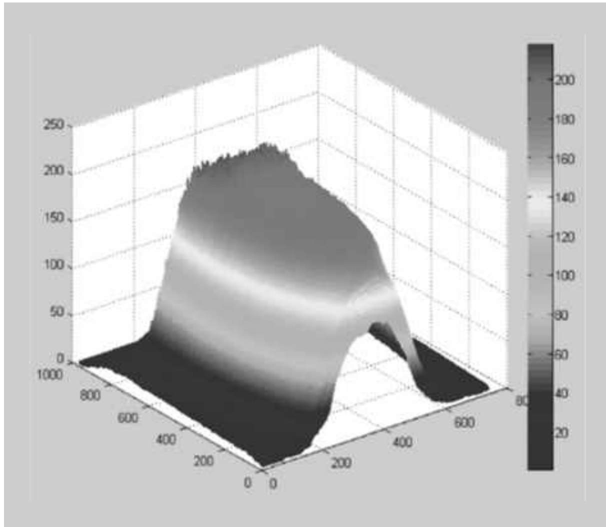


Fig. 10. The RGB values for the flat illuminated surface of the facade, as in Fig.9, a.

After qualitative assessment, a quantitative assessment is available in Table 5, where the reflected luminous flux is evaluated at every step.

A fast comment is very important, because after sixth inter-reflections, the luminous flux has decreased significantly and may be neglected. Even in this particular situation, value of OUF changes very fast and becomes bigger than 1 (or 100 %), indicating that OUF could not be used for as a quality light pollution indicator.

4. MEASURING THE OUF AUGMENTATION

A higher OUF represents a good objective for designing to obtain low light pollution, even if it will not be an objective criterion. Using inter-reflections, where the facade gives the possibility to increase the luminance of the facade, with the same luminous flux emitted by the luminaires. An experimental demonstration will bring the scale of benefit when inter-reflections on facade are involved. A simple test bench was used, consisting in a floodlight working tangential on a planar surface. This initial configuration serves like a referential for the situation when the planar surface is replaced by a decorative prismatic profile surface of 3cm at an angle of 80°. The field luminance was measured, using a photo camera with the same parameters of exposure and particular transformation from RGB to luminance [13, 14]. In Fig.8 the visual aspect of the bench and in Fig.9 the luminance (cd/m^2) are presented.

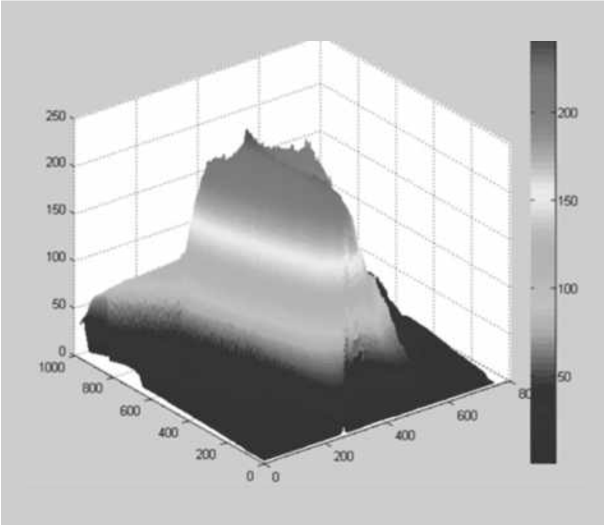


Fig. 11 The RGB values for the prismatic concavity illuminated in the same condition as in Fig. 10

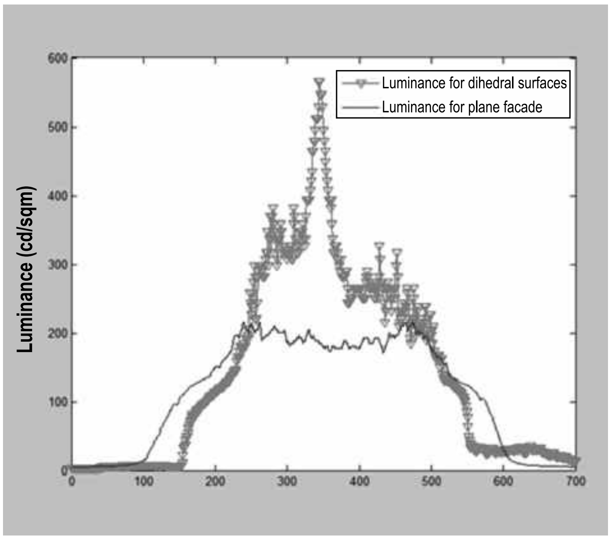


Fig. 12 Luminance comparison (cd/m2) for central field of the images from Fig.8, with specification x-y in Fig. 9

The initial results for Fig.9 (a) are presented in Fig.10, where it can be noticed that the luminance in the central illuminated region is cvasi constant, with RGB level close to the value of 180.

After the introduction in the luminous field of a small prismatic concavity (without any other change), the luminance field generates different results, as shown in Fig. 11.

In Fig. 11 it is illustrated that the data from Fig.9 (b), and the luminance in the central field has an obvious increase with maximum RGB values close to 230. The interior dihedral angle has a higher luminance, which is a positive effect considering the accent on the facade. It is worth mentioning that this effect is obtained with the same lighting configuration as in Fig.8.

Even after a qualitative conclusion obtained from Fig. 10 as compared with Fig.11, a quantitative assessment of the luminance is necessary, based on the fact that the CCD sensor (used for this work is NIKON D5300 photo camera) has not linear characteristics [13, Fig.1] and introduces a saturation effect for higher values of luminance. Using an experimental OECF (optoelectronic conversion function) obtained for our photo camera and considering the particular settings (exposure time 1/20s, diaphragm F8 and ISO100), luminance (cd/m^2) for those two different hypothesis is presented.

