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Mehdi EL AMINE, Jerome PAILHES, Nicolas PERRY - Critical review of multi-criteria decision aid methods in conceptual design phases: application to the development of a solar collector structure - In: 24th CIRP Design Conference 2014 - Mass Customization and Personalization, Italy, 2014-04-14 - Proceeding of the 24th CIRP Design Conference 2014 - Mass Customization and Personalization - 2014

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Critical review of multi-criteria decision aid methods in conceptual design phases: application to the development of a solar collector structure

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Abstract

At each stage of the product development process, the designers are facing an important task which consists of decision making. Two cases are observed: the problem of concept selection in conceptual design phases and, the problem of pre-dimensioning once concept choices are made. Making decisions in conceptual design phases on a sound basis is one of the most difficult challenges in engineering design, especially when innovative concepts are introduced. On the one hand, designers deal with imprecise data about design alternatives. On the other hand, design objectives and requirements are usually not clear in these phases. The greatest opportunities to reduce product life cycle costs usually occur during the first conceptual design phases. The need for reliable multi-criteria decision aid (MCDA) methods is thus greatest at early conceptual design phases. Various MCDA methods are proposed in the literature. The main criticism of these methods is that they usually yield different results for the same problem [22,23,25]. In this work, an analysis of six MCDA methods (weighed sum, weighted product, Kim & Lin, compromise programming, TOPSIS, and ELECTRE I) was conducted. Our analysis was performed via an industrial case of solar collector structure development. The objective is to define the most appropriate MCDA methods in term of three criteria: (i) the consistency of the results, (ii) the ease of understanding and, (iii) the adaptation of the decision type. The results show that TOPSIS is the most consistent MCDA method in our case.

Key words: Multi-criteria decision aid methods; Selection methods; Aggregative methods; Innovative design; Conceptual design; Consistency

1. Introduction

Decision making is an inherent task in the product development process. It can be broken into (i) conceptual design decisions, when decision makers have to choose between several design concepts, and (ii) embodiment design decisions, when designers have to optimize design variables for the selected concepts. In this paper, we treat only the problem of conceptual design decisions.

Nomenclature

xi	interpretation values
PI	performance index

Decision support was first proposed by Nobel Prize winner Herbert Simon in the nineteen sixties [1]. In a broad sense, decision making is conducted in four steps: (i) identifying the problem (ii) generating design alternatives, (iii) evaluating design alternatives via evaluation schemes, and (iv) selecting the best alternative. The research community in decision support methods usually recognize that the most critical step in decision making process is how to choose among a given number of design alternatives (step (iv)). The ability of decision makers to make the best choice is strongly conditioned by two factors: (i) having a clear definition of design objectives and requirements, and (ii) being able to evaluate or predict the performance of the proposed alternatives. However, uncertainties and vagueness are inherent in engineering design and they characterize both

design objectives and alternatives evaluation schemes. This is particularly true in the first steps of conceptual design. The decisions taken at this design phase have the greatest influence on overall product life cycle cost. In order to minimize risk and reduce the cost of regret in later processes, companies often opt for a least commitment and late design decisions during product development process. This usually implies the development of several design concepts in parallel to finally settle down the optimal solution. Indeed this strategy is effective to minimize risk. It is very important to adopt appropriate methodologies and theories to structure and ease decision making process. This can significantly reduce product development lead-time as well as the amount of human and material resources involved in the development process.

As shown in Fig. 1, multi-criteria decision making process can be decomposed into three principal steps: (i) an observation step, when data are collected about each alternative, (ii) an interpretation step, when decision makers express their preferences for each design criterion on the basis on data collected in the observation step, and (iii) a results analysis step, when decision makers combine interpretation step outcomes for different design criteria in order to determine the best alternative(s).

Because of the great difficulty for decision makers to intuitively follow this process, especially to combine information in appropriate ways (step 3 of decision making process), MCDA methods can be used to aid in multi-criteria decision making.

The preference expression mode used in step (ii) can have an important influence on decision making results [23]. The different expression modes used by the MCDA methods are: direct rating, pairwise comparisons, and lotteries. Each mode has its advantages and disadvantages. There are three factors to consider when choosing the preference expression mode: (i) it must be adapted to the type of information available on the design alternatives (step 1 in decision making process), (ii) decision makers must feel comfortable when using it, and (iii) the type of yielded information must be adapted to the decision situation.

