Decision making in selecting the best matching hybrid lighting system

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ABSTRACT: Part of the lighting designer's task is to decide whether daylight or electric light best meet user needs, architectural requirements and lighting guidelines. The desire to maximize the benefits of both daylight and electric systems has lead to the recent development of a number of hybrid lighting systems, each with different characteristics and performance. These systems offer many advantages, but because of their nature, they present very different decision making problems to designers than those of conventional lighting methods. A multi-criteria decision making approach is suggested to help this process, in which alternatives and criteria were defined and treated numerically to select the preferred choice. Sensitivity analysis has been carried out to examine the impact of modifying the importance of the criteria in the alternative selection. Results imply that the on-going criteria tend to influence alternatives ranking more than the one-off criteria.

Keywords: Hybrid lighting systems, Decision making, Alternatives, Criteria, Sensitivity analysis

1. INTRODUCTION

Daylight is the preferred source in buildings due to its beneficial effect on human well-being and performance. Its potential to conserve energy and hence protect the environment has stimulated interest as an electric lighting substitute. The recent development of 'daylight guidance technology' allows redirection of daylight into areas of buildings that cannot be lit using conventional glazing. The main guidance types are the commercially successful tubular daylight guidance systems, and the newer hybrid daylight/electric systems (HLS). The later has different approaches to combine both sources of light; which consequently led to a large diversity in terms of light collecting, guiding and distributing, in terms of costs and benefits, and in terms of performance and influences. Because of the variations in the HLS, the decision maker(s) need to know which system best suits building needs and budget. This study investigates selecting alternative HLS and develops a decision making procedure which can be applied to real cases.

2. HYBRID LIGHTING SYSTEMS

Throughout the last decade many HLS have been developed in which daylight is captured and combined with electric light prior to delivery within a building via an output device similar to a luminaire.

HLS consist of three parts. The external part, mostly called *collector*, collects and concentrates sunlight. The internal part, mostly called *diffuser,* spreads transported daylight in the required space. G*uidance system*; which delivers collected sunlight to the diffuser.

A variety of methods are used to collect sunlight, deliver it into remote spaces, and distribute it over required area. Control systems regulate the electric flux output to top up deficiency of natural light supply. The current study will investigate only the three HLS considered have high potential to penetrate the market. These are; hybrid solar lighting (HSL) and solar canopy illuminance system (SCIS) which have been installed for real demonstration, and Parans system which is commercially available.

2.1. Hybrid Solar Lighting

The Hybrid Solar Lighting (HSL) collector is a 1.22m-diameter parabolic sun-tracking mirror with an elliptical secondary mirror (Fig. 1-A). The latter separates the visible and infrared portions of sunlight and focuses the visible sunlight into a bundle of optical fibres; which delivers the sunlight to the end of a side emitting acrylic rod located inside a conventional electric luminaire also equipped with dimmable fluorescent lamps. A control system tracks the sun; light sensors monitor daylight levels; and electronic dimming ballasts regulate the electric light output to a pre-determined level **[1]**. A second type of luminaire uses end emission from the fibres and has a light distribution similar to a parabolic reflector lamp.

2.2. Parans System

The Parans sunlight collector is a roof or façade mounted 1m^2 modular solar panels containing 64No Fresnel lenses (Fig. 1-B). Each lens is able to track and concentrate sunlight into optical fibre. Sixteen fibres are combined into a cable each of maximum length 20m. The tracking is controlled by a microprocessor which is continually fed information from a photo-sensor which scans the sky to detect sun path. The system has five luminaire types, three of which are hybrid luminaires equipped with fluorescent or CF lamps which dim automatically depending on sunlight conditions **[2]**.

