THE BENEFIT/COST IN URBAN LIGHTING

Eduardo R. MANZANO†, Ramon SAN MARTIN ‡
†Universidad Nacional de Tucumán
‡Universitat Politècnica de Catalunya

Abstract

Urban lighting should be designed and managed in order to work efficiently preserving quality values as high as possible during life cycle, all this at reasonable costs. In order to relate quality service and costs the design of new urban lighting installations and the evaluation of existing installations can be done though a benefit/cost approach. A quantification of the benefit based on quality service parameters as the lighting level, the permanent failure rate, and the lighting system operation time, is proposed. For design purposes factors as mechanical degree protection, environmental pollution, lamp survival and maintenance policies are analysed under a life cycle benefit/cost approach and the results obtained are indicated. In order to evaluate existing installations the benefit/cost life cycle analysis is applied to a town where an external contractor does the lighting maintenance. At representative city sectors the lighting parameters, energy consumption and maintenance historical records were registered. The results of actual installations and comparisons with simulated situations are described and results discussed. Lighting installation performance can also be traced by periodical evaluations of the benefit/cost ratio and parameters used for simulating behaviour can even be adjusted to make a more reliable analysis.

1 Introduction

A methodology to evaluate urban lighting installations, focused on the overall quality service has been proposed based on the Benefit/Cost ratio [1]. The benefit is assessed in terms of factors linked to the service, that is to say the performance during the use of the installations. The factors taken into consideration have been illuminance, failure rate and time of operation of the installations. These factors have been evaluated taking, as a reference, suitable values established by standards or recommendations. The costs of installation, energy, maintenance, refurbishment and disposal during the life cycle of the installations are considered in relation to the financial cost of money.

The application of the methodology has been analysed in two situations: the design of new installations and the evaluation of existing installations. When considering the design of new installations, different alternatives have been simulated studying the effect of the specific characteristics of the installations in the benefit/cost relationship. When considering existing installations, the methodology has been applied to a town and the results have been compared to an ‘optimal’ situation. This has enabled to assess the existing situation and to adjust maintenance policies.

2 The benefit/cost ratio

A procedure based on the determination of the ratio benefits /annual operation costs, for planning and controlling lighting management, requires to establish which are the benefits and costs and to quantify both.

The benefit that citizen and road drivers get from urban lighting is to find appropriate visual conditions to precede safety, creating an ambient of security and comfortable use. Quantifying these aspects presents certain difficulty; this is why it is convenient to look for a more operative indicator relating, illuminance ($K(E)$), the necessary operation time ($K(T_O)$), reliability and failure duration ($K(PFL)$). The benefit can be defined as the multiplication of these factors, where the relative weight of each one is considered as equal for the moment.
The benefit can be quantified as:

$$B = K(E) \times K(T_O) \times K(PFL) \tag{1}$$

K(E) depends of the road average illuminance (E), which limitations, in spite to be known is chosen as a magnitude representative of the lighting level due to its ease of measurement, low cost of the measurement equipment's, use habit and besides to the fact that it can be compared with reference values conveniently established. Minimum maintained values are used as reference (E_m). $K(E)$ varies according to table 1

Table 1 Factor *K(E)*

E	$E < E_m/2$	$E_m/2 \leq E < E_m$	$E \geq E_m$
$K(E)$	0	$(2E/E_m)$ -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 multiplication of these factors gives the maintenance factor (*MF*). After a certain period of time:

$$E = E_O \times MF \tag{2}$$

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 2.

Table 2 Maintenance factor according to maintenance policy

Maintenance policy	***MF***
GR+GC: Group lamp replacement and group luminaire cleaning.	$LLMF \times LSF \times LMF$
SR+GR+GC: Spot lamp replacement + group lamp replacement + group luminaire cleaning	$LLMF \times LMF$
SR+GC: Spot lamp replacement and group luminaire cleaning	(*LLMF* average value from 0 to $2T_{50\%}$) x *LMF* [1]
SR+SC: Spot lamp replacement and simultaneous luminaire cleaning	(*LLMF* average value from 0 to $2T_{50\%}$) x (*LMF* average value from 0 to $2T_{50\%}/T_O$) [1]

$T_{50\%}$: average rated life, time over which *LSF* falls to 50% in reference conditions.
T_O: annual lamp operating time [hours].

Maintenance factor components are associated to exponential curves for calculations. *LOR* curves for different degrees of ingress protection IP and pollution are used from CIE [2]. *LSF* curves were used from data collected and presented in [1] and curves for *LLO* are employed from manufacturers average data. To evaluate existing installations local data are collected before and after cleaning and lamp replacement operation at random selected luminaires.

