APPLYING MULTI-CRITERIA DECISION ANALYSIS FOR SELECTING STREET LIGHTING LUMINAIRES

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Summary

Aim of this paper is to present a multicriteria decision methodology for choosing the appropriate luminaire for lighting provincial streets, which belong to various classes of EN 13201. To begin with, five different types of low wattage street luminaires (70-85W) are presented, each one representing a different lighting technology from the ones mentioned above. Each type of luminaire is evaluated using a consistent set of criteria, namely price, energy efficiency (lm/W), light output ratio, lamps' lifespan, illuminance at the street level and illuminance uniformity. A certain weight is attributed to each one of the criteria. Consequently, the ELECTRE I multicriteria method is applied. The concordance and discordance indices are computed associating each ordered pair of luminaires. Moreover, a concordance and discordance threshold is defined. As a result, the outranking relations between the luminaires are found, the outranking graph is constructed and the kernel is deducted. Finally, the results of the method enable the decision maker to make the optimal selection of the most suitable street luminaire for each type of street.

1. Introduction

Nowadays, a wide variety of lighting technologies exist and it's not always clear what type of luminaire is suitable for each application. Especially in road lighting, the most usual types of luminaires are the ones using mercury vapour lamps, high pressure sodium lamps and metal halide lamps. The share of light emitting diodes and –secondary- of induction lamps increases rapidly. Each type of luminaire has different attributes concerning price, energy efficiency and lighting performance. Furthermore, some types of luminaires can be more suitable than others for illuminating a certain type of road or street. Therefore, the decision to choose the optimal road luminaire for each case is a rather complicated one. The decision maker needs to take into account all the factors mentioned above.

2. Overview of the decision methodology

In order for the decision maker to make the appropriate selection, a multicriteria methodology is needed. In this paper the ELECTRE I method is implemented. It is a family of multi-criteria decision analysis methods that originated in Europe in the mid-1960s. The acronym ELECTRE stands for: ELimination Et Choix Traduisant la REalité (ELimination and Choice Expressing REality). ELECTRE I was the first outranking multicriteria method and was proposed in 1968 by Bernard Roy. The ELECTRE I method is essentially applied to the treatment of discrete alternatives valued quantitatively, to a partial ordination of the alternatives. The aim of the method is to separate from the whole of the alternatives, the ones which are preferred in the majority of the evaluation criteria and don't cause an unacceptable level of discontentment on other criteria. The modeling of the decision maker's global preference is obtained via an outranking relation *S* defined on the set *A* of actions. This relation is denoted by the letter «*S*» and means for every pair of actions (a, b)$\in AxA$:

aSb ⇔ *«a is at least as good as b»*

ELECTRE I requires the following data:

- Weighting coefficients or weights of criteria $p_1, p_2, \ldots, p_n$ which sum to 1
- Concordance threshold *s*, which is a real number varying from 0.5 to 1, i.e. $s \in (0.5,1]$
- Veto thresholds $v_1, v_2, \ldots, v_n$ which are *n* real numbers defined to control the big differences between the evaluations of two actions.

The outranking relation *S* is defined in the following way:

aSb ⇔ *(a, b)* satisfies both the conditions of concordance and non discordance.

Concordance condition: A concordance index is defined for each pair of actions *(a, b)*, as follows:

$$C(a,b): AxA \rightarrow [0,1]$$

$$C(a,b) = \sum_{i^*} p_{i^*} \; with \; i^* \in \{i / g_i(a) < g_i(b)\}$$

The pair of actions (*a*, *b*) satisfies the concordance condition when: $C(a,b) \geq s$

The pair (*a*, *b*) satisfies the non discordance condition when:

$$g_j(b) - g_j(a) < v_j, with \; j \in \{j / g_j(a) < g_j(b)\}$$

The index *j** belongs to the set of criteria for which the action *b* is preferred to *a*, while *vj** is the veto threshold of criterion *j**. In case a difference of evaluations in favor of action *b* overcomes the veto threshold of a criterion, this criterion poses veto to the outranking of *b* by *a*.