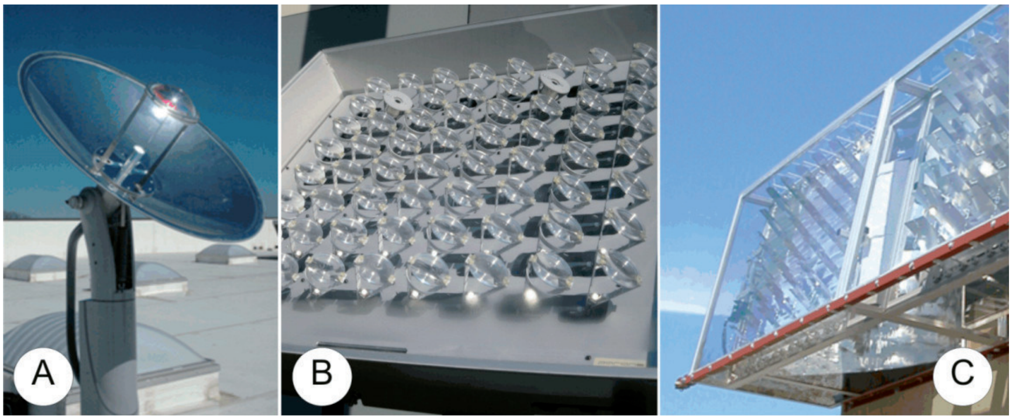

Figure 1: A: HSL collector, B: Parans collector, C: SCIS collector

2.3. Solar Canopy Illumination System

Solar Canopy illuminance System (SCIS) is a facade mounted system collects sunlight using a grid of mirrors located inside an enclosure. On the façade each unit is approximately 3m wide x 1.2m high (Fig. 1-C). This is connected to a 0.25m high duct which extends some 10m into a building. The orientation of the mirrors changes with sun position. By a series of lenses and mirrors the light is concentrated and redirected into a rectangular cross section guide lined with multilayer optical film (MOF) which has high reflectance at all angles, and optical lighting film (OLF) which reflects light preferentially. Fluorescent lamps located inside the guide. Sunlight travels along the guide using total internal reflection within the MOF until hits an extractor material made of OLF. This diffusely reflects the light and the portion that no longer meets the angular conditions for total internal reflection exits the guide via the bottom surface. A control system maintains the desired interior illumination level **[3]**.

3. NEED FOR DECISION MAKING

Broad variation in HLS characteristics means decision must be made based on system performance, economics, relationship with the host building and nature of HLS components. Each of collector, guidance and diffuser may vary in size, mounting method, flexibility and technology; hence vary in performance, economics, compatibility and suitability. Selecting a HLS for purpose and budget has to take in consideration these variables.

3.1. Systems components and technologies

- *Collector:* in HSL is a roof mounted mirror, while in Parans it is a roof or façade mounted solar panels, though it is a facade attached canopy in SCIS. All collecting devices are strongly recommended to be south oriented.

- *Guidance:* both HSL and Parans guide sunlight via flexible fibre optic cables of few centimetres diameter, whilst SCIS uses a 60cm-wide x 25cm-high rigid ducts. Fibre optics lengths are as long as 20m, meanwhile illuminance ducts are of about 12m.

- *Diffuser:* HSL outputs are either a side emitting acrylic rod located inside a conventional 1.2m x 0.6m electric luminaire, or end emission fibres have a light distribution similar to a parabolic reflector lamp. Parans custom designed luminaires are PMMA diffusing sheets with sizes from 45 x 45 cm to 90 x 90 cm, or spotlight luminaire. SCIS employs the traditional 60cm-wide linear ceiling luminaire.

- *Technology:* both HSL and Parans system use high-tech to collect sunlight, which track sun path and highly concentrate its ray (up to 1000 times) to be transferable via small sections of fibre optics. SCIS tracks and concentrates sunlight some ten times and deliver it via relatively big ducts.

3.2. Systems influences

The variations described above, in components and technologies, lead to differences in performance, economics, compatibility and suitability.

3.2.1. Lighting performance

Lighting performance can be determined by the amount of delivered sunlight, overall efficiency and lighting quality. High concentration of sunlight makes system work efficiently only under clear sky condition, whilst a low concentration level allows a portion of skylight to be delivered. Overall efficiency depends on optical characteristics of every component and number of optical processes, where light loss occurs with every process. Uniform distribution and consistency level enhance lighting quality. Efficient diffusers allow light to be evenly distributed and avoids lighting problems. Sunlight concentration affects lighting consistency; the more concentration, the less consistency is obtained.

3.2.2. Economic performance

Economical performance is vital for HLS to be a convincing alternative to electric lighting systems. Lifetime costs and benefits determine whether it can replace conventional electric system or not. Costs include initial and running costs. Both costs and benefits include tangible and intangible aspects. Initial capital cost depends on manufacturing complexity and production volume. Installation cost depends on system size, weight, mountain location, building modification necessity, and labour skills required. Intangible cost may occur in loosing rental area for ducts routes or so. Benefits may include for example, besides saving energy, improving building occupant's well-being due to the beneficial effects of enhanced daylight, thus raising users' productivity.