$K(T_O)$, 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 (refer to table 3)

Table 3 Factor *K(To)*

T_O	$T_O<0{,}95T_{OR}$	$0{,}95T_{OR}< T_O< T_{OR}$	$T_O \geq T_{OR}$
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 were benefit is null PFL_{max}=3%. Refer to table 4.

Table 4 Factor *K(PFL)*

PFL	$\leq PFL_{min}$	$PFL_{min}<PFL< PFL_{max}$	$>PFL_{max}$
K(PFL)	1	$1 - (PFL-PFL_{min}) / (PFL_{max}-PFL_{min})$	0

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 consumption
- Management: maintenance operations, control, inspections, administrative etc.
- Periodical lamp disposal
- Retrofit and final installation disposal

The maximum Benefit/Cost ratio value for different cleaning and group replacement periods can be used for the management planning. This allows the application of a maintenance policy, which can be subsequently adjusted by control data.

3 The design using benefit/cost ratio

The *B/C* ratio as a design tool was analysed for installations fulfilling the lighting quality figures from table 5. To reduce the study, a single side arrangement installation was used (figure 1) where the variable parameters considered were: column height (6m≤*H*≤17m), bracket length (0m≤*E*≤3m), tilt angle (0°≤*T*≤15°), luminaire separation (15≤*S*≤80m), road width (*A*=6m and 8m), 4 luminaire types

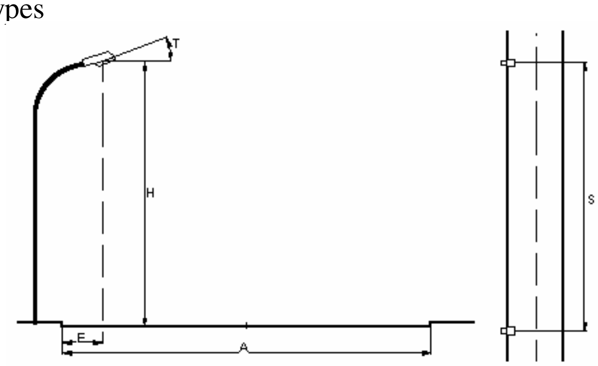

Figure 1 Lighting installation arrangement

<table>
<tr><th>E_{ave}</th><th>L_{ave}</th><th>$U_0\geq$</th><th>$U_L\geq$</th><th>$TI\%\leq$</th></tr>
<tr><td>10</td><td>0,5</td><td rowspan="5">0,4</td><td rowspan="2">-</td><td rowspan="3">-</td></tr>
<tr><td>15</td><td>1</td></tr>
<tr><td>20</td><td>1,2</td><td>0,5</td></tr>
<tr><td>25</td><td>1,5</td><td rowspan="2">0,7</td><td rowspan="2">10%</td></tr>
<tr><td>35</td><td>2</td></tr>
</table>

Table 5 Lighting quality criteria

and 2 lamp types (HPS 100,150,250, 400W and Mercury 125, 250, 400W), road CIE R3 qo = 0,07, *LSF* average from manufacturers and *LSF* local data from [1], four maintenance policies (table 2) and group lamp replacement and luminaire cleaning periods between 2 months and 6 years.

As an example, the *B/[AOC/(lx.m^2)]* maximum obtained for a 8m width road, HPS 250W lamp, high pollution ambience category, luminaire sealed protection IP2, IP5, IP6 and LSF from [1] are indicated in figure 2 for E_{ave} 10, 15, 20, 35 lx according to table 5.

