Light & Engineering
Vol. 10, No. 4,pp 53 - 60, 2002

LIGHTING POLLUTION THE BENEFIT/COST APPROACH

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SUMMARY

One of the urban lighting objectives is to extend people's activities during night. In this case lighting is linked with functions as visibility, safety, security and visual appearance of the surroundings. Considering these aspects, a current design criteria evaluates the benefit/ cost relationship during the life cycle (LC) of the lighting installations. The benefit in this case is associated to quality parameters of the lighting service like lighting level, failure rate, actual switching schedule and appearance. Other factors related to environmental impact like unnecessary energy consumption, lamp disposal and lighting pollution are interrelated and should also be considerate in the design process.

Lighting is essential, but it is a source of pollution. Lighting pollution to a certain extent keeps relationship with the energy waste and could be evaluated by means of the benefit/cost relationship.

The present paper describes the use of the benefit/cost LC analysis of conventional installations for urban lighting, considering the upper luminous flux emitted directly from lighting installations and emitted by urban surface reflection. In these cases the benefits/ cost relationship is analysed and the results obtained discussed.

Key words: Urban lighting, Lighting Pollution.

1. INTRODUCTION

The major environmental impact due to urban lighting systems is during running time. The consequences can be associated to:

a) CO_2 generation due to electric energy produced by fossil fuelled power stations
b) Lamps disposal, from spot and group replacement maintenance operations containing mercury, which is necessary in discharge lamps for a more efficient energy use.
c) Light pollution, a night sky brightness or sky glow caused by the scattering of light in the atmosphere. This is a primary concern for astronomers. Sources are luminaires projecting light above the horizontal plane and light reflected from illuminated surfaces such us urban roads.
d) Light trespass, which is light that strays from its intended purpose becoming an annoyance or nuisance for people.
e) Environmental effects, on plants and animals over the behaviour, growth and feeding.

Most of the measures in order to reduce the environmental impact can be carried out at the design stage adopting an efficient design adjusted to the just necessary lighting levels and this should be followed by an appropriate maintenance policy during the installation life.

2. DESIGN CRITERIA

Urban lighting installations are designed according to visual performance, comfort, aesthetics, economy or other criteria; and frequently are built in a relatively short period of time. Yet they have a life of service that lasts many years. During design the future management and maintenance policy should be considered in order to guarantee a correct performance, reduce deterioration making installations profitable avoiding any waste of energy and in hence environment impact. A wider approach design criteria should consider the life cycle analysis, where aspects such as management, maintenance, operation, energy consumption, disposal etc. are desirable to be considered. From these point of view the design should also consider:

- Lighting requirements and operation time
- Efficient lighting installations
- Planning according to service factors

2.1 LIGHTING REQUIREMENTS AND OPERATION TIME

To create the appropriate lighting conditions care should be taken to consider quantity and quantity lighting at a reasonable cost, maintaining these conditions through the installation life.

Some of the quality criteria from the reliability and visual perception point of view could be guaranty with high lighting levels, however this will cause high-energy consumption therefore it is necessary to establish a lighting scale according to the visual demand and zone characteristics. The criteria used to scale lighting levels depends on:

- User type: pedestrian, cyclists, and car drivers
- Traffic characteristics: volume, speed limits.
- Ambience: environment perception, security.

Uniformity and glare is also need to be considered. The CIE 136 [3] can be used as a guide reference to establish appropriate lighting requirements.

About the lighting installation operation, it is necessary to set lighting switching controls to the necessary timeframe according to geographical position and to test periodically the correct operation. To save energy and in hence reduce environmental impact it is convenient to study the possibility of establishing a second timeframe within which lighting levels can be reduced. Included in the design stage this can also save capital and labour costs of future refurbishments. The decision to install energy saving systems by reducing levels should take into account:

a) that the lighting reduction levels are possible as a consequence of less visual demand due to traffic reduction or pedestrian presence and that security and safety is not affected
b) the cost of regulation systems is profitable by energy savings

Switch off lights when not required for safety is a measure to reduce lighting pollution. In this respect lighting curfew is proposed when installations are near to astronomical observatories establishing a new timeframe within which lighting levels can be reduced or switch off.

2.2 EFICIENT LIGHTING SYSTEMS

The selection of the system of lighting will affect the energy efficiency and therefore the costs of exploitation through the combination of the following factors: the lamps luminous efficacy, the luminaire efficiency, installation efficiency and depreciation.

