OPTIMIZING ENERGY EFFICIENT LIGHTING USING MULTI-CRITERIA ANALYSIS

Madias, E.-N.D.[1], Kontaxis, P.A.[1,2], DoulosL.T.[1], TopalisF.V.[1]
[1] National Technical University of Athens, Zografou, Greece
[2] Technological Educational Institute of Athens, Egaleo, Greece
madias@mail.ntua.gr

ABSTRACT

Aim of this paper is the optimal selection of energy saving solutions implementing multicriteria analysis in order to reduce artificial lighting consumption in buildings. The method is applied to an educational building in which solutions such as luminaires with energy efficient lamps, occupancy sensors, photosensors and electronic ballasts are proposed to increasing energy saving without making large-scale renovations and disturbing its operation. According to "ELECTRE I" method, a consistent set of criteria comprised of the features mentioned above is specified for each alternative selection. Each criterion is attributed to a certain weight. The concordance and discordance indices are computed associating each solution for energy saving. Moreover, concordance and discordance thresholds are defined. As a result, the outranking relations between each implementation are found, the outranking graph is constructed and the kernel is deducted.

Keywords: Energy efficient lighting, Daylighting, Energy saving, ELECTRE I

1. INTRODUCTION

Lighting consumes more than20% of the total produced electrical energy and it represents 35% of the electricity consumption of commercial buildings. It influences the total energy balance of a building because the luminaires generate heat that increases the load of the cooling system. As a rule of thumb, each luminaire unit contributes to an additional one-half unit of electricity for space cooling due to the contribution of the heat generated by it. The energy savings due to reduced lighting loads can directly reduce air-conditioning energy usage by an additional 10% to 20%.

Harvesting daylight and by the usage of high performance energy efficient luminaires and lamps, high rates of energy saving can be achieved. It cannot only reduce the lighting consumption but it can be very efficient in reducing peak electrical loads.

2. THE DETERMINED TECHNOLOGIES FOR ENERGY SAVING

Electric power consumption in commercial buildings that are used for educational purposes is separated into lighting and air-conditioning. Many interventions can be done with various costs, levels of function interruption and energy saving percentages. The principles of energy saving as applied to lighting control can be summed up as: choosing efficient light sources, installing occupancy sensors that automatically switch off lighting when the room is not occupied, dimming the light sources so that they can produce the required lighting level and finally balancing artificial light and daylight to achieve the appropriate level of illuminance using photosensors.

For the specific case study the simplest interventions, as referred above, have been selected, generally with low cost and without disturbing the building function.

Five different luminaires with fluorescent lamps were selected and their attributes are presented in table 1. The first one is the φ_{su} percentage from the DIN classification, the second is the efficacy of the luminaire, the third the lifetime of the lamp and the fourth the total cost of the luminaire and the lamps.

Table 1 – Luminaires and lamps specifications

	LL 1	LL 2	LL 3	LL 4	LL 5
DIN Classification (φ_{su})	3	6	4	4	5
Efficacy (lumen/W)	82.4	94.3	88.6	66.7	69.3
Lamp lifetime (h)	24000	24000	20000	10000	8000
Cost (€)	509	418	365	150	170

Five different photosensors with electronic dimmable ballasts (EDB) were selected and their specifications are presented in table 2. Two specifications for the photosensors are selected, the saturation (from the light) and the photosensor spectral correction coefficient (PSCC) which is defined as the examined sensor illuminance to V(λ) illuminance. Regarding the electronic dimmable ballasts,the selected specifications concern the power factor at 20% of the dimming level, which is a typical level for a usual dimming system and the consumed power (as percentage of the nominal power). The total cost (photosensor plus EDB) was the fifth specification.