In Fig.11 the luminance field has different colour map as compared to Fig.10, but it can be noticed that the effective differences are very high. To obtain the increase in intensity, the luminance values from the direction x-y (the horizontal line in Fig. 9) are extracted and presented on the same plot and the same axis for a better comparison as in Fig. 12.

In absolute values, the amplification effect of the luminance is greater than double, and this is another interesting effect, giving the possibility to obtain the same visual effect with less luminous flux and less light pollution. A supplementary comment is necessary for the high level of the luminance in Fig. 12, which was chosen due to the small scale of the model.

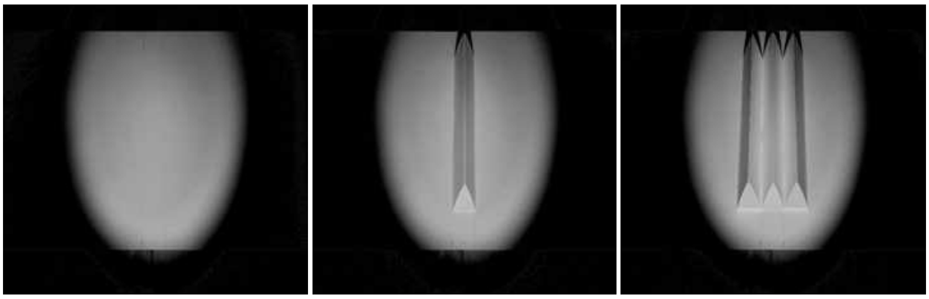
5. LUMINANCE GAIN ON MULTI LONGITUDINAL PROFILES

For architectural details, the luminance gain generated by the longitudinal profiles could be useful to decrease the floodlighting level, due the increasing of luminance contrast on some window frames, for example. The decreasing of the general floodlighting represents the method to reduce the light pollution. To demonstrate how the luminance gain occurs, one study not a prismatic concavity as in Fig.8, but one compare the luminance obtained from a flat facade (Fig.13, a) with a facade with one longitudinal (triangular) profile (Fig.13, b), respectively three longitudinal profiles (Fig.13, c).

The transversal luminance, for the midle of the scene, will demonstrate the luminance gain, as in Fig.14.

Finally, introducing three longitudinal profiles, one can compare all three scenes.

The profiles dimensions are 25 mm at the base and 48 mm in height, and the material is bright



a) The flat facade b) Facade with one profile c) Facade with three profiles

Fig. 13 Luminance gain on longitudinal triangular profiles

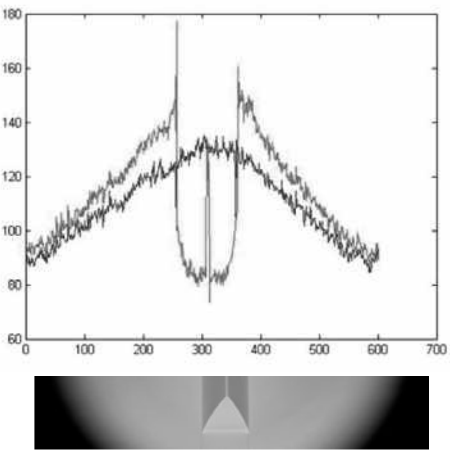


Fig. 14 Luminance gain (cd/m²) from one longitudinal profile (upper curve) compared with the flat facade luminance (lower curve)

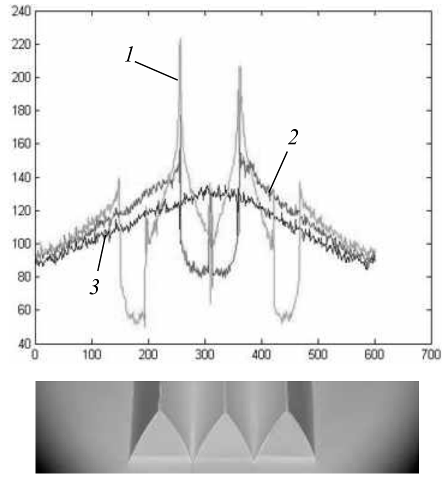


Fig. 15. Luminance gain (cd/m²) from three longitudinal profiles (1) compared with the single profile luminance (2) and flat façade luminance (3) as reference

white paint. The geometry and the electrical parameters were constant for all the scenes.

A single profile don't produce a significant luminance gain (curve 2, Fig.15), but multiplying the profiles, the effect will be more intensive in the concavity, where the inter-reflections will be present (curve 1, Fig.15), producing 160 to maximum 200 cd/m² compared with 120 cd/m² as initial value, for flat facade. The luminance gain of 50 % is very important, especially for the close observer. This could encourage the lighting designer to reduce the general (average) illuminance level, knowing that some details on the facade will generate increased luminance levels.

6. CONCLUSIONS

OUF augmentation (calculated and measured) shows that a greater OUF don't represent a criterion for lower light pollution. The OUF is one important criterion, but only in the early steps of the designing process, giving some information about the direct light spill to the sky.

If the inter-reflections are considered, the situation is different. Using the small scale profiles existing on the facades, some important luminance gain could be obtained. Due this, the design process could decrease the general floodlighting, with an important effect for light pollution reduction. Starting from luminance gain of 50 %, this could be the reduction ratio for the floodlighting, a very interesting challenge.

Reducing the light pollution is possible maintaining the beautification of the facades. This is possible if the facade details could be involved in a creative way, changing the philosophy of the "wall of light" with one of "beauty of the details". The details will be more visible due the luminance contrast as in Fig.15, obtained not by using the shadows, but through luminance gain.

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light on human wellbeing, biodiversity, visibility of stars, safety and energy waste.

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