Usually in the lamp selection the first criteria used is the luminous efficacy (lumens/watt) because the higher the lumens/watt, the less is the energy needed in order to achieve the same illuminance. However good colour rendering frequently does not follow efficacy. In situations where colour is important the criterion of decision could be altered. In spite of this fact HPS lamps are gradually replacing

Mercury colour corrected lamps of less efficacy but with a better colour rendering. A complete replacement may possibly not occur due to the existence of commercial areas and green parks areas where colour preference is more important than efficiency.

The luminaire efficiency (ratio of luminous flux emitted by a luminaire to that emitted by the lamp) depends on how effective are the combination reflector, bowl and lamp size to project luminous flux. Flux from small tubular lamps is easy to control compared with ovoid lamps with phosphors interior coating because the size shades part of the light output.

The efficiency of the lighting system in relation to the area to be lit depends not only in lamp luminous efficacy and luminaire efficiency but also in installation geometry, that is: luminaire spacing, mounting height, overhang, tilt angle, road width and road reflectance properties for luminance calculations. The luminance yield (or illuminance yield) is used in this case to describe the efficiency of the lighting system to lit the road surface in order to provide the necessary lighting level. Nevertheless some luminous flux is necessary to create an attractive visual environment controlling any possible glare, light trespass and light pollution [1].

To keep at height values the efficiency of the lighting system maintenance is necessary, controlling lamp mortality, lamp lumen output reduction, luminaire depreciation by dust and dirt accumulation and failure of other electric components. To compensate these depreciating factors, installations are oversize by a factor known as maintenance factor (MF), which is a function of the luminaire characteristics, environment pollution and maintenance policy.

2.3 PLANNING ACCORDING TO SERVICE FACTORS

A detailed planning is necessary to determine the number, location and characteristic of the lighting units to satisfy the lighting requirements, but planning should also consider quality service factors. An indicator of quality service was proposed [1] based on the benefit/annual operational cost ratio where the benefit depends:

- lighting level (K(E)),
- the necessary operation time ($K(T_O)$),
- reliability and failure duration (K(PFL)),

In spite that we know that these factors are only part of the lighting benefit, for planning purposes, they take into account the service quality. The benefit can be quantified as:

$$B = K(E) \times K(T_O) \times K(PFL) \qquad (1)$$

K(E) depends of the road average illuminance (E). Minimum maintained values are used as reference (E_m). K(E) varies according to:

E	**E** $<E_m/2$	$E_m/2 \le$ **E** $< E_m$	**E** $\ge E_m$
K(E)	0	(2**E**/ E_m) -1	1

Due to depreciation, illuminance decreases with time, starting from the initial values when installation is new (E_O). Depreciation is caused by lamp lumen output reduction (lamp lumen maintenance factor LLMF), lamps failures (lamp survival factor, LSF) and the reduction of luminaire output flux by ageing and dirt accumulation (luminaire maintenance factor LMF). The product of these factors after a given interval of time is known as the maintenance factor (MF). After a certain period of time:

$$E = E_O \cdot MF \qquad (2)$$

Maintenance counteracts depreciation; therefore E will depend of the adopted maintenance policy. Four possible maintenance policies have been assumed, for which the MF is indicated in table 1.

Maintenance factor components are associated to exponential curves for calculations. LMF curves for different degrees of ingress protection IP and pollution are used from CIE [2]. LSF curves were used from data collected (presented in reference [1]) and curves for LLMF are employed from manufacturers average data.

K(T_O), is the operation time factor. The scheduled reference time used is T_{OR} , that is the annual necessary operating time which depends of the geographical situation.

T_O	T_O<0,95T_{OR}	0,95T_{OR}<T_O< T_{OR}	T_O≥T_{OR}
K(To)	0	T_O/T_{OR}	1

The system reliability factor is described by the percentage of permanent failure luminaire observed, **K(PFL)** accepting a first limit PFL_{min}=1% from which the factor decreases lineally up to an unacceptable second limit where benefit is null PFL_{max}=3%.

PFL	≤ PFL_{min}	PFL_{min}<PFL< PFL_{max}	>PFL_{max}
K(PFL)	1	1 - (PFL-PFL_{min}) / (PFL_{max}-PFL_{min})	0

For design proposes and maintenance policies without spot replacement PLF is calculated from: (1-LSF).