Table 2 – Photosensors and ballasts specifications

	PB 1	PB 2	PB 3	PB 4	PB 5
Saturation (lux)	3000	1350	17000	2700	1500
PSCC	1.677	1.661	1.846	2.064	1.449
PF at 20% of dimming level	0.78	0.89	0.72	0.93	0.71
Consumed power (% nominal)	27	25	32	36	23
Cost (€)	245	208	115	209	408

Finally, five different wireless occupancy sensors were chosen and their specifications are presented in table 3, namely the distance coverage, the detection speed, the cost and the battery lifetime.

Table 3 – Occupancy sensors specifications

	OS 1	OS 2	OS 3	OS 4	OS 5
Coverage (m)	12	10	8	9.5	9.5
Detection speed (m/sec)	10	3	20	18	3
Cost (€)	65	83	82	60	84
Battery lifetime (Y)	9	5	3	4	5

3. OVERVIEW OF THE “ELECTRE I”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. “ELECTRE I” method is essentially applied to the treatment of discrete alternatives valued quantitatively, to a partial ordination of the alternatives. The aim of themethod 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 modelling 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)$\in A\times A$: $aSb \Leftrightarrow$ *«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: $aSb \Leftrightarrow (a, b)$ 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:

$$C(\alpha,b): A\times A \rightarrow [0,1], \qquad C(\alpha,b)=\sum_{i^*} p_i, with\, i^* \in \{i/g_i(a)<g_i(b)\}$$

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 favour 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:

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

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

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.

4. OPTIMIZING THE ENERGY SAVING MEASURES

The method of "ELECTRE I" is applied three times, one for each intervention. No discordance conditions are applied to any of the interventions. The first step of the "ELECTRE I"method is the weights determination for each one of the specifications (figure 1).

The direct luminous flux at the working level from the DIN classification is the most important specification because it shows the light at the working level. Hence, the weight of this specification is 40%. The lamp efficacy is the second most important specification and its weight is 30%. The last two specifications, related with the cost of the intervention, are the lamp lifetime (20%) and the total buying cost of the luminaire and the lamp together (10%).

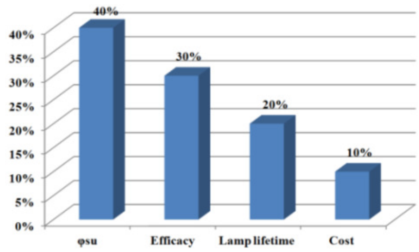

Figure 1 – Luminaires and lamps weights for "ELECTRE I" method

The next step of the method is the construction of the concordance index. 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 for luminaires and lamps (LL)

	LL 1	LL 2	LL 3	LL 4	LL 5
LL 1	1	0.1	0.3	**0.6**	**0.6**
LL 2	**0.9**	1	**1**	**1**	**1**
LL 3	**0.7**	0	1	**0.6**	**0.6**
LL 4	0.4	0	0.4	1	0.2
LL 5	0.4	0	0.4	**0.8**	1

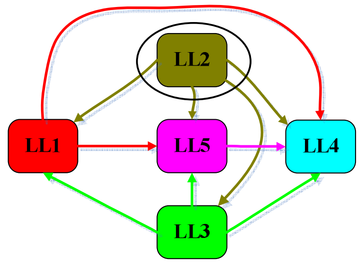

Figure 2 – Outranking graph for luminaires and lamps

The outranking relations are found using a sensitivity threshold s of 0.6. If the corresponding cell of the matrix has a value greater than or equal to 0.6 a set of luminaire-lamp outranks another set of luminaire-lamp. The cells of the matrix with such a value are marked with bold letters in a yellow background. At the first line of the index (for example), the luminaire-lamp 1 (LL1) outranks the LL4 and LL5.

The next step of the method is the design of the outranking graph (figure 2). The final step is the determination 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 LL2, which outranks every other alternative. So, the optimal solution belongs to LL2.

