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A Review and Comparative Analysis of Methods for Determining Criteria Weights in MCDM Tasks

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Abstract **– To select optimal solutions in multicriteria decision-making (MCDM) problems, many practical approaches have been developed. In almost all of these approaches, it is necessary to assess the importance of individual criteria for decision makers. Subjective assessments of importance are transformed into numerical assessments of decision weights by applying appropriate computational procedures. A large number of methods for determining the weights of the criteria have been proposed. These methods differ in their operating principles and in the calculation procedures underlying each method. The paper presents the most well-known methods and provides a brief comparative analysis.**

Keywords **– Criteria weights, multicriteria decision making, ordinal comparison of criteria, relative importance of criteria, relative quantitative comparison of criteria.**

I. Introduction

In the second half of the 20th century, practical needs caused a rapid development of theoretical and practical foundations of decision making. One of the areas of decision-making tasks is multicriteria decision making (MCDM). A characteristic feature of such problems is that the analysis of decisions and the choice of the optimal decision take place in the absence of risk. On the other hand, in such problems it is necessary to define principles, on whose basis the choice of solutions in the Pareto set is made under contradictory values of the criteria.

Many powerful practical approaches to solving MCDM problems have been proposed. In all of these approaches, the relative importance of the criteria whose values characterise the alternative solutions plays an important role.

The importance of the criteria must be assessed. The results of the assessment are expressed in the form of criteria weights. Each of the weights reflects the ordinal or relative importance of the corresponding criterion.

The paper is organised as follows. Section II presents the best-known methods for determining criterion weights, which are based on the ordering of criteria by importance. Section III discusses some commonly used methods for determining criterion weights, based on the assessment of the relative importance of criteria. Section IV summarises the main points of the work.

II. Methods for Determining Criteria Weights in MCDM Tasks

A. Rank Ordered Centroid Technique (ROC)

The ROC technique was proposed by Barron & Barrett [1]. The calculation of criterion weights is made on the basis of this sequence of procedures:

1. Ordinal ranking of criteria by importance. Provided that n criteria are specified, the most important criterion is assigned a score 1 while the least important criterion is assigned a score n.
2. Criteria weight calculation is performed using (1)

$$w_j = \frac{1}{n}\sum_{k=j}^{n}\frac{1}{k} \tag{1}$$

where k – the score of the relevant criterion in the ranked sequence of criteria, n – the total number of criteria.

If subjective ordinal ranking is performed by a single expert, the estimates serve as a basis for further caslculations. Instead, if ordinal ranking is carried out by a group of experts, and the results of specific rankings do not coincide, first, it is necessary to determine the average results of rankings and then to order the attributes and assign scores to them. Let us illustrate the procedure of averaging the results of expert evaluation.

Example 1. Suppose, there are four experts: e_1, e_2, e_3, and e_4. Their task is to assign weights to these three criteria: c_1, c_2 and c_3 based on the ROC method. The results of preliminary ordinal ranking of criteria by importance are given in Table I.

TABLE I
Results of Preliminary Ordinal Ranking of Criteria by Importance

Criteria / Experts	c_1	c_2	c_3
e_1	3	2	1
e_2	3	1	2
e_3	3	2	1
e_4	2	3	1
Average values of ranks	2.75	1.75	1.67

The number at the intersection of the i-th row and the j-th column shows the place of the j-th criterion according to the evaluation of the i-th expert in the sequence of criteria rank ordered by importance. The bottom row of Table I shows the average values of criteria ranks that are calculated as arithmetic

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mean values of the numbers in the corresponding column of the table.

As a result of preliminary evaluation, we have the following ranked sequence of criteria: $c_3 \succ c_2 \succ c_1$. Now, let us assign these scores to the criteria: $c_3 - 1$, $c_2 - 2$, $c_1 - 3$.

Let us calculate the values of criteria weights by (1).

$$w_3 = \frac{1}{3}\left(\frac{1}{1}+\frac{1}{2}+\frac{1}{3}\right) = 0.333{\cdot}1.833 = 0.610 ;$$

$$w_2 = \frac{1}{3}\left(\frac{1}{2}+\frac{1}{3}\right) = 0.333{\cdot}0.833 = 0.277 ;$$

$$w_1 = \frac{1}{3}\cdot\frac{1}{3} = 0.111 .$$

B. Rank Summed Weighting Technique (RS)

The RS technique is proposed in [2]. Criteria weight values are calculated following this sequence of procedures:

1. Subjective ordinal ranking of criteria by importance. The most important criterion is assigned a score 1, the least important criterion is assigned a score *n*.
2. Criteria weights are calculated using (2)

$$w_j = \frac{2\left(n+1-j\right)}{n\left(n+1\right)} , \quad (2)$$

where j – the score of criterion c_j; n – the total number of criteria.