All the costs obtained from local data, are reduced to "uniform present worth annual values" to consider the time value of money in a life cycle analysis (20 years). What is called the annual operational cost (*AOC*) is calculated by this means. The *AOC* of a lighting installation can be grouped in:

- Capital: the annual amortisation cost from invested capital
- Energy: active and reactive
- Management: maintenance operations, control, inspections, administrative, etc. consumption
- Periodical lamp disposal
- Retrofit and final installation disposal

The *Benefit/[AOC/(m².lx)]* ratio is calculated for the different policies, cleaning and group replacement periods. The maximum value is used as the criteria to select the maintenance policy. The number of luminaires is calculated with the MF from the selected policy giving the maximum *Benefit/[AOC/(m².lx)]*.

3. ANALYSIS OF URBAN LIGHTING INSTALLATIONS

In order to study the extent of light pollution from conventional urban lighting installations, different cases were evaluated over the base that all satisfy the same lighting requirements as minimum maintained values. Lighting requirements selected, similar to the CIE M3 classifications are indicated in table 2 for urban areas with the addition of road average illuminance E_{ave} ≥ 15 lx.

Luminaires with HPS lamps (100, 150, 250 and 400W) and LPS lamps (90, 135 and 180W) were selected for a single-side arrangement located in a street cavity as indicated in figure 1.

The street width and buildings heights were considered of 20m, (possible average value in Barcelona). The optimum number, location and geometry of lighting units were calculated to produce the *maximum Benefit/[AOC/(m².lx)] ratio* as indicated in section 2.3. The best solutions found, with seven types of selected luminaires, are indicated in table 3.

Table 1: Maintenance factor for different maintenance policies.
$T_{50\%}$: average rated life, time over which LSF falls to 50% in reference conditions.
T_O: annual lamp operating time [hours].

Maintenance policy	MF
GR+GC: Group lamp replacement and group luminaire cleaning.	LLMF x LSF x LMF
SR+GR+GC: Spot lamp replacement + group lamp replacement + group luminaire cleaning	LLMF x LMF
SR+GC: Spot lamp replacement and group luminaire cleaning	(LLMF average value from 0 to 2$T_{50\%}$) x LMF [4]
SR+SC: Spot lamp replacement and simultaneous luminaire cleaning	(LLMF average value from 0 to 2$T_{50\%}$) x (LMF average value from 0 to 2$T_{50\%}$/T_O) [4]

Light & Engineering
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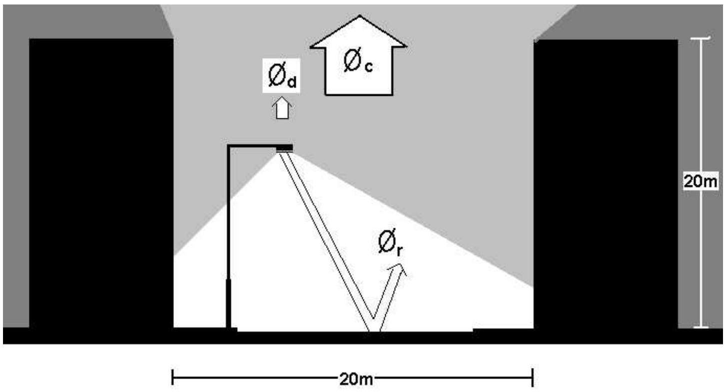


Figure 1: Street cavity limited by the street surface, facades of side buildings and a virtual ceiling plane in order to evaluate light pollution.

$L_{ave} \geq 1 cd/m^2$ (average road surface luminance)
$U_O = L_{min}/L_{ave} \geq 0{,}4$ (overall uniformity)
$U_L = L_{min}/L_{max} \geq 0{,}5$ (lengthwise uniformity)
$E_{ave} \geq 15 lx$(average road illuminance)
TI% ≤ 15% (threshold increment
Road surface CIE: R3 qo=0,07
Reflectance:
ρ_{walls}=40%, ρ_{road}=10%, ρ_{kerb}=20%

