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THE IMPORTANCE OF THE PHOTOMETRIC DISTRIBUTION OF LUMINAIRE AND ITS INFLUENCE ON LIGHT POLLUTION

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ABSTRACT
If we want to illuminate something properly and therefore reduce light pollution as much as possible, we should ensure that the light reaches only the areas where it is needed. Therefore we need to manage the light flux emitted by the lamp as effectively as possible.

*"**Light pollution,** weather it keeps you awake through a bedroom window or impedes your view of the night sky, is a form of pollution" and should be reduced.*
Artifitial lighting has become indispensable in all parts of everydays life. But, together with success, expansion brings abuse, errors... Certain installations, badly adopted to their environment, generate nuisant light by:
- spreading light outside the areas that are supposed to be lit,
- causing glare for the inhabitants,
- lighting fasades and exterior of privat properties unapropriately.

In some European countries, recommendations, with the aim to limit different kinds of light pollution, have been already proposed.
International Commission on Illumination issued in 1997 the latest Guidelines for minimizing sky glow (TC 4-21). Obtrusive light was analysed in terms of quantity, direction and spectre for causing nuisance giving rise to annoyance, discomfort, distraction and reduction in the ability to see essential information. **Sky glow** represents light zone on the night sky, extensive and diffused, which is visible in the direction of cities, airports, industrial and sports centres. We can distinguish:
- natural glow due to radiance of celestial sources and luminiscence of the upper atmosphere,
- artifitial glow due to artifitial radiance that consists of:
  - direct light from lamps and luminaires towards the sky,
  - light reflected from the lit surfaces.

Artifitial glow does not depend exclusively on the instalation, but also on the athmospheric conditions: humidity, clouds, haze, pollution…
It appears that:
- the ground reflection intervenes in a preponderant way in the light reemission in the upper hemisphere whatever the luminaire's photometric distribution is;
- at an equal luminance level of 1 cd/m^2, the luminance efficiency of the semi cut-off luminaire gives the possibility to increase the spacing and thus to decrease the luminaire's electrical power.

The **design of the luminaire and the lighting scheme** are two of the most important factors that have to be taken into account. The **photometric distribution**, as a direct result of different combination of light source, reflector and protector, is of great importance.
This paper will try to demonstrate that street lighting luminaires with semi cut-off photometric distribution with a high luminous efficiency will produce a lower light pollution than the cut-off luminaire.

THE DESIGN OF A LIGHTING SCHEME

We should take the following factors into account when designing a lighting installation:
- the level required in view of environmental factors, governed by standards.
- integration of the fitting within its environment;
  - colour temperature and reflection; the choice of lamp;

- shape and colour of the luminaire. This should match the environment and be in harmony with the rural and urban planning.
- choice of locations. These are not always freely available. In any new project the lighting should be viewed as a central element of the design.
- financial aspect:
  - the wattage used; the annual cost of electricity,
  - the cost of installation; the fewer the fixtures needed the cheaper this will be,
  - maintenance; the lamps and control gear should be easy to replace. This component of total costs, that is often overlooked, should be budgeted for in advance.

THE DESIGN AND CHARACTERISTICS OF A LUMINAIRE

In simple terms, luminaire consists of a mirror (reflector), placed around a lamp, all contained in a protective casing that can be fixed to a lamppost.

The mirror plays a dual role:

- combined with the lamp it should maximize luminous efficiency,
- together with its casing, it should guarantee luminous efficiency over a sustained period.

Luminaires should give maximum luminous efficiency, not just when being new, but over a long period of time (in exploitation). They should direct the light from the lamp onto, as big as possible part of the surface needed to be illuminated, as efficiently as possible and with the best possible photometric results.

Luminous Efficiency of a Luminaire

A large lamp takes up a large part of the reflector, and so, once reflected by the mirror, the light from the top part of the lamp cannot escape and is therefore re-absorbed.

However, a lamp with a small, tubular burner, such as an HPS lamp, has a small volume in proportion to the reflector. This allows us to select a reflector which will prevent light spreading behind the lamp, enabling us to focus it for the best results.

The same principle applies to long lamps, such as fluorescent tubes and LPS lamps. Since it is not possible to control the transverse distribution, the luminous efficiency of the lamp/reflector combination will be reduced.

The total luminous efficiency of the light source is represented by the number of lumens, or the quantity of light emitted by the lamp per single Watt of power, taking into account the power consumption of a control gear. The data given correspond to lamps the most frequently used in street lighting. The luminaire efficiency represents the percentage of light emitted by the lamp that reaches the surface to be illuminated.

The following table shows how the total luminous efficiency of a lighting installation depends on lamp efficiency on one hand and luminaire efficiency on the other.