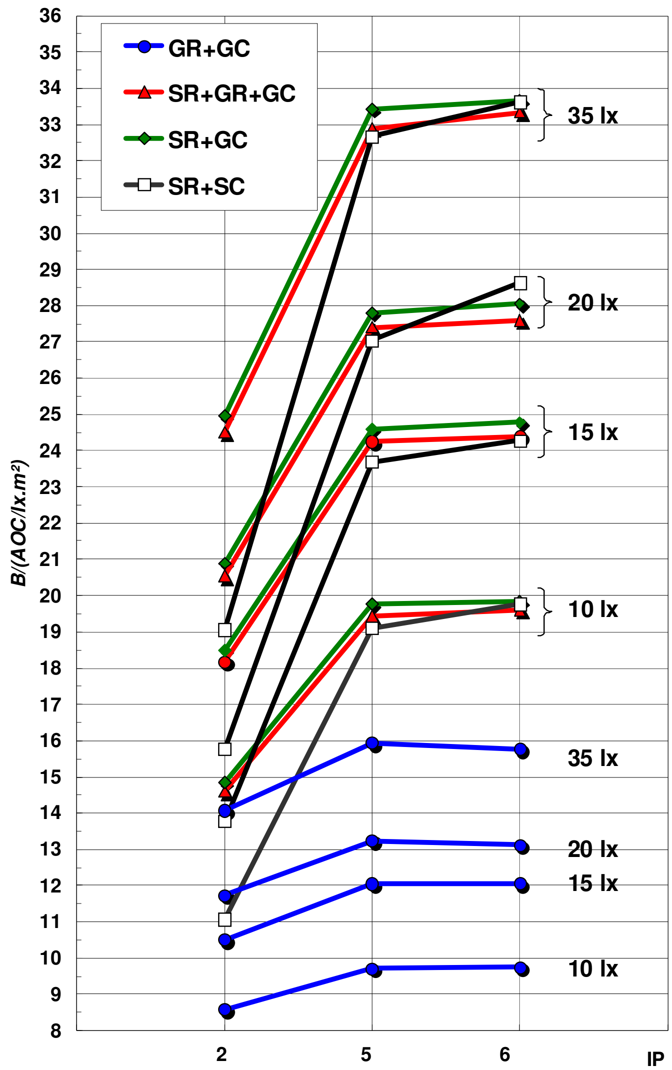

Figure 2 *B/[AOC/(lx.m^2)]* maximum with a one side, 8m width road, HPS 250W lamp, high pollution ambience category, luminaire IP2, IP5, IP6 and *LSF* from [1] for the different E_{ave} from Table 5.

From de results obtained we can conclude:

- ❑ *B/[AOC/(lx.m^2)]* maximum compared with minimum cost criteria has, as an advantage, the fact that it considers quality service factors as the installation failure rate (associated to lamp mortality) that is lacking in a minimum cost analysis.
- ❑ There is a dependency of *B/[AOC/(lx.m^2)]* maximum with E_{ave}, U_O, U_L and the lit area although the annual operational costs have been referred to lx and m^2. Because of this fact *B/C* must be calculated in any case in order to compare installations by means of these criteria.
- ❑ Regarding to the effect of maintenance policies, ambient pollution, IP luminaire sealing protection and *LSF* it can be concluded that:
  - *SR+GR+GC* and *SR+GC* in high-polluted areas with luminaires IP2 or IP5 are the most convenient. *SR+SC* with IP6 is the most convenient. *GR+GC* is the worst policy in all cases except with IP2 luminaires.
  - Installations where the ambient category shifts from low polluted to high polluted experiment a *B/[AOC/(lx.m^2)]* reduction of 20% using IP2 luminaires, 5% with IP5 and 3% with IP6.
  - IP2 luminaires with *SR+GR+GC* or *SR+GC*, have the lowest *B/[AOC/(lx.m^2)]*, with an average difference of 25% compared with IP5 and IP6 while IP5 and IP6 luminaires differ in 1,4% making IP6 more convenient than the others.
  - Uses of local data for *LSF* instead of average manufacturer data in *B/[AOC/(lx.m^2)]* calculation produces differences of -45% in the values with a *GR+GC* policy. This is because

mortality from actual installations is greater (10% per year). As Benefit is affected by mortality, the optimum situation is reached with shorter group lamp replacement periods to compensate the increasing failure rate that otherwise would occur. Policies with spot replacement show differences of only 1% because spot labour and lamp cost relative to the overall cost are not so important nevertheless if only maintenance cost are considered an increase of 8% is produced.

❑ The optimum lamp group replacement (T_L) and luminaire cleaning (T_C) periods (average for 10lx $\leq E_{ave} \leq$ 35lx) obtained with the *B/[AOC/(lx.m^2)]* maximum criteria are indicated in Table 6:

Maintenance Policies	Luminaire seal protection	Pollution category	Lamp	T_L	T_C
SR+GR+GC and *SR+GC*	IP2	High	HPS 250W	3 years	1 year
			Merc. 400W	1 year	3 to 4 month
SR+GR+GC	IP5 and IP6 D		HPS 250W	4 years	1 to 3 years
			Merc. 400W	1 year	1 year

Table 6 Optimum lamp group replacement (T_L) and luminaire cleaning (T_C) average periods for the *B/[AOC/(lx.m^2)]* maximum criteria

3 Evaluating existing installations by benefit/cost ratio

A town closed to Barcelona, having 78.000 inhabitants, 6.800 light points (luminaire + column) controlled by 100 switchboards was chosen in order to evaluate the B/C ratio application. The city was first sorted in order to group lighting installation according to common features like road categories, illuminance level, luminaire type etc. Four roads types were considered to be appropriate. A second sorting was done in these areas for the analysis through isolating the lighting installations connected to the same switchboard because energy consumption and switching times are measured and controlled in each switchboard. The roads and switchboards selected (indicated in figure 3) were:

- Residential roads (switchboards 35 and 36),
- Industrial roads (switchboard 45),
- Main roads (switchboards 1, 2, and 29) and
- Secondary roads (50).