Mathematically, ELECTRE I outranking relation is defined as follows:

$$\mathbf{aSb} \leftrightarrow C(a,b) = \sum_{i^* \ni \{i / g_i(a) \geq g_i(b)\}} p_{i^*} \geq s \quad with \; 0.5 < s \leq 1 - min \, p_{j \in F} \; \{concordance \; condition\}$$

$$\mathbf{AND} \; \forall j \in F, g_j(b) - g_j(a) < v_j \; \{non \; discordance \; condition\}$$

The final step is the construction of an outranking graph {A} and the deduction of the kernel {K}. The outranking graph visualizes the outranking relationships between the alternatives. The kernel of the graph is a subset *K* of *A* which satisfies two conditions:

$$(1) \forall b \in A - K, \exists a \in K / aSb$$

$$(2) \forall a_1 \in K \; and \; a_2 \in K \leftrightarrow a_1 \$ a_2 \; and \; a_2 \$ a_1$$

According to this definition, the kernel should include the best and incomparable actions of the set *A.* Of course the decision analyst must propose to the decision maker only one action as his best choice [1-3].

3. Application of the methodology to lighting classes CE4 and ME4

3.1 Configuration of the lighting system

In this paper five most commonly used lighting technologies for roadway lighting are evaluated: luminaires with high pressure mercury vapor, high pressure sodium, induction, metal halide and LED luminaires. All luminaires are of low wattage.

Two independent case studies have been assumed, the first concerning the lighting of a road belonging to the CE4 class and the second concerning the lighting of a road belonging to the ME4b class, according to the classification of the EN13201 [4]. Both roads comprise of two lanes, have a total width of 8m and a total length of 1 km. The photometric height of the luminaires for both cases is 7m, their inclination 10^o, the total reflectance of the road is 0.08 and the reduction factor is 0.8. The candidate luminaires are evaluated using a consistent set of criteria: average illuminance of the road (lx) and illuminance uniformity (for CE lighting classes), average and longitudinal luminance (cd/m^2) and luminance uniformity (for ME lighting classes), initial cost consisting of purchase & installation cost (Euro), yearly cost of electricity (Euro/y), light output ratio (LOR), luminaire efficacy (lm/W) and lifespan of the lamps (hrs). The calculation of the lighting parameters for each luminaire is performed using RELUX software package. The results of the calculation are the average illuminance of the road, the uniformity and the maximum distance between the luminaires in order to comply with the requirements of EN13201.

3.2 Optimization of the CE4 lighting class system

The lighting system, as described in section 3.1, is calculated applying the requirements of EN13201 regarding CE4 lighting class: Average illuminance at least 10 lux, illuminance uniformity at least 0.4 [4]. The calculated distance between luminaires provides the number of luminaires per 1 km of road length by dividing the 1 km of the road by that distance. Besides, the costs of purchase, installation and electricity are computed. The lighting data and parameters as well as the criteria of the decision methodology are shown in Table 1.

A certain weight is attributed to each one of the criteria. The sum of the weights is equal to 1. The weights for each criterion are presented in Table 2.

A new index is being made presenting the sum of the weights of the criteria for which, each type of luminaire outranks the others. The results are presented in Table 3. For example, in the first row of this table, the weights of the criteria for which the high pressure sodium luminaire outranks the LED luminaire (denoted Sodium ***S*** LED) are presented and the weights of the criteria for which the LED luminaire outranks the high pressure sodium luminaire are noted with zeros. The last column presents the sum of the weights of the criteria for which the sodium luminaire is superior to the LED luminaire, namely 0.3.

Table 1: Data of the road of lighting class CE4.

Type of lamp	Distance (m)	Cost of 1 luminaire (€)	Lamp Wattage* (W)	Luminaire wattage* (W)	Number of luminaires	Illuminance (lx)	Uniformity	Initial cost** (€)	Electricity cost** (€)	LOR*	Efficacy* (lm/W)	Lifespan* (hrs)
						Criteria						
Sodium	21	135	70	80	48	10.0	0.60	-42480	-1424	0.77	54	28000
LED	27	400	75	75	38	16.0	0.41	-43700	-1057	0.88	92	100000
MH	22	150	70	80	46	12.6	0.41	-41400	-1364	0.79	62	14000
Induction	22	250	85	95	46	10.3	0.41	-46000	-1620	0.74	52	100000
Mercury	12	130	80	90	84	10.3	0.74	-73920	-2803	0.70	28	16000

*Nominal values.

**The initial cost (purchase+installation) and the electricity cost are noted by a minus sign.

Table 2: Weights of the criteria of road CE4.