Various MCDA methods are proposed and adopted by researchers and engineers to support design decision-making in engineering design. Choosing the most suitable MCDA method to compare multiple alternatives is a critical issue because these methods may yield different results for the same problem [22,23,25]. There are two families of MCDA methods: (i) multi-criteria selection methods, where interpretation step results are taken into account simultaneously to compare alternatives, and (ii) aggregative methods, where interpretation step results are aggregated into a single variable called performance index (PI) that reflect the

performance of the design alternatives.

In the next section, the MCDA methods analyzed in our study are presented. After that, the industrial case study is presented and examined. Then, in Section 4, the objectives of the study and the proposed approach are presented. Finally, the results and the interpretations are presented and recommendations are given at the conclusion.

2. Presentation of MCDA methods

In this work, five aggregative methods (weighed sum, weighted product, Kim & Lin, compromise programming, and TOPSIS) and one selection method (ELECTRE I) were considered.

The weighted sum is the most widely used aggregation method. The weights assignment reflects the proportional importance of the different aggregated variables. However, the major disadvantage of this method is that it doesn't satisfy the principle of annihilation, which is generally not acceptable in design decision problems. The performance index is expressed by:

(1)

With

The weighted product (WP) provides a conservative aggregative method that satisfies the principle of annihilation. However, the meaning of weights is less intuitive than weighted sum. They reflect the exponential relative importance, and not proportional between variables. The performance index is expressed by:

(2)

With

Kim & Lin [4] is the most conservative aggregative method. It also satisfies the principle of annihilation. However, the biggest disadvantage is that it does not allow any kind of compensation. Its use is thus very limited in engineering design. The performance index is expressed by:

(3)

TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) is a compensatory method that was developed by Hwang (Hwang and Yoon [9]) and widely applied by other researchers (Deng et al. [10]; Tsaur et al. [11]; Opricovic and Tzeng [12]; Cheng et al. [13]; Montanari [14]; Tong et al. [15]; Tzeng et al. [16], etc.). In conceptual design, TOPSIS has been used in a very limited way [27]. The basic principle

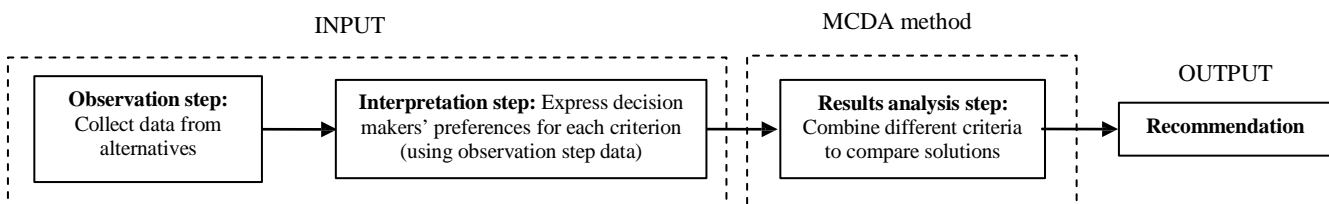


Fig. 1. Schematization of the decision making process.

of TOPSIS is that the best alternative should have the shortest distance from the ideal solution and the farthest distance from the negative-ideal solution. The TOPSIS procedure consists of the following steps: (i) calculate the normalized decision matrix, (ii) calculate the weighted normalized decision matrix, (iii) determine the ideal and negative-ideal solution, (iv) calculate the separation measures from the ideal and negative-ideal solution (respectively and) by using the n-dimensional Euclidean distance, (v) calculate the relative closeness to the ideal solution, and (iii) calculate the performance index of each solution by the following formula:

$$\text{Performance Index} = \frac{d_j^-}{d_j^+ + d_j^-} \quad (4)$$

The separation measures from the ideal and negative-ideal solution are calculated by the following formula:

$$d_j^+ = \sqrt{\sum_{k=1}^n (w_k (x_{kj} - x_k^+))^2} \quad (5)$$

$$d_j^- = \sqrt{\sum_{k=1}^n (w_k (x_{kj} - x_k^-))^2} \quad (6)$$

With : The minimum interpretation value for criterion j

: The maximum interpretation value for criterion j

Compromise Programming (CP) was developed by Yu [17] and Zeleny [18]. The basic principle of CP is that the best alternative should have the shortest distance from the ideal solution. The performance index is expressed by:

$$\text{Performance Index} = \frac{d_j^-}{d_j^+ + d_j^-} \quad (7)$$

With

Where and have the same meaning as in TOPSIS. The parameter p defines the desired type of distance. In this study, the CP method has been applied twice by using the parameter p equal to 1 and 2.