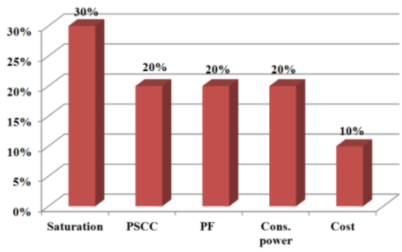

Figure 3 – Photosensors and ballasts weights for "ELECTRE I" method

As far as the photosensors and the ballasts are concerned, the attribute with the greatest weight (30%) is the saturation because the photosensor terminates its wright function over the limit of saturation. The photosensor spectral correction coefficient (PSCC), the power factor (PF) and the power consumption of the ballast are less significant than the saturation, but they affect the photosensor function and the power of the lighting control system. Finally, the cost must be taken into account as it affects the final decision (figure 3). Likewise, the sensitivity threshold is 0.6in this case. The cells of the concordance index with a value greater than 0.6 are being marked with bold letters in a yellow background (table 5). The outranking graph is presented in figure 4.

Table 5 – Concordance index for photosensors and ballasts (PB)

	PB 1	PB 2	PB 3	PB 4	PB 5
PB 1	1	**0.8**	0.3	0.4	**0.9**
PB 2	0.2	1	0.3	0	**0.6**
PB 3	**0.7**	**0.7**	1	0.3	**0.9**
PB 4	**0.6**	**1**	**0.7**	1	**0.9**
PB 5	0.1	0.4	0.1	0.1	1

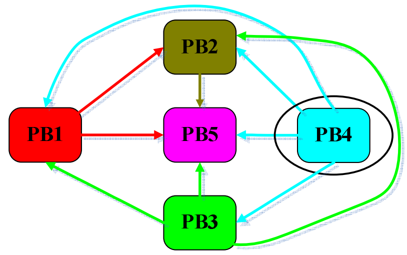

Figure 4 – Outranking graph for photosensors and ballasts

The kernel contains only the photosensor-ballast 4 (PB4) which outranks every other alternative. The optimal solution belongs to PB4.The specification of the occupancy sensors with the greater weight is the distance coverage (40%) and after it the detection speed with weight 30%. Coverage and detection speed are related with the efficient function of the sensor. The cost (20%) and the battery lifetime (10%) are financial variables and have the less weight in the implementation of the method (figure 5).

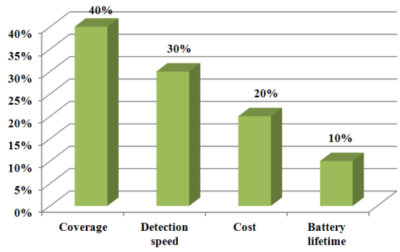

Figure 5 – Occupancy sensors weights for "ELECTRE I" method

The sensitivity threshold is also 0.6 for this case. The cells of the concordance index with a value greater than 0.6 are being marked with bold letters in a yellow background (table 6). The outranking graph is presented in figure 6.

Table 6 – Concordance index for occupancy sensors (OS)

	OS 1	OS 2	OS 3	OS 4	OS 5
OS 1	1	**0,8**	0,5	**0,7**	**0,8**
OS 2	0,2	1	**0,7**	**0,7**	0,4
OS 3	0,5	0,3	1	0,5	0,3
OS 4	0,3	0,3	**0,5**	1	0,3
OS 5	0,2	**0,6**	**0,7**	**0,7**	1

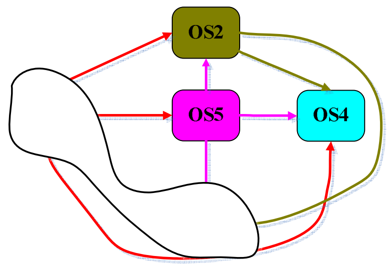

Figure 6 – Outranking graph for occupancy sensors

In this case, the kernel contains the occupancy sensors 1 (OS1) and 3 (OS3). OS1 outranks every other alternative except OS3 while OS3 was outranked by two of the other three occupancy sensors. The optimal solution between OS1 and OS2 (kernel) belongs to OS1 because it has one-half greater distance coverage, battery with three times greater life time and the cost is about 25% less. The OS3 has twice the speed detection than OS1, but the detection of 10m/sec that the OS1 has is sufficient enough for lighting control applications.