3.2.3. System-building relationship (compatibility)

System-building relationship can be determined by system's ability to adapt to new and existing buildings. Structural supports may be required to hold collectors weight and resist the wind force. Facade attached collectors influence its appearance. Interior design may be affected by system guidance and outputs. Wall and ceiling holes are required to accommodate the guidance, which additionally needs to meet fire protection compartment requirements. Big-section guidance may need special arrangements. Horizontal routes need to be coordinated with other building networks. Vertical routs may disturb space function or interior design.

3.2.4. Possibility of use (suitability)

Diversity in HLS features enables them to fit into different building forms and types. Facade mounted systems suit multi-storey buildings regardless number of stories; however they are strongly recommended to be south oriented. Sunlight can be delivered up to 20m into the building. Roof mounted systems are more suitable for deep-plan buildings with an average of three stories. High attention has to be paid in low rising buildings to avoid sunlight obstructs. Guidance ducts with side emitting provide linear luminaires that are more likely to be used in open plans. End emitting guidance provide variety of spot luminaire and conventional like luminaires which can be used for a wide range of purposes.

4. DECISION MAKING METHODOLOGY

The objective of the decision maker(s) is to rank alternatives in terms of their ability to meet building (or space) needs and budget, and come up with a choice of one of them. To make a perfect decision some criteria have to be defined and the performance of each alternative has to be measured in terms of these criteria. Because of the variety of alternatives and the decision criteria, the Multi-criteria decision making (MCDM) approach appears to be a reasonable way to make these decisions.

In this paper, three HLS assumed alternatives for a general case and decision has to be made to decide the best selection. A set of criteria was defined, depending on HLS analysis, to measure alternative performance. The decision criteria have been assigned importance weights. A widely used MCDM method is utilized to rank the alternatives; after applying three-step process in which weighting (of criteria), rating (of performance) and evaluating (of alternatives) have been carried out. Impact of changes in the evaluation process inputs on the decision making output has been discussed.

An online survey was conducted, targeted at decision makers in the fields of building design and operating. This was designed to measure to what extend each HLS component or requirement was been preferred. The decision criteria relative importance weights were derived from recipients responses. Forty-eight responses were received from twelve countries spread in five continents. The values obtained were used to examine the MCDM method and the impacts of changes in importance weights and performance measures.

5. MULTI-CRITERIA DECISION MAKING

The MCDM is one of the most well known branches of decision making. It uses numeric techniques to help decision maker(s) choose among a discrete set of alternative decisions. This is achieved on the basis of the impact of the alternatives on certain criteria thereby on the overall utility of the decision maker.

5.1. The MCDM problem

Although MCDM methods may be widely diverse, many of them have certain aspects in common. These are the notions of alternatives and criteria. Alternatives usually represent the different choices of action available to the decision maker(s). Decision criteria represent the different dimensions from which the alternative can be viewed. Each criterion needs to be assigned relative weight of importance **[4]**.

An MCDM problem, with *m* alternatives *and* n criteria, can be easily expressed in a matrix format. A decision matrix *A* is an (*m x n*) matrix; in which decision maker(s) has to determine a_{ij} measures the performance of alternative A_i when it is evaluated on terms of decision criterion C_j (for $i = 1, 2, 3, ..., m$, and $j = 1, 2, 3, ..., n$). For each criterion the decision maker(s) has to determine its importance, or weight w_j. Figure 2 represents the typical MCDM problem examined in this paper.

	Criteria				
Alts	**C_1** (w_1	**C_2** w_2	**C_3** w_3	**...** ...	**C_n** w_n)
A_1	a_{11}	a_{12}	a_{13}	...	a_{1n}
A_2	a_{21}	a_{22}	a_{23}	...	a_{2n}
A_3	a_{31}	a_{32}	a_{33}	...	a_{3n}
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
A_m	a_{m1}	a_{m2}	a_{m3}	...	a_{mn}

Figure 2: A typical decision matrix

Three steps have to be followed, as presented in sections 6.1 – 6.3 respectively, to utilize MCDM:

A. Define the set of alternative and the set of decision criteria.
B. Attach numerical measures to the relative importance of the criteria and to the impacts of the alternatives on these criteria.
C. Process the numerical values to determine a ranking of each alternative.

5.2. The weighted product model

The weighted product model (WPM) can be considered a modification of the weighted sum model (WSM); the earliest and probably the most widely used method **[5]**. Whilst the WSM should be used only when the decision criteria can be expressed in identical units of measure, the WPM eliminate any units of measures which makes it suitable for the current application.