The ELECTRE I is an outranking method that is widely used by decision makers in many fields. It was first developed by Benayoun et al. [17]. The ELECTRE I procedure consists of the following steps: (i) define a concordance index for each pair of alternatives, it represents the sum of weights of attributes for which alternative A is better than B, (ii) define a discordance index for each pair of alternatives. It denotes the absolute difference of this pair of attributes divided by the maximum difference over all pairs, (iii) establish threshold values for the two indices, (iv) generate the set of alternatives that is not outranked by any other alternative. In order to obtain an overall ranking of the alternatives, many threshold values are used in our study and each alternative is ranked according to how many times it belong to the set of non-outranked alternatives.

3. Presentation of industrial case

A previous work has been performed within a design department developing a collector for a solar thermal power plant with Fresnel mirrors. The main function of the solar collector is to concentrate and redirect solar radiation into the absorber tubes to heat up the transfer medium in absorber tubes. The recovered heat is then used to generate high pressure steam which drives a turbine to produce electricity. The solar collector is composed of a reflecting glass and a metal structure, whose function is to give and maintain reflecting glass shape (Fig. 2). A support solution is performed between the reflecting surface and the metal structure to ensure the connection between the two. Solar collector is driven by a rotation movement in order to pursue the movement of the sun.

In order to maintain a good thermal efficiency of the plant, a high reflection performance is required from the collector. This implies that the elastic deformation of the structure must remain as low as possible. A high level of precision must also be considered when manufacturing the collector.

The technology of solar thermal power plant with Fresnel mirrors is relatively recent and thus the historical background is limited. This induces a real difficulty when evaluating design alternatives. The implementation site also has a strong influence on collector design: climatic data, market data, etc. The difficulty is that the choice of implementation sites is not made and there is a variety of possible implementation sites where the conditions may vary significantly.

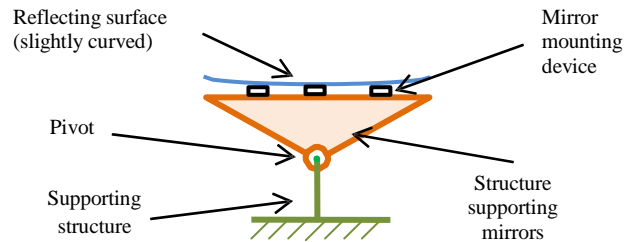


Fig. 2. Schematization of solar collector structure.

In this study, we treat only the preliminary design of the metal structure (see Fig.2). Three main solutions have been proposed for the metal structure: truss structure (S1), sandwich structure (S2) and tube structure (S3). Compared to the tube and truss structure, the sandwich structure is the most mature solution. Its behavior is well characterized by the company due to the many prototypes that have been made. By contrast, truss and tube structures are new solutions for the company and there are much less mature than the sandwich solution. As the product development progresses, the behavior models used become more and more accurate especially due to prototypes testing. Rectifications are introduced to the three solutions throughout the development process.

The criteria taken into account in this study are: elastic deflection (C1), angular elastic deformation (C2), raw material cost (C3), durability (C4), development time (C5), ease of industrialization (C6), adaptation to the mirror mounting solution (C7), adaptation to the guidance solution (C8).

The development process is composed of three major milestones. At each milestone, a set of tasks is planned in order to investigate the performance of each concept. These actions generally consist in: numerical analysis and prototyping/tests. At the end of each milestone, an assessment grid is established to synthesize investigation works of designers. The results are discussed by different actors participating in the development process. The development team decides then what concepts should be eliminated and what actions must be done for the next milestone. In this study, we treat the decision making problem at the first milestone.

4. Objectives and approach

In the present study, various MCDA methods were tested and analyzed based on the conceptual design phase of a solar collector of a thermodynamic solar power plant. The objective is to evaluate the appropriateness of MCDA methods in our context.

The first step of our study is to evaluate weights for the different criteria. It is difficult and risky to directly assign weights to criteria because they are from different natures. In our study, pairwise comparison was used because it is more appropriate to this case. Using the semantic scale in Table.1, the judgment matrix was constructed. The results are given in Table. 2. The matrix normalization method [26] was then used to calculate criteria weights from the judgment matrix. In order to limit the inconsistencies that occur when performing pairwise comparisons, the Consistency Ratio (CR) proposed by Saaty [3] was used as a guidance to check for consistency. As recommended by Saaty [3], a value of 0,1 was used as threshold for CR.

Table. 1 Semantic scales used (a) for direct rating; (b) for pairwise comparison.