Criterion	**Weight**
Illuminance	0.10
Uniformity	0.10
Initial cost	0.20
Electricity cost	0.20
LOR	0.15
Efficacy	0.15
Lifespan	0.10
Sum	1.00

Table 3: Sums of the weights of the criteria for the outranking relations between the luminaires (road CE4).

	Illuminance	Uniformity	Initial cost	Electricity cost	LOR	Efficacy	Lifespan	SUM
Sodium *S* LED	0.0	0.1	0.2	0.0	0.00	0.00	0.0	0.3
Sodium *S* MH	0.0	0.1	0.0	0.0	0.00	0.00	0.1	0.2
Sodium *S* Induction	0.0	0.1	0.2	0.2	0.15	0.15	0.0	0.8
Sodium *S* Mercury	0.0	0.0	0.2	0.2	0.15	0.15	0.1	0.8
LED *S* MH	0.1	0.1	0.0	0.2	0.15	0.15	0.1	0.8
LED *S* Induction	0.1	0.1	0.2	0.2	0.15	0.15	0.1	1.0
LED *S* Mercury	0.1	0.0	0.2	0.2	0.15	0.15	0.1	0.9
MH *S* Induction	0.1	0.1	0.2	0.2	0.15	0.15	0.0	0.9
MH *S* Mercury	0.1	0.0	0.2	0.2	0.15	0.15	0.0	0.8
Induction *S* Mercury	0.1	0.0	0.2	0.2	0.15	0.15	0.1	0.9

The next step of the method is the construction of the concordance index. Each cell of this square index contains the sum of the weights of the criteria, for which each luminaire outranks its pair. The elements, which are above the main diagonal of the matrix are the sums presented in the last column of Table 3. Since the sum of the weights of all criteria is one, the elements below the main diagonal are calculated by subtracting their symmetrical cells from one. The concordance index is presented in Table 4.

Table 4: Concordance index (road CE4).

	Sodium	LED	MH	Induction	Mercury
Sodium		0.3	0.2	**0.8**	**0.8**
LED	**0.7**		**0.8**	**1.0**	**0.9**
MH	**0.8**	0.2		**0.9**	**0.8**
Induction	0.2	0.0	0.1		**0.8**
Mercury	0.2	0.1	0.2	0.2	

Using a sensitivity threshold **s** of 0.7 all outranking relations are found. In other words, a luminaire “A” outranks luminaire “B” if the corresponding cell of the matrix has a value greater than or equal to 0.7. The cells of the matrix with such a value are marked with bold letters. For example, a luminaire with high pressure sodium lamp outranks the luminaire with induction lamp and the luminaire with mercury vapour lamp.

The next step of the method is the construction of the outranking graph where the outranking relationships are depicted (Fig. 1). No discordance conditions are applied in this case study.