Table 1. Luminous efficiency

LAMP	TOTAL LUMINOUS Eff. of Light Source	LUMINAIRE EFFICIENCY* (%)	TOTAL EFFICIENCY (lm/W)
Incandescent Lamp	15	10	1.5
Fluorescent Lamp	90	25	22
HPMV	50	30	15
HPS elliptical	95	30	28
HPS tubular	95	45	43
LPS 36 - 180 W	120 - 170	25	30 - 42

* Efficiency for an installation where the road width is equal to the fixture height (L/H = 1).

Luminous efficiency

The table shows that the greatest efficiency can be expected from an installation fitted with the HPS tubular lamp. After that comes the LPS installation, but due to the size of the light source, it is impossible to exploit its high efficiency completely.

- Ø By managing the light flux efficiently we can obtain the required levels of lighting using lamps of smaller wattage.

Mechanical characteristics

In view of climatic conditions: temperature, wind and rain, vandalism and atmospheric pollution, the aim is to keep the fixture in an "as new" condition for its whole working life, which can be up to 30 years.

With this in mind Schréder has developed a "Sealsafe®" optic that is hermetically sealed. Its tightness degree corresponds to IP66.

- Ø By ensuring that the optic cannot become fouled, an installation need no longer be over/sized. Furthermore, the Sealsafe® system prevents the light flux to be diffused from the protector in an uncontrolled manner.

RESTRICTION OF THE UPWARD LUMINOUS FLUX WHEN DESIGNING AN INSTALLATION

Functional Luminaires

The light coming from street luminaires must not be emitted above the horizontal.

This can be achieved by equipping the fixtures with effective mirror optics with a flat glass or curved glass protector. This affects the distance between the lampposts, which is reduced to achieve a uniform light distribution. Some examples of these optics are:

- refractor with broad emission of light, whereby the distance between the posts can be increased,
- deep bowl protector with broad emission for average distances between posts,
- curved tempered glass to restrict light pollution and give visual comfort for the driver,
- flat glass gives a very concentrated spread of light.

ULOR (Upward light output ratio) is the proportion of the flux of the lamps of a luminaire that is emitted above the horizontal when the luminaire is mounted in its normal, designed position.

DLOR (Downward light output ratio) is the proportion of the flux of the lamps of a luminaire that is emitted below the horizontal when the luminaire is mounted in its normal, designed position,

UWLR (Upward waste light ratio) is the proportion of the flux of a luminaire that is emitted above the horizontal when the luminaire is mounted in its installed position.

$$\mathbf{UWLR = ULOR / (ULOR + DLOR)}$$

The following table compares the UWLR for various optics and their effect on the wattage. The first four optics are fitted with tubular lamps and effective mirrors, each with different protector: flat glass, curved tempered glass, refractor and deep bowl. The first optic is the same as the later, but equipped with a coated elliptical lamp. The sixth comprises an LPS lamp with refractor.
The final version is a fixture with an upright elliptical lamp and no optic in particular.

(1) The first column gives the percentage of downward flux (DLOR).

(2) The second column gives the percentage of upward flux (ULOR).
(3) The third column gives the value of the UWLR = (ULOR / (DLOR + ULOR))
(4) The fourth column gives the total light flux required from the lamp to achieve an average luminance of 1 cd/m^2. (D = 40m, b = 6m, H = 8m)

Table 2

	1	2	3	4	5	6	7	8
OPTIC	h **DLOR (%)**	h **ULOR (%)**	**UWRL (%)**	F **req. flux (lm)**	F **upw (%)**	F **refl (lm)**	F **total upw (lm)**	**P (W)**
Tubular + flat glass	72.8	0	0	13420	0	1954	1954	141
Tubular + curved tempered glass	85	0.07	$8*10^{-2}$	11655	8	1981	1989	123
Tubular + refractor	79.6	2.8	3.4	10000	280	1592	1872	105
Tubular + deep bowl	81.5	1.8	2.2	11200	202	1826	2028	118
Ovoid coated + deep bowl	68.1	1.5	2.1	18550	278	2526	2805	195
LPS + refractor	67.3	3.95	5.5	18500	730	2490	3220	108
Ovoid coated without optic	47.5	40	45.7	32700	13080	3106	16186	344

(1) The fifth column gives the direct upward flux for the luminaire: $\Phi upw = ULOR * 100 * \Phi req$.
(2) Since the illuminated area reflects a part of light - we can consider them as a secondary light source - in this case a road surface with an average reflection factor of 20 %, we should bear this in mind when calculating the total upward flux quoted in the sixth column:

$$\Phi refl = \Phi req * DLOR * \rho$$

Average reflection factor:

- For asphalt road surface we need ±18 lux to achieve a luminance level of 1 cd/m^2
- For concrete road surface we need ±12 lux to achieve a luminance level of 1 cd/m^2

Where $L = \rho \cdot E/\pi \Rightarrow \rho = (L/E)\cdot\pi$
Asphalt: $\rho = (1/18)\cdot\pi = 0.17$
Concrete: $\rho = (1/12)\cdot\pi = 0.26$
Average: $\rho \approx 0.2$

(1) The seventh column gives the total upward flux: $\Phi tot\ upw = \Phi upw + \Phi refl$
(2) The final column shows the wattage consumed by the HPS and LPS lamps and control gear at the required luminous flux to achieve a luminance value of 1 cd/m^2.