(a)		(b)	
Satisfaction degree	Interpretation value	Relative priority degree	Judgement value assigned
Extremely high	1	Capit	1
Very high	0,9	très	1
High	0,8	très	1
Fairly high	0,7	assez	1
Moderately high	0,6	assez	1
Moderate	0,5	Moyen	1
Moderately low	0,4	moderate	1
Fairly low	0,3	1	1
Low	0,2	1	1
Very low	0,1	1	1
Null	0	1	1

After the evaluation of criteria weights, the next step is the evaluation of alternatives against each criterion (the interpretation step). A direct rating was used to evaluate each alternative against each criterion. This preference expression mode was used because it is simple and it yields a cardinal rating. Pairwise comparison is more suitable to deal with qualitative criteria and uncertainty in data. However, it yields ordinal evaluation of alternatives which is not suitable to use with aggregative methods. In order to help decision makers to

assign interpretation values, the semantic scale in Table. 3 was used. The results of the interpretation step are presented in Fig. 2.

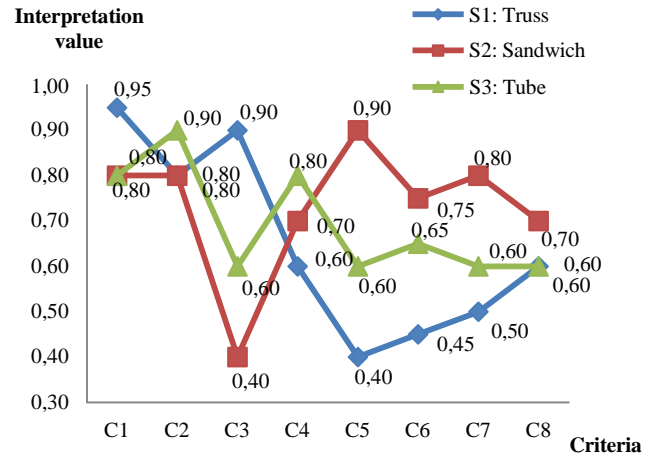


Fig. 3. Interpretation results

Based on the interpretation results (Table. 2) and criteria weights obtained by pairwise comparisons, different MCDA methods were used to rank alternatives. From this survey, MCDA methods were evaluated in terms of three criteria: (i) the consistency of results, (ii) the ease of understanding and, (iii) the adaptation the decision type.

Table 2. Evaluation of criteria weights by pairwise comparisons

	C1	C2	C3	C4	C5	C6	C7	C8
C1		0,14	0,13	0,20	0,20	0,13	0,17	0,50
C2			0,20	0,50	3,00	0,20	0,33	5,00
C3				3,00	7,00	4,00	5,00	8,00
C4					2,00	0,25	3,00	5,00
C5						0,17	0,50	4,00
C6							5,00	7,00
C7								5,00
C8								
Final criteria weight	0,02	0,08	0,38	0,12	0,05	0,25	0,09	0,02

4.1. The consistency of results

The consistency of results is very important criterion of MCDA methods. It measures the closeness of the result given by the MCDA method to what really corresponds to decision makers' preferences. In our study, this criterion was evaluated by comparing the ranking results given by MCDA methods to the intuitive ranking addressed by decision makers

4.2. The ease of understanding

This aspect measures the effort and the time required for the decision makers to understand the MCDA method (assumptions, tradeoffs, and procedures of method). The less time and effort required to understanding the method, the better decision makers will use the method and the more effective the method will be [21]. Experienced decision makers generally prefer simple, more transparent methods [20]. The MCDA methods were tested by three persons participating in the development project. The methods were

then ranked on a scale of 1 to 5 (1 if the method is very difficult to understand and 5 if the method is very easy to understand).

4.3. Adaptation to the decision type

It is important that the type of decision given by the MCDA method corresponds to the type of decision expected by decision makers. For example, if the decision makers want to get a cardinal ranking of alternatives, then an outranking method is not appropriate.

5. Results and interpretation

As shown in Fig. 4, clear discrepancies are observed in the ranking of alternatives between compensatory and non compensatory aggregation methods. All the compensatory aggregation methods (weighted sum, TOPSIS, compromise programming with $p=1, 2$) yield the following ranking: $A1 \rightarrow A3 \rightarrow A4$. On the other hand, the two non-compensatory strategies (Kim & Lin and weighed product) yield the following ranking: $A3 \rightarrow A1 \rightarrow A4$. ELECTRE I yields the same ranking as compensatory aggregative methods.