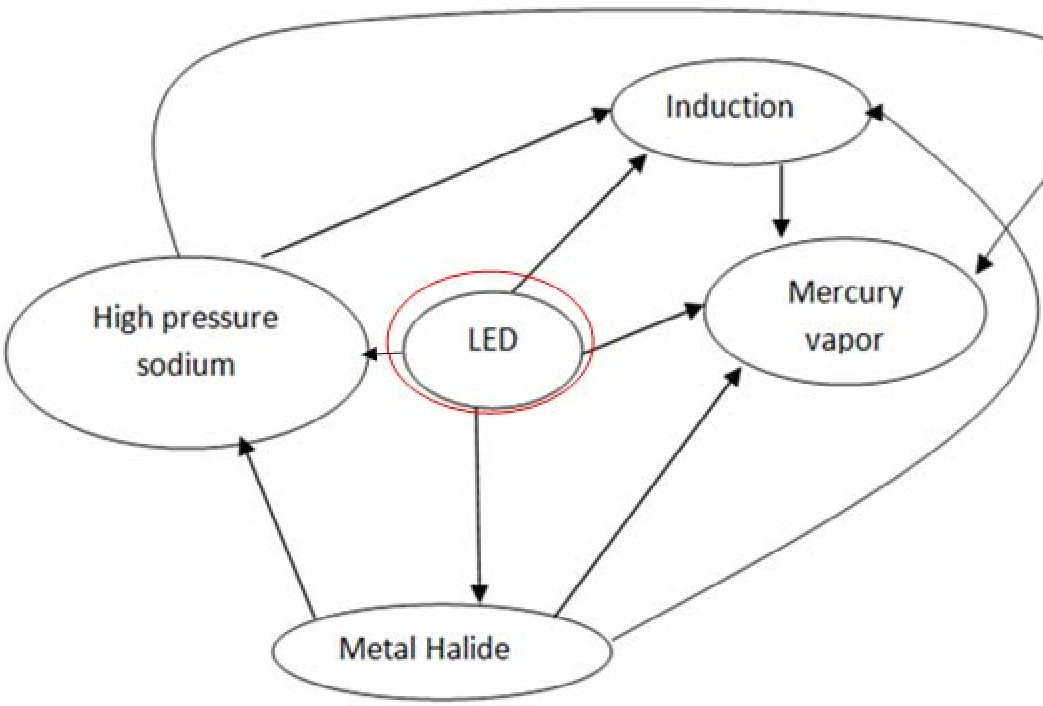

Figure 1: Outranking graph for the road of CE4 lighting class.

The final step is the deduction of the kernel which contains the alternatives that are better than others but there is no outranking relationship between them. In this case, the kernel contains only the LED luminaire which outranks every other alternative. Consequently, the optimal solution for the lighting of the road, belonging to the CE4 class, is the LED luminaire, which is sketched with a red circle.

3.3 Optimization of the ME4 lighting class system

The lighting system, as described in section 3.1, is calculated applying the requirements of EN13201 regarding ME4b lighting class: Longitudinal luminance at least 0.75 cd/m^2, overall uniformity at least 0.4, longitudinal uniformity at least 0.5, surrounding ratio at least 0.5, threshold increment not surpass 15% [4]. The calculated distance between luminaires provides the number of luminaires per 1 km of road length by dividing the 1 km of the road by that distance. Besides, the costs of purchase, installation and electricity are computed. The lighting data and parameters as well as the criteria of the decision methodology are shown in Table 5.

Table 5: Data of the road of lighting class ME4b.

Criteria

Type of lamp	Distance (m)	Cost of 1 luminaire (€)	Lamp Wattage* (W)	Luminaire wattage* (W)	Number of luminaires	Luminance (cd/m^2)	Uo	U_l	Initial cost** (€)	Electricity cost (€)	LOR*	Efficacy* (lm/W)	Lifespan* (hrs)
Sodium	18	135	70	80	56	0.83	0.51	0.93	-49560	-1661	0.77	54	28000
LED	36	400	75	75	28	0.91	0.54	0.80	-32200	-779	0.88	92	100000
MH	24	150	70	80	42	0.84	0.57	0.89	-37800	-1246	0.79	62	14000
Induction	17	250	85	95	59	0.81	0.46	0.86	-59000	-2078	0.74	52	100000
Mercury	10	130	80	90	100	0.86	0.54	0.98	-88000	-3337	0.70	28	16000

*Nominal values.

**The initial cost (purchase+installation) and the yearly cost of electricity are noted by a minus sign.

A certain weight is attributed to each one of the criteria. The sum of the weights is equal to 1. The weights for each criterion are presented in Table 6.

Table 6: Weights of the criteria of road ME4b.

Criterion	Weight
Luminance	0.07
Overall Uniformity	0.07
Longitudinal Uniformity	0.06
Initial cost	0.20
Electricity cost	0.20
LOR	0.15
Efficacy	0.15
Lifespan	0.10
Sum	1.00

A new index is being made presenting the sum of the weights of the criteria for which each type of luminaire outranks the other (Table 7). The concordance index is shown in Table 8. The sensitivity threshold is also 0.7 for this case. The cells of the concordance index with a value greater than 0.7 are being marked with bold letters. No discordance conditions are applied in this case also. The outranking graph is the same as before (Figure 2).

Table 7: Sum of the weights of the criteria for the outranking relations between the luminaires

Road ME4b	Luminance	U_0	U_l	Initial cost	Electricity cost	LOR	Efficacy	Lifespan	SUM
Sodium *S* LED	0.00	0.00	0.06	0.0	0.0	0.00	0.00	0.0	0.06
Sodium *S* MH	0.00	0.00	0.06	0.0	0.0	0.00	0.00	0.1	0.16
Sodium *S* Induction	0.07	0.07	0.06	0.2	0.2	0.15	0.15	0.0	0.90.
Sodium *S* Mercury	0.00	0.00	0.00	0.2	0.2	0.15	0.15	0.1	0.80
LED *S* MH	0.07	0.00	0.00	0.2	0.2	0.15	0.15	0.1	0.87
LED *S* induction	0.07	0.07	0.00	0.2	0.2	0.15	0.15	0.1	0.94
LED *S* Mercury	0.07	0.07	0.00	0.2	0.2	0.15	0.15	0.1	0.94
MH *S* induction	0.00	0.00	0.00	0.2	0.2	0.15	0.15	0.0	0.90
MH *S* Mercury	0.00	0.00	0.00	0.2	0.2	0.15	0.15	0.0	0.77
Induction *S* Mercury	0.00	0.00	0.00	0.2	0.2	0.15	0.15	0.1	0.80

Table 8: Concordance index (ME4b).