This shows that a fixture equipped with a **tubular lamp and flat glass has the lowest direct upward flux.**
If, however, we take the light reflected by the road surface into consideration, it seems that a **tubular lamp with a refractor optic is best suited in terms of light pollution and wattage**. By making optimal use of the light flux we can install less wattage for the same degree of illumination.

Ø Luminaires fitted with coated elliptical lamps give one-and-a half times more upward flux and consume about twice as much energy. Installations with LPS lamps are the most economical, but have slightly higher upward flux values.

- Fixtures with vertical lamps are not at all recommended. The wattage is at least three times higher and the upward light flux is 8 times higher for the same level of lighting.
- Clearly, most of the light pollution attributable to street lighting is caused by these out-dated luminaires.

We can take a look at "the recommendations for sky glow limits" of the draft report TC 4-21 of CIE (97-02-21), the different zones E1 to E4 and the minimum distance (in km) of these specific zones to a location with a specific zone rating.

Table 3

Recommendations for the limitation of sky glow		
ZONE	**UWLR (%)**	**Astronomical Activities**
E1	0	Observatories of (inter)national standing
E2	1 – 5	Postgraduate and academic studies
E3	0 – 15	Undergraduate studies, amateur observations
E4	0 – 25	Casual sky viewing

Table 4

Minimum distance (in KM) of specific zones to a location with a specific zone rating			
Zone rating of reference point	Zone rating surrounding zones distance (km) to borderline of surrounding zones		
	E1 – E2	E2 – E3	E3 – E4
E1	1	10	100
E2		1	10
E3			1
E4	No limits		

If we compare these tables with the calculated values of the UWLR's of the different optics and lamps, it shows that only a flat glass and curved tempered glass achieve a value ≈ 0% UWLR (=E1). All optics with tubular lamps comply with a zone rating E2. LPS – optics nearly achieve this E2. Again, it is showed clearly that fixtures with vertical lamps and/or no effective optics give the highest rating of UWLR and don't even achieve a zone rating E4.
We have to mention that the UWLR – Classification does not totally correspond with the total reflection flux. Flat glass optics with a UWLR of 0, produces, for the same luminance level more light pollution and consumes more energy than that a refractor optic with a UWLR of 3,4 %.

If we compare the results for HPS and LPS for a motorway installation, this means a lighting scheme where luminaires are placed on the central reserve, the differences decrease.

The following table gives by analogy with table 2, a comparison between the upward flux and the consumed wattage:

	Φ req./100m (lm)	Φupw (lm)	Φrefl (lm)	Φ total refl (lm)	P (W)
LPS	104000	4108	13998	18106	604
HPS	92000	1656	14996	16652	733
			Δ	1454	129
				+ 8.7 %	- 17.9 %

Table 5 For an increase of 9 % of upward flux, there's a decrease of 18 % of consumed power.
LPS is recommended by the astronomers and because of its monochromatic light, which can be filtered very easily, is not of any interest in relation to sky glow.

Projectors
When illuminating buildings we should follow a number of rules.

- Switch off the lighting after 24:00 if possible;
- Direct light downwards wherever possible to illuminate, not upwards. If there is no alternative to up lighting, then the intelligent use of shields and baffles will help to reduce spill light to minimum.
- To keep glare to a minimum, ensure that the main beam angle of all luminaires directed towards any potential observer is kept below 70° / 75°.
- Where possible use projectors with asymmetrical beams. This will enable you to adjust the projector almost parallel with the illuminated surface.
- Rather than illuminating the whole monument with a large projector, use smaller luminaires placed as close to the building as possible. This will help to avoid loss of flux.

CONCLUSION

If we ensure that light reaches the areas we want to illuminate, and only there, we can reduce light pollution. Therefore we need to manage the light flux emitted by the lamp as effectively as possible by using high efficiency optical systems.
In conclusion, it is safe to say that everything is at hand to reduce light pollution considerably. The latest generations of lighting installations have been designed with this in mind. This is also true for decorative, functional lighting, where, until now, the technique has never been used.
Clearly all of these possibilities will affect the final cost of the installation Reduced distances means more posts and more luminaires.
Of course, decorative aspect of the installation should not be disregarded. Designing of lighting schemes, therefore, represents a complex task, in spite of all tools available, and is to be done by experts, who can combine all the different aspects of a scheme. Choosing and installing the new generation equipment is the first step to be made in realising a good lighting installation.
The more the fittings are performant in their field of application there will be less light pollution to worry about.

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