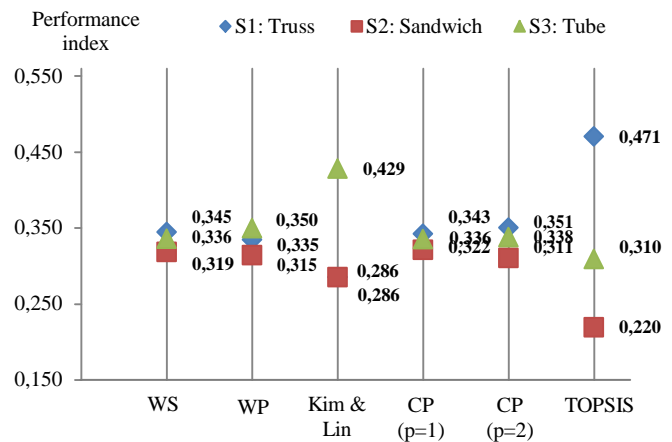


Fig. 4. Ranking of alternatives by each aggregative method.

Apart from TOPSIS and Kim & Lin aggregation methods, the performance indexes obtained by the other aggregation methods are very close together. It is thus difficult and risky to draw a conclusion based on these results since a small error in interpretation values could reverse the ranking. Kim & Lin aggregation is not suitable for our case because it does not provide any kind of compensation.

According to the interpretation results (Fig. 3), the truss alternative highly satisfies the criterion of raw material cost which is the most important criterion. In contrast, because of its low maturity, it collects low interpretation values (Fig. 3) for other criteria, in particular for the criterion 'ease of industrialization' which also has a very strong importance in our case. Therefore truss alternative obtains a low performance index by conservative aggregative methods. But the important fact that should be considered here is that the truss structure is a novel and immature alternative compared with the others. The potential of improvement is thus high. That is why this alternative was particularly attractive for decision makers. This statement was intuitively felt by

decision makers and it was highlighted strongly by TOPSIS and little by the other compensatory aggregative methods. For the other two solutions, the ranking yielded by compensatory aggregative methods is also coherent with the preferences of decision makers. From this observation we can estimate the consistency of evaluated MCDA methods in our case.

It can be remarked that TOPSIS intensifies the relative importance between alternatives compared to other compensatory aggregative methods. This intensification effect can be attributed to two factors: (i) the two reference points (ideal and negative-ideal solutions) are obtained according to the alternatives tested (relation (5) and (6)), and (ii) this method uses an Euclidian distance to calculate the closeness of alternatives to the reference points.

For the criterion of 'ease of understanding', WS and Kim & Lin were the easiest methods to understand, followed by WP, CP, TOPSIS and finally ELECTRE I which was particularly difficult to understand by decision makers who participate in the survey. Table 4 gives more details about the evaluation of MCDA methods against this criterion.

For the criterion of 'adaptation of the decision type', the most adapted decision type in our case is the cardinal ranking. Ordinal ranking (yielded by ELECTRE I) is not suitable because decision makers need to know how much better an alternative is over the others in order to be able to make a decision. Aside from ELECTRE I, all the other methods respect this criterion since they yield a cardinal ranking.

Another disadvantage of the ELECTRE I method is that it evaluates a criterion even if it has a weight equal to zero. This can mislead the decision maker, since the discordance calculation does not consider the value of the weights. The use of ELECTRE I is clearly not suitable in our case.

Table 5. Evaluation of MCDA methods against the three criteria.

	Consistency	Ease of understand	Adaptation of the decision type
WS	Average	5	Good
WP	Poor	4	Good
Kim & Lin	Poor	5	Good
CP (p=1)	Average	3	Good
CP (p=2)	Average	3	Good
TOPSIS	Good	2	Good
ELECTRE I	Poor	1	Poor

6. Conclusion

A comparative study of different MCDA methods was performed in this paper based on an industrial case study of a solar structure development. The study focused on the two main steps of decision making: the interpretation step and result analysis step (Fig. 1). Even if pairwise comparison seems to be more suitable to deal with qualitative criteria, the direct rating was privileged in the interpretation step because it allows having cardinal interpretation values which are much more suitable to use with aggregative methods. Many MCDA methods were then used to rank alternatives. It was found that the ranking differs between conservative and non-conservative methods.

Generally it was found that the results yielded by compensatory aggregative methods are more consistent. TOPSIS was the most consistent with decision makers' preferences because the results yielded by this method respect very well the decision makers' preferences. However, in the final design phases, it could be more appropriate to use non compensatory aggregation methods because the potential of improvement is low and decision makers cannot afford to take risks.

A further investigation should be done in a future works in order to evaluate more efficiently the performance of the MCDA methods. For example, a sensitivity analysis could be performed in order to evaluate the robustness of these methods with respect to uncertainties in interpretation values or criteria weights. Further industrial cases of product development could also be considered.

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