If criteria evaluation by importance is done by a group of experts, the averaged criteria ranks are first calculated. Based on the results obtained, scores are assigned to all criteria.

Example 2. Let us take the results of final criteria ranking by criteria from Example 1 as a basis: $c_3 - 1$, $c_2 - 2$, $c_1 - 3$.

Let us calculate the values of criteria weights according to (2).

$$w_3 = \frac{2\left(3+1-1\right)}{3\left(3+1\right)} = \frac{2{\cdot}3}{3{\cdot}4} = 0.500 ;$$

$$w_2 = \frac{2\left(3+1-2\right)}{3\left(3+1\right)} = \frac{2{\cdot}2}{3{\cdot}4} = 0.333 ;$$

$$w_1 = \frac{2\left(3+1-3\right)}{3\left(3+4\right)} = \frac{2{\cdot}1}{3{\cdot}4} = 0.167 .$$

C. Rank Reciprocal Weighting Technique (RR)

The RR technique is proposed in [2]. Criteria weights are calculated based on this sequence of procedures:

1. Subjective ordinal ranking of criteria by importance. The most important criterion is assigned a score 1, the least important criterion is assigned a score *n*.
2. Criteria weights are calculated according to (3):

$$w_j = \frac{\frac{1}{j}}{\sum_{k=1}^{n}\frac{1}{k}} . \quad (3)$$

If criteria evaluation by importance is done by a group of experts, then score assignment to the criteria is made based on the average results of ranking of individual experts.

Example 3. Let us take the results of final criteria ranking by criteria from Example 1 as a basis: $c_3 - 1$, $c_2 - 2$, $c_1 - 3$.

Let us calculate the values of criteria weights by (3).

$$w_3 = \frac{\frac{1}{1}}{\frac{1}{1}+\frac{1}{2}+\frac{1}{3}} = \frac{1}{1.833} = 0.545;$$

$$w_2 = \frac{\frac{1}{2}}{\frac{1}{1}+\frac{1}{2}+\frac{1}{3}} = \frac{0.500}{1.833} = 0.273;$$

$$w_1 = \frac{\frac{1}{3}}{\frac{1}{1}+\frac{1}{2}+\frac{1}{3}} = \frac{0.333}{1.833} = 0.182.$$

D. Simple Pairwise Comparison (SPC)

The essence of *Simple Pairwise Comparison* is a pairwise comparison of the whole set of criteria by importance. The values of criteria are calculated based on the generalized results of pairwise comparisons. The SPC technique does not require ranking all criteria by importance. As this method uses ranking on pairs of attributes, we will ascribe it to the methods of the first group.

Criteria weights are calculated according to the following sequence of procedures:

1. Pairwise comparison across all criteria by importance.
2. Finding the number of points for each criterion using the results of their pairwise comparison.
3. Calculation of criteria weight values. For each j-th criterion, the value of its weight, w_j is calculated as the ratio of the number of points assigned to that criterion to the total number of points.

Example 4. Let there be three criteria: c_1, c_2, and c_3. A pairwise comparison of the criteria by importance is made, and these results are obtained:

$c_3 \succ c_1$, $c_3 \succ c_2$ $\rightarrow c_3 - 2$ points;

$c_2 \succ c_1$ $\rightarrow c_2 - 1$ point;

$c_1 - 0$ points.

The least important criterion, c_1, has a score of zero points. Thus, it follows that this criterion will have the weight value equal to 0. To avoid such a situation, a fixed number of points is added to the number of points for each criterion. In the above-mentioned example, we will add 1 point for each criterion. As a result, we have $c_3 - 3$ points, $c_2 - 2$ points, $c_1 - 1$ point.