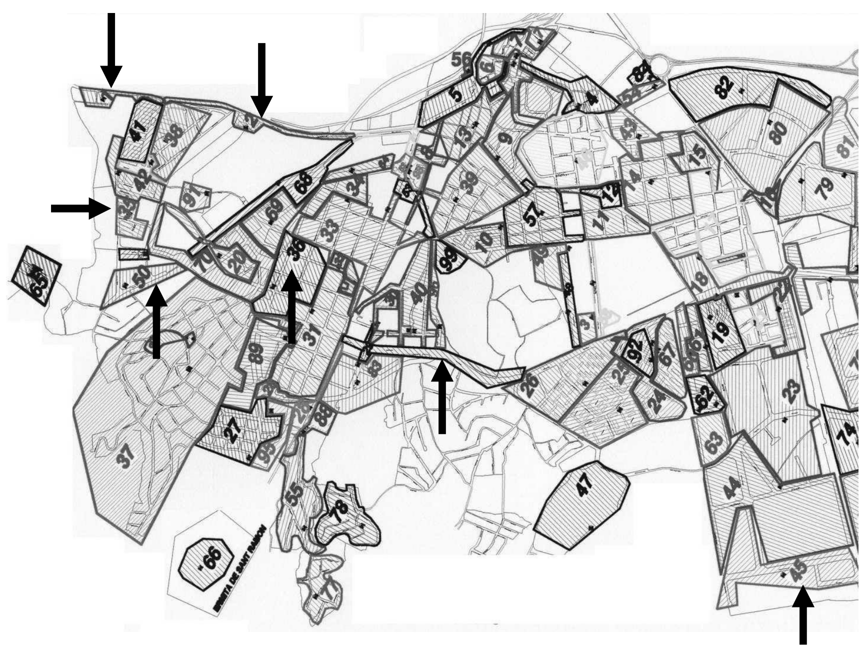

Figure 3 Roads and switchboards selected from the city

From each installation the data collected was:

- characteristics: lamp type, luminaire IP, pollution degree
- maintenance policy, relamping and cleaning periods

• permanent failure rate
• E_{ave} at the present time and after cleaning and relamping operations
• switching time schedule
• energy tariff contract
• cost: installation, maintenance, energy, disposal etc.

From the data collected the *B/C* ratio was calculated for each switchboard, considering four special situations to be compared one against each other:

actual: *B/C* ratio value calculated for the lighting installation with maintenance policy, energy consumption and lighting service quality parameters (E_{ave}, failure rate, switching operation times) at the present time.

efficient: *B/C* ratio value calculated as *actual B/C* ratio but with a theoretical energy efficient consumption.

optimum: *B/C* ratio value calculated as *efficient B/C* ratio but with a theoretical optimum maintenance policy obtained by the *B/[AOC/(lx.m^2)]* maximum criteria.

optimum design: *B/C* ratio theoretical value calculated with a new design according to the functional needs energy efficient practice and with the optimum maintenance policy.

The actual *B/C* value can be compared with the different theoretical situations. A difference between the *actua*l and the *efficient B/C* ratio will be associated to an energy problem. A difference between the *actua*l and the *optimum B/C* ratio will be associated to maintenance policy problem. A difference between the *actua*l and the *optimum design B/C* ratio will be associated to an inappropriate design. If the is any significant difference, a more deep analysis will be necessary to identify the specific source. For each switchboard (horizontal axis of figure 4) and all the situations above described the *B/C* ratios were calculated and indicated in figure 4.