In the WPM each alternative is compared with the others by multiplying a number of ratios, one for each criterion. Each ratio is raised to the power equivalent to the relative weight of the corresponding criterion.

In order to compare two alternatives A_K and A_L the following product **[6]** has to be calculated:

$$R(A_K/A_L) = \prod_{j=1}^{n} \left(a_{Kj} / a_{Lj} \right)^{w_j} \qquad (1)$$

Where n is the number of criteria, a_{ij} is the performance measure of the i^{th} alternative in terms of the j^{th} criterion, and w_j is the weight of importance of the j^{th} criterion.

If the term $R(A_K/A_L)$ is greater than one, then it indicates that alternative A_K is more desirable than alternative A_L. The best alternative is the one that better than or at least equal to all the others.

6. DECISION MAKING PROCESS

In order to apply the WPM method, four inputs have to be determined. These are the alternatives, the criteria, relative importance weights of the criteria and performance measures of the alternatives. Then pair-wise comparison will be made to rank the alternatives and determine the preferred choice.

6.1. Defining the alternative and criteria

Suppose decision maker(s) is planning to install HLS, review of HLS **[7]** shows that HSL, Parans and SCIS systems are intending to be the most promising HLS. Therefore, they are defined as the most suitably available alternatives.

Defining appropriate criteria able to measure different aspects of the alternatives are more complicated. The defined criteria should be systemic, reliable, measurable and comparable **[8]**. Defining criteria in this study based on the authors knowledge and analysis of hybrid systems' components and performance; previously discussed in Sec. 3. Criteria defined to cover architectural, technical, economical and operational aspects (see list of the criteria in table 1). Social criteria, such as users' productivity improvement or building prestige enhancement due to use of natural light, may be considerable if electric lighting system is considered one of the alternatives.

Table 1: Decision criteria relative importance weight

Decision Criteria	Relative Weight
Lighting Quality & Quantity	13.1 %
Ease of Maintenance	12.1 %
Cost	12.1 %
Fire hazard	11.9 %
Luminaire Flexibility	10.8 %
Light Guidance Size	10.3 %
Possibilities of use	10.2 %
Light Collector Location	9.9 %
Ease of Installation	9.5 %

6.2. Numerical measures

Importance weights and performance measures are unavailable data and have to be determined by decision maker(s). Numerical values of the weights or the performance can be determined by subjective, objective, or combined methods. The subjective methods depend only on the preference of decision maker(s). Contrarily the objective values are obtained by mathematical methods based on the analysis of initial data. It can said that none of them is perfect, so combined methods are suggested **[8]**.

In this paper, combined method was used. Values obtained from the survey are the recipients' subjective evaluation. These values numerically treated to obtain the importance weights and performance measures. Practically, decision maker(s) in each case has to determine the more likely related values for their situation; taking into account building use type and times, building form and orientation, location and budget.

6.2.1. Weighting

Recipients have weighted the criteria and the importance weights averages have been calculated. Then normalized to add up to one and ranked as listed in table 1. In reality, change of priorities responses to decision maker(s) appraisal of the real situation, which is possibly depends on client's needs, customers' complains or even feed backs. Reprioritization leads to changes in the criteria importance weights, and as a result changes in the alternatives preferences. For instance, an existing building with low clear height; light guidance size will be of greater importance than new building or high clear height building. 'Light collector location' criterion, in another example, may be of high priority in a building with a sensitive iconic form.

6.2.2. Rating

Performances of alternatives corresponding to each criterion have been derived from recipients' preferences. For example, regarding 'light collector location' preferences; valid responses percentages were as follows: 65.6% prefers roof mounting, 9.4% facade attached, 6.3% facade concealed, and 18.8% any method. HSL, as a roof mounted system, obtained performance measure of 84.4% (65.6% + 18.8%). Since Parans is a roof mounted or facade attached system, it obtained 93.8%. SICS, a facade attached or concealed system, obtained 34.5%.

Since performance measure corresponds to decision criteria, corresponding to 'light collector location' criterion in iconic building will widely vary. Roof mounted method may obtain in this case 100% preference rather than 65.6% to avoid influencing elevations appearance, or obtain 0% if it is a doom roofed building and roof mounting is conceptually unacceptable. In order that, as said in the weighting, in reality change of rating could happen in response to specific situations.