In total, we have six points for all criteria. Let us calculate criteria weights.

$$w_3 = \frac{3}{6} = 0.500\ ;\ w_2 = \frac{2}{6} = 0.333\ ;\ w_1 = \frac{1}{6} = 0.167\ .$$

The advantage of this group of methods is their simplicity. Experts are only required to make an ordinal comparison of criteria by importance or, even simpler, a pairwise comparison of criteria by importance. One shortcoming of these methods is that the values of criteria weights only depend on the places of criteria in their ranked sequence. Information about relative importance of criteria is completely ignored when either of those methods is employed. For this reason, in literature these methods are frequently called approximated methods.

Practical use of this group of methods is limited by situations where, for one reason or another, assessment with regard to relative importance of criteria is not possible or these methods are used for a preliminary analysis of complex decision-making situations.

A comparative analysis of ROS and RS techniques is provided in [3]. More extensive reviews and analyses of the methods of this group are presented in [4]–[6].

III. Methods Based on Relative Quantitative Comparison of Attributes by Importance

E. Simple Multi-Attribute Rating Technique (SMART)

The SMART technique was proposed in [7], [8]. The calculation of criteria weights is made on the basis of the following sequence of procedures:

1. Subjective ordinal ranking of criteria by importance. The procedure corrresponds to the ranking procedures in the methods of the first group.
2. Selecting a reference attribute. In the SMART method, the least important attribute is usually selected as the reference attribute.
3. Assigning a fixed number of points to the reference attribute. As a rule, a number of points equal to or greater than 50 is assigned for the reference criterion.
4. Assigning in sequence a number of points for all criteria that reflect the extent of importance of each criterion with respect to the reference point.
5. Assigning a number of points for each criterion that is equal to the sum of points initially assigned to that criterion and a number of points assigned to the reference criterion.
6. Calculation of criteria weight values. The value of weight for specific criterion is determined as the ratio of the final number of points given to that criterion to the sum total of the points across all criteria.

Example 5. Let us take the results of criteria ranking with respect to importance as a basis. The results of expert evaluations and relevant calculation values are given in Table II.

The sum of points in the 3rd row of Table II is 400. Dividing the total number of points for each criterion by the total sum of points, we obtain the value of weight of this criterion that is shown in the corresponding cell of the 4th column of Table II.

TABLE II

Results of Expert Evaluation and Calculation Results in Example 5

Criteria	**Number of points**	**Total number of points**	**Criteria weights, w_j**
1	2	3	4
c_1	50	50	0.125
c_2	100	150	0.375
c_3	150	200	0.500

The advantage of the SMART technique is that it does not require to perform all procedures of initial evaluations if a certain criterion/criteria is added to the initial ranked sequence of criteria or if a certain criterion/criteria is removed from that sequence. This statement does not apply to cases when the added criterion is the least important criterion or the least important criterion is removed from the sequence.

The disadvantage of the method is the dependence of the calculated values of weights on the number of points assigned to the least important criterion.

F. Swing Weighting Technique (SWING)

The SWING technique was proposed in [8]; it includes the following sequence of procedures:

1. Subjective ordinal ranking of criteria with respect to importance.
2. Assigning some fixed number of points to the most important criterion.
3. Assignment of numbers of points for each of the following criteria, representing the degree of importance of that criterion with regard to the reference (most important) criterion.
4. Calculation of criteria weight values as the ratio of the numbers of points assigned to the relevant criteria to the total number of points.

Example 6. Let us take the results of ranking criteria by importance $c_3 \succ c_2 \succ c_1$ from Example 1 as a basis. Let us assume that as a result of expert evaluation, these numbers of points are assigned for those criteria: c_3 – 100, c_2 – 70, c_1 – 40.

The total number of points is equal to 210. Let us calculate the weights of these criteria.

$$w_3 = \frac{100}{210} = 0.476;\ w_2 = \frac{70}{210} = 0.333;\ w_1 = \frac{40}{210} = 0.190.$$

The advantage of the SWING technique is that it does not require re-assignment of points to criteria if a criterion (criteria) is removed from their initial sequence or some new criterion (criteria) is added to the existing sequence. This statement does not apply to the removal of the most important criterion or the addition of a new criterion that claims to be the most important criterion.

The disadvantage of the SWING technique is that it provides a rather limited range within which the numbers of points assigned to the criteria can be located.

More information about SMART and SWING techniques, as well as other similar methods can be found in [9], [10].