Table 2: Lighting requirements similar to CIE class M3 for the case studied

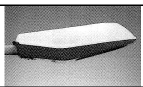
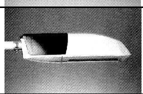
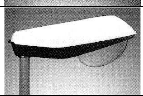
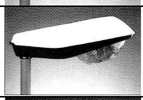
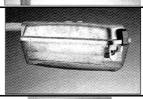
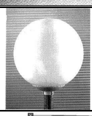
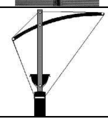
Nº	Luminaire	Enclosure (Bowls)	Lamp type	IES Classification			Flux output [%]		
				Type	Longitudinal	Cutoff	Downward	Upward	Total
1		Clear flat glass	HPS tubular 250W	I	Short	Cutoff	70.6	0	70.6
2		Clear curve glass	HPS tubular 250W	I	Short	Cutoff	76.7	0	76.7
3		Polycarbonate	HPS tubular 250W	I	Short	Cutoff	71.4	0	71.4
4		Prismatic glass	HPS tubular 250W	II	Medium	Cutoff	81.6	0	81.6
5		Clear acrylic	LPS 180W	IV	Medium	Non-cutoff	73.1	5.2	78.3
6		Opal globe	HPS ovoid 250W	V	Very Short	Non-cutoff	35.05	43.65	78.7
7		Diffusor screen	HPS tubular 400W	II	Very Short	Cutoff	32.1	0	32.1

Table 3: Details of luminaires selected for the study with lamp combination producing the *maximum Benefit/[AOC/(m^2.lx)] ratio* to satisfy lighting requirements. Al luminaires are IP5 in average pollution environment [3]. Maintenance policy used was group lamp replacement and group luminaire cleaning plus spot replacement.

In table 3, luminaires 1 to 4 are frequently used in urban lighting. Luminaire 5 with LPS are more used in the European northern countries. The globe, luminaire 6 with upper flux emission, in spite of the low efficiency is still in use that is the reason while it was included in the present study.

Luminaire 7 with diffusor screen 7 is indicated for special decorative applications or to enhance space with low glare and high uniformity. However to show the limitations to extend the use for other areas it was also included in the study.

In order to evaluate lighting pollution the following parameters were calculated:

a) Upward light output ratio (ULOR): proportion of the lamps flux of the luminaire emitted above the horizontal ($\gamma \geq 90°$) when luminaire is mounted in its normal designed position.

b) Upward light output ratio installed (ULORinst.): proportion of the flux of the luminaire emitted above the horizontal ($\gamma \geq 90°$) when luminaire is mounted in its installed position. Recommended values are indicated by CIE [5] in table 4.

c) Direct Unit Uplight Density (DUUD): upward direct flux emitted by the installation in the street cavity (ϕ_d in figure 1) divided by the street area.

d) Total Unit Uplight Density (TUUD): upward flux emitted by the installation and reflected by all surfaces in the street cavity ($\phi_d+\phi_r$ in figure 1) divided by street area. This is equivalent to the ceiling street cavity illuminance.

The results obtained for the different installations studied are summary in table 5.

Table 4: Recommendations for the limitation of sky-glow and description of the environmental zones according to the CIE zoning system.

Zone rating	Description	$ULOR_{inst}$ [%]
E1	Areas with intrinsically dark landscapes: National Parks, Areas of outstanding natural beauty (where roads usually are unlit);	0
E2	Areas of “low district brightness”: generally outer urban and rural residential areas (where roads are lit to residential road standard);	0 – 5
E3	Areas of “middle district brightness”: generally urban residential areas (where roads are lit to traffic route standard);	0 – 15
E4	Areas of “high district brightness”: generally urban areas having mixed residential and commercial land use with high night - time activity.	0 – 25

Table 5: Summary of the results obtained for the different lighting installations studied.

Enclosure	**Clear flat Glass** (1)	**Clear curve glass** (2)	**Prismatic glass** (4)	**Poly-Carbonate** (3)	**Clear Acrylic** (5)	**Opal globe** (6)	**Diffusor screen** (7)
Lamp	HPS-Tubular	HPS-Tubular	HPS-Tubular	HPS-Tubular	LPS	HPS-Ovoid	HPS-Tubular
Power	250W	250W	250W	250W	180W	250W	400W
Flux [Lm]	32.000	32.000	32.000	32.000	33.000	27.000	55.000
Tilt angle in C90	20	5	0	15	15	0	0
Spacing	43,5	58,8	58,8	47,6	34,5	9,8	20,4
Luminaries/Km	24	18	18	22	30	103	50
{B/[AOC/(lx.m²)]}max	**30,42**	**39,44**	**39,77**	**32,25**	**31,18**	**7,25**	**11,61**
Eo	25,1	20,3	20,8	22,9	28,2	24,3	35,5
Ef	18,2	15,4	16,1	17,2	15,7	15,4	19,1
ULOR	0,00	0,00	0,08	0,00	5,20	43,65	0,00
$ULOR_{inst}$	**1,11**	**0,11**	**0,10**	**0,81**	**7,84**	**55,48**	**0,00**
DUUD [Lm/m²]	0,047	0,0014	0	0,0215	0,667	27,9	0
TUUD [Lm/m²]	**1,96**	**1,82**	**1,91**	**1,81**	**3,82**	**36,60**	**3,85**