6.3. Determining alternatives ranking

Decision matrix includes all alternatives and decision criteria was set in as illustrated in table 2. Obtained relative weight of importance of decision criteria and performance measures of alternatives were filled in the matrix. Considering presented values in table 2, equation 1 was used to compare each two alternatives together. The following relations are produced:

$$R_{(HSL/Parans)} = (0.30/0.18)^{0.121} \times (0.57/0.54)^{0.095} \times \ldots \times (0.17/1.00)^{0.102} = 1.03 > 1$$

Similarly, we also get:

$$R_{(HSL/SCIS)} = 1.15 > 1, \qquad R_{(Parans/SCIS)} = 1.12 > 1$$

Table 2: Decision making matrix

	Decision Criteria	**Cost**	**Ease of installation**	**Ease of maintenance**	**Collector location**	**Guidance size**	**Luminaire flexibility**	**Light quality & Quantity**	**Fire hazard**	**Possibilities of use**
Alts	*Weight*	0.121	0.095	0.121	0.099	0.103	0.108	0.131	0.119	0.102
HSL	*Rating*	0.30	0.57	0.72	0.84	0.87	0.93	0.42	0.50	0.17
Parans	*Rating*	0.18	0.54	0.53	0.94	0.90	0.93	0.09	1.00	1.00
SCIS	*Rating*	0.91	0.17	0.38	0.34	0.30	0.50	1.00	0.50	0.33

(0) rate means no fit at all, (1) rate means excellent fit.

Therefore, the best alternative in this case is HSL system, since it superior to all other alternatives, then Parans, and finally SCIS.

7. SENSITIVE ANALYSIS

7.1. Background and definition

In the WPM method weights assigned to the decision criteria attempt to represent the genuine importance of the criteria. In the above case, 'light quality 'criterion obtained the best weight, therefore it intuitively attempts to be believed the most important criterion. Since the defined criteria in the current case have different units of measure, and cannot be all expressed in quantitative terms, then it is difficult to represent accurately the importance of these criteria. In a situation like this, the decision making process can be improved considerably by identifying the critical criteria. Sensitivity analysis is the approach by which the critical criteria can be identified to determine what is the *smallest* change in the current weights of the criteria, which can *alter* the existing ranking of the alternatives? The most critical criterion can be determined to see whether it will alter the rank of any two alternatives or just change the rank of the best alternative.

7.2. Determining the most critical criterion

Let $\Delta'_{k,i,j}$ ($1 \leq i \leq j \leq m$ and $1 \leq k \leq n$) denote the minimum percent of change in the current weight w_k of criterion C_k so that the ranking of alternatives A_i and A_j will be reversed. When the WPM method is used, the quantity $\Delta'_{k,i,j}$ is given as follows **[5]**:

$\Delta'_{k,i,j} > Z$ if, $0 \leq Z \leq 100$

$\Delta'_{k,i,j} < Z$ if, $Z < 0$

Where Z is defined as:

$$Z=[(\log(\prod_{y=1}^{n}(a_{iy}/a_{jy})^{w_y}))\text{x}100\ ]/[(\log(a_{ik}/a_{jk}))\text{x}w_k] \quad (3)$$

Also, the following constraint has to be satisfied:

$$\Delta'_{k,i,j} \leq 100 \quad (4)$$

In order to determine the most critical criterion a total of *n x m (m – 1)* values need to be calculated. For example, the minimum quantity (expressed as %) needed to change the current weight of 'light quality', so consequently the current ranking of HSL and Parans systems will be reversed; can be calculated using relation (3) as follows:

$$Z_{(HSL/Parans)} = \frac{\log(\,(0.30/0.18)^{0.121}\text{ x }(0.57/0.54)^{0.095}\text{ x } \dots \text{ x }(0.17/1.00)^{0.102}}{\log\ (0.42/0.09)} \text{ x } \frac{100}{0.131} = 12.83$$

The quantity 12.83 satisfies (4) as it is less than 100. Therefore the value of $\Delta'_{k,i,j}$ have to be bigger than 12.83. Thus the modified weight w^* of the 'light quality' criterion has to be reduced 12.83% at least. It can be calculated as follows (before normalization):

$$w^*_K = w_k - (w_k \text{ x } \Delta'_{k,i,j})$$
$$= 0.131 - (0.131 \text{ x } 12.83\%) = 0.114$$

The use of the modified weights values (after normalization) makes the relation $R_{(HSL/Parans)}$ equal to one. Any further reduction in the modified weight of 'light quality' criterion makes $R_{(HSL/Parans)}$ less than one, which accordingly reverses the rank and makes Parans alternative superior to HSL.