G. Step-Wise Weight Assessment Ratio Analysis (SWARA)

The SWARA technique was first proposed in [11]. As noted in [12], the method is known as an expert-focused approach in which all criteria are first ranked in an ordinal manner according to the level of their importance. If the ranking is performed by a group of experts, the average ranks for each criterion across the entire set of experts are used. Then the following procedures are performed on the ranked sequence of criteria.

1. The most important criterion is assigned a degree of importance equal to 1.
2. Starting from the second most important criterion, the degree of importance of the current j-th criterion, s_j, is assigned relative to the previous criterion j–1.
3. The values of the coefficients k_j are calculated according to (4):

$$k_j = \begin{cases} 1, j = 1 \\ s_{j+1}, j > 1 \end{cases}. \tag{4}$$

4. The intermediate values are calculated by (5):

$$q_j = \begin{cases} 1, j = 1 \\ \dfrac{q_{j-1}}{k_j}, j > 1 \end{cases}. \tag{5}$$

5. The values of criteria are calculated by (6):

$$w_j = \frac{q_j}{\sum_{j=1}^{n} q_j}. \tag{6}$$

Example 7. Let us take as a basis the sequence of criteria $c_3 \succ c_2 \succ c_1$ that are ranked by importance from Example 1. Let us apply the above procedures of assignments and calculations to that sequence. The results are summarised in Table III.

Column 2 of Table III presents scores s_j of relative importance of criterion c_j with regard to criterion c_{j-1}. The example under consideration presents the values of s_j averaged over the entire set of experts. The procedures for calculating these values are similar to the procedures of calculating the average rank values in Table I.

TABLE III
RESULTS OF APPLYING A SEQUENCE OF PROCEDURES TO DETERMINE CRITERIA WEIGHTS BASED ON THE SWARA TECHNIQUE

	Assessment of comparative importance, s_j	**Coefficient, $k_j = s_{j+1}$**	**Intermediate value, $q_j = \frac{q_{j-1}}{k_j}$**	**Weight, $w_j = \frac{q_j}{\sum_{j=1}^{3} q_j}$**
1	2	3	4	5
c_3, (j = 1)		1	1	0.468
c_2, (j = 2)	0.530	1.530	0.653	0.306
c_1, (j = 3)	0.350	1.350	0.484	0.226

The advantage of the SWARA technique is that it is simple and easy to implement. The technique requires only a small number of pairwise comparisons; its application does not require any measurement scales; so it is easier for experts to express their subjective judgements.

Another advantage of this technique is that in the process of subjective evaluation of the relative importance of criteria, experts can express their preferences regarding the strategy for further development of organisation, enterprise or industry [13]. The disadvantage of the SWARA technique is that it is conceptually impossible to verify the consistency of individual experts' assessments.

In [14], authors propose these two modifications of the SWARA technique: (1) for each of the criteria its average rank of relative importance is calculated as the geometric mean of individual experts' assessments; (2) the value of relative importance, s_j is determined as the difference $s_j = \overline{p}_{j-1} - \overline{p}_j$, where $\overline{p}_{j-1}$ and $\overline{p}_j$ – are average ordinal estimates of importance of criteria c_{j-1} and c_j, respectively.

The SWARA technique has found rather widespread use in MCDM. Among others, papers [12]–[16] should be mentioned.

H. Analytic Hierarchy Process (AHP)

The AHP technique was proposed in [17]. The primary goal of that technique was subjective pairwise comparison of alternative decisions (alternatives) by preference. By aggregating the results obtained, one can get a list of alternatives ranked with respect to the degrees of their preference.

By interpreting criteria as alternative decisions, the AHP technique can be used to make pairwise comparison of criteria by their importance and to determine the values of criteria weights on that basis.

The experts have to represent the results of their subjective assessment of the relative importance of criterion c_i compared to criterion c_j on the Saaty scale. On this scale, the following verbal expressions of those degrees of importance correspond to numerical grades of importance:

1 – Equal importance;
2 – Low importance;
3 – Medium importance;
4 – Above average importance;
5 – Moderately strong importance;
6 – Strong importance;
7 – Very strong importance;
8 – Very very strong importance;
9 – Absolute importance.

Let us present procedures of criteria weight determination based on the APA technique, using an illustrative example. The experts are requested to pairwise compare three criteria c_1, c_2 and c_3 by importance expressing their assessments on the