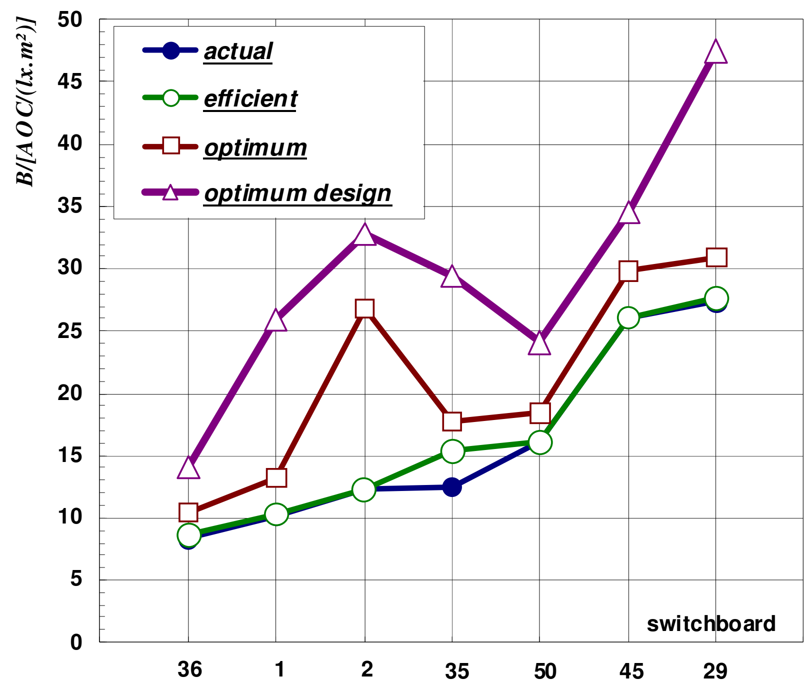

Figure 4 B/[AOC/(lx.m^2)] values for the sample of installations studied.

In figure 4, the *B/C* ratio for the *actual* situation (full spots) is overlapped by the *B/C* ratio for the *efficient* situation (circle spots) except at switchboard 35 where an increase in energy consumption has increased also the costs and therefore reduced the *actual B/C* ratio. The source of this difference was found to be additional lighting power not included in the inventory. Indicated by square spots, the *B/C optimum* ratio shows a possible improving by changing the maintenance policy. A closer look to switchboard 2 reveals that the actual E_{ave} is lower than the reference illuminance, a fact which is not convenient to compensate by means of maintenance but with a proper renovation of the installation. The *B/C optimum design* values are indicated with triangle spots. The great difference is observed in switchboards 1, 2, 36 and 29 that correspond to the oldest installation. The *B/C* ratio alone could not be a sufficient argument for a renovation, others indicators, like simple payback could add additional information.

4 Conclusions

The *B/C* ratio can be used as a criterion for urban lighting installations design and also as a evaluation tool for existing lighting installations. In the last case, if the sample analysed is big enough the results can be extrapolated to the entire city. Periodical controls (6 to 12 month periods) measuring and checking the *B/C* parameters can allow to trace the evolution on time, to adjust the parameters involved and the lighting management. Research is going on in order to include additional parameters and to improve the efficiency of data collection.

5 Symbols

AOC: Annual operational cost based on a uniform present worth life cycle analysis
$B/[AOC/(lx.m^2)]$ maximum: maximum Benefit to annual operational cost ratio per lux and square meter
$T_{50\%}$: average rated life, burning lamp hours when 50% of a sample has failed
T_0: annual lamp operating time [hours]
IP2 IP5 or IP6: luminaire sealed degree protection against dust and water
GR+GC: Group lamp replacement and group luminaire cleaning
SR+GR+GC: Spot lamp replacement + group lamp replacement + group luminaire cleaning *SR+GC*: *SR+SC*: Spot lamp replacement and simultaneous luminaire cleaning
T_L: group lamp replacement period
T_C: group cleaning luminaire period
LSF: Lamp survival factor. Percentage of survival lamps after a period of time
LLMF: Lamp lumen maintenance factor
LMF: Luminaire maintenance factor
MF: Installation maintenance factor
E_{ave}: Minimum mainteined average illuminace over de road surface [lx]
L_{ave}: Minimum mainteined average luminance over de road surface [cd/m²]
U_0: Overal luminance uniformity $U_0 = L_{mín}/L_{ave}$
U_L: Lenghwise luminance uniformity
TI%: Threshold increment, glare limitation criteria

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7 References

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Eduardo R. MANZANO†, Ramon SAN MARTIN ‡
†**Universidad Nacional de Tucumán**, FCEyT, Depto. de Luminotecnia Luz y Visión
Av. Independencia 1800, 4000, Tucumán, Argentina
Tel./Fax: +54 381 4361936
e-Mail: emanzano@herrera.unt.edu.ar, manzano@pe.upc.es
‡**Universitat Politècnica de Catalunya**, ETSEIB, Depto. de Projectes d'Enginyeria
Av. Diagonal 647, planta 10, 08028, Barcelona, Spain

Tel.: +34 93 401 71 68/9 Fax: +34 93 334 02 55
e-Mail: sanmartin@pe.upc.es