	Sodium	LED	MH	Induction	Mercury
Sodium		0.06	0.16	**0.90**	**0.80**
LED	**0.94**		**0.87**	**0.84**	**0.87**
MH	**0.84**	0.13		**0.90**	**0.77**
Induction	0.10	0.16	0.10		**0.80**
Mercury	0.20	0.13	0.23	0.20	

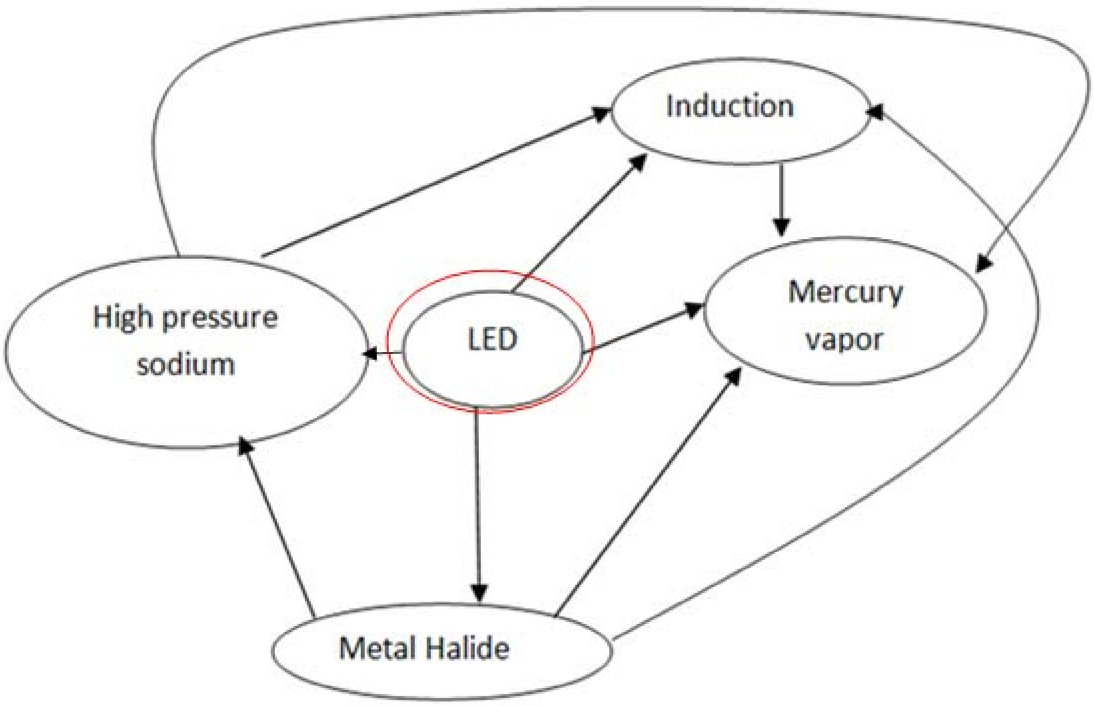

Figure 2: Outranking graph for the road of ME4b lighting class.

The final step is the deduction of the kernel which contains only the LED luminaire, because it outranks every other alternative. Consequently, the optimal solution for the lighting of a road, belonging to ME4b class, is the LED luminaire, which is sketched with a red circle.

4. Conclusions

The usage of multicriteria methodologies is a reliable solution for decision problems, which are complex and the decision maker needs to take into account multiple criteria that often collide with each other. In this paper, the usage of ELECTRE I determined a solution for the optimal selection of a luminaire used for the lighting of provincial streets and roads. Further research could be conducted, concerning the application of multicriteria methods in lighting e.g. for evaluating lighting systems for other types of roads, buildings, tunnels, avenues etc.

5. References

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