4. DISCUSSION

All installations were design to satisfy, from functional point of view, minimum maintained lighting requirements. Nevertheless aesthetics luminaire design factors were not considered as part of the benefit, fact that can have an additional value in case of special applications. On the other hand ecological cost were also not considered in the benefit factors.

The possible lamp alternatives and maintenance policies were selected with the maximum *Benefit/[AOC/(m²*.lx)]* ratio criteria. From this approach, light pollution was evaluated in each case. In table 3, luminaires fitted with prismatic glass (N° 4) and clear curved glass (N° 2) produce the greater *Benefit/[AOC/(m²*.lx)]* ratio; while the installations with luminaires fitted with polycarbonate, acrylic and flat glass (N° 1,3,5) produce a similar *Benefit/[AOC/(m²*.lx)]* ratio. On the other hand the installations with reflecting screen and globe present the lowest values.

From the light pollution point of view, the case of installation with globe $ULOR_{inst}$ ≈ 55% is the only one with an unaccepted value according to table 4. This agrees with the lowest value found for *Benefit/[AOC/(m²*.lx)]* ratio. Installations fitted with prismatic and curved glass and with the greatest values of *Benefit/[AOC/(m²*.lx)]* ratio turn out to be those of lower $ULOR_{inst}$ (≈ 0.1%). The remaining installations are also in a same group giving similar $ULOR_{inst}$ values. All could be used in E2 category, excepted installation with LPS and acrylic bowl that falls in E3 category. However the limitations given by table 4 do not consider the nature of the emitted light. With LPS lamp luminous emission presents a smaller dispersion than HPS lamp, fact that is indicated in CIE 126 [5]. Therefore the LPS with acrylic bowl could possibly be used in zone E2.

The installation with prismatic glass luminaire (IES classification II cutoff medium) gives the highest Benefit*/[AOC/(m²*.lx)]* ratio and an $ULOR_{inst}$ value similar to the N° 1, 3, and 5 luminaires. This type of light distribution can possibly be better than type I cutoff short distribution as it produces bigger spacing and in hence bigger Benefit*/[AOC/(m²*.lx)]* ratio (except for the curve glass luminaire that shows similar results).

The $ULOR_{inst}$ depends of the luminaire tilt angle fact that is not considered in ULOR, however the tilt angles used in the installation studied were not an additional problem.

The $ULOR_{inst}$ does not give information about the effect of surface reflection. TUUD considers surface reflection and it is indicated in the last row of table 4. Case N°2, 4 and 7 give the lower $ULOR_{inst}$ value, however case N 7 has near twice upwards light contribution as case 5 while case 2 and 4 are similar to 1, and 3. This fact can make necessary to consider installation uplight contribution including surface reflectance.

5. CONCLUSIONS

Even though light pollution has not been incorporated in the Benefit/AOC ratio, it is observed that installations with height Benefit/AOC ratio values are those, which present low light pollution. Efficiency is close related to a height Benefit/AOC ratio and light pollution is in some way a waste of energy that can be minimise but not eliminated while surface reflection is necessary to achieve visibility.

The Benefit/AOC criteria could possibly include, if necessary, aesthetics and environmental factors. In that case a merit rating scale can be used based on qualitative aspects.

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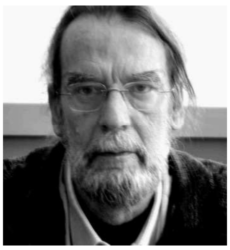

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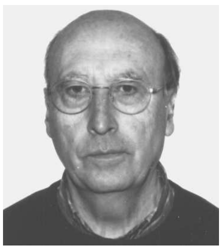

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