5. DISCUSSION ON THE RESULTS AND CONCLUSIONS

The optimal selections of each case study are the luminaire-lamp 2, the photosensor-ballast 4 and the occupancy sensor 1. The luminaire 2 has the best φ_{su}in accordance to DIN classification and is equipped with a lamp that has the greater efficacy, satisfactory average lifetime and relatively high but not the highest cost. The photosensor 4 has an adequate saturation level and the highest PSCC. The ballast has the highest PF, the highest power consumption and the combination of both (photosensor-ballast) is of relatively low cost. The occupancy sensor 1 has the greatest coverage and the longest battery lifetime among all sensors, the second lowest cost and the third greatest speed detection. Each one of the optimal selections is energy efficient and the technical specifications are guaranteeing the efficient function of the control system and the maximization of energy saving. The usage of multicriteria methods, such as “ELECTRE I”, is reliable for decision problems, which are complex (as the criteria are many and conflicting) and the decision is not obvious.

ACKNOWLEDGMENT

European Union European Social Fund OPERATIONAL PROGRAMME EDUCATION AND LIFELONG LEARNING investing in knowledge society MINISTRY OF EDUCATION & RELIGIOUS AFFAIRS, CULTURE & SPORTS MANAGING AUTHORITY Co-financed by Greece and the European Union NSRF 2007-2013 programme for development EUROPEAN SOCIAL FUND

This research has been co-financed by the European Union (European Social Fund – ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF)- Research Funding Program: **THALES**. Investing in knowledge society through the European Social Fund.

REFERENCES

YOUNG, Y., JOO KONG, H., KIM, H., TAI KIM, J. A field survey of visual comfort and lighting energy consumption in open plan offices.*Energy and Buildings* 2012, 46, 146–151

MASOSO, O., GROBLER, L. The dark side of occupants’ behaviour on building energy use.*Energy and Buildings* 2010, 42, 173–177

RYCKAERT, W., LOOTENS, C., GELDOF, J. HANSELAER, P., Criteria for energy efficient lighting in buildings.*Energy and Buildings* 2010, 42, 341–347

YUN, G., SHIN, H., KIM, J. Influence of window views on the subjective evaluation of discomfort glare.*Indoor and Built Environment* 2011, 20, 65–74

LI, D., TSANG E. An analysis of measured and simulated daylight illuminance and lighting savings in a daylit corridor.*Building and Environment*2005, 40, 973-982

DOULOS, L., TSANGRASSOULIS, A., TOPALIS, F. Quantifying energy savings in daylight responsive systems: the role of dimming electronic ballasts.*Energy and Buildings* 2008, 40, 36–50

DOULOS, L. Development of a system of automatic adjustment of artificial lighting for the optimized exploitation of daylight. PHD Thesis, 2010, National Technical University of Athens

DOULOS, L., TSANGRASSOULIS, A., TOPALIS, F. The role of spectral response of photosensorsin daylight responsive systems.*Energy and Buildings* 2008, 40, 588–599

FIGUEIRA, J., GRECO S., EHRGOTT, M. State-of-Art of Multiple Criteria Decision Analysis, 2005, Kluwer Academic Publishers

SISKOS, Y. Decision Models, 2008, New Tech Publications

MADIAS, E-N., DOULOS, L., KONTAXIS, P., TOPALIS, F. Applying multi-criteria decision analysis for selecting street lighting luminaires.*Balkan Light 2012*, 66-73

ANDER, G. Daylighting performance and design, 2003, Wiley

JENNINGS, J., RUBINSTEIN, F., DIBARTOLOMEO, D., BLANC. S. Comparison of control options in private offices in an advanced lighting control testbed.*Journal of the Illuminating Engineering Society* 2000, 29, 2, 39–60

SIMPSON, R. Lighting control-technology and applications, 2003, Focal press