Working as above for all possible pairs of alternatives, all possible *Z* values can be determined as depicted in table 3. Note that n/f stands for non-feasible value, which is value that cannot satisfy the constraint given as (4). That means it is impossible to reverse the existing ranking of pair of alternatives by making changes on the current weight of the corresponding criterion. It can be observed that the criterion with the highest weight is the critical criterion in two cases only.

Table 3: All possible Z values

	Decision Criteria								
Pairs of Alternatives	**Cost**	**Ease of installation**	**Ease of maintenance**	**Collector location**	**Guidance size**	**Luminaire flexibility**	**Light quality & Quantity**	**Fire hazard**	**Possibilities of use**
HSL/Parans	42.12	524.24	70.89	-249.07	-934.81		**12.83**	-31.39	-14.14
Parans/SCIS	-58.78	105.30	282.87	115.01	100.41	172.38	**-36.25**	138.01	101.40
HSL/SCIS	**-105.70**	123.60	182.02	157.73	126.33	211.58	-124.4		-197.26

7.3. Degree of criticality

Importance ranking of the criteria may change after determining the critical criteria. The criticality degree, D'_k, of criterion C_k is the smallest percent amount by which the current value of w_k must change, so that the existing ranking of the alternatives will change **[5]**. That is, the following relation is true:

$$D'_k = \min_{1 \le i < j \le m} \{ |\Delta'_{k,i,j}| \}, \text{ for all } n \ge k \ge 1$$

Therefore, from table 3, the criticality degrees are as depicted in table 4.

Table 4: The criticality degree of the criteria

Decision Criteria	***D'***
Lighting Quality & Quantity	12.83
Possibilities of use	14.14
Fire hazard	31.39
Cost	42.12
Ease of Maintenance	70.89
Light Guidance Size	100.41
Ease of Installation	105.30
Light Collector Location	115.01
Luminaire Flexibility	172.38

8. DISCUSSION

Although HLS have a common concept they vary in features. That what makes a rational choice is a very difficult decision. Thus, this work aims to practice a method by which a particular HLS can be identified ideal for a particular application. The MCDM offers numerical methods to help decision maker(s). The WPM method, a dimensionless MCDM method, was utilized to make a decision in a general case, in which a HLS is desired to be selected.

In order to apply the WPM method, a set of three HLS was nominated as alternatives. A set of nine decision criteria were defined based on alternatives' components and performance analysis. The relative importance weights of the criteria and the alternatives performance were derived from decision makers' responses to an online survey. Changes in these values are more likely to happen with every new situation to reflect the new circumstances.

'Light quality' and 'ease of maintenance' criteria, as whole life aspects, were selected by the surveyed decision makers as the most important criteria, in addition to the 'cost' criterion. Contrarily, 'ease of installation' criterion, as one-off aspects, emerged as the least important criterion. The criterion elected by decision maker(s) as the most important one is not necessarily to be the most influential or critical one; especially in cases where different units of measurement were used. Therefore, the criticality degree can be measured by the criterions ability to change the alternative ranking. The smaller change in the criterion weight required to alter the ranking, the more critical the criterion is. Thus, criterion that cannot alter alternatives ranking whatever change to its weight can be eliminated.

A sensitivity analysis was carried out to determine critical degrees of the criteria. 'Light quality', the most important criterion was the most critical one as well. Only 12.83% reduction in its relative weight is enough to nominate Parans system the best alternative instead of HSL. In order to bring SCIS to the top, the 'cost' criterion is the critical one and its relative weight has to be increased 105.7% at least. Meanwhile, only 58.78% raise is enough to reverse SCIS rank with Parans system.

Alternatives performance show close similarity on some criteria and wide variation on others. For example, HSL and Parans obtained 0.57 and 0.54 values respectively in terms of 'ease of installation', whilst SCIS obtained only 0.17, as SCIS collector and guidance are much bigger in size and weight, thus more supports and building modification are needed. In terms of 'cost' a big variation exists which reveals the decision makers acceptance of the systems' payback periods. The difference between 0.91 obtained by SCIS and 0.18 obtained by Parans reflects the big difference between the costs of both of them. Similarly, Parans obtained 0.90 in terms of 'guidance size', whilst SICS obtained only 0.30 which demonstrate the difference between the small-diameter fibre optic cables and the big-section illuminance ducts. Sensitivity analysis can be carried out to determine the critical changes in performance measures to change alternatives ranking. For example, to know the minimum change in Parans measure in terms of the cost to be ranked the best alternative. Performance measures sensitivity analysis is a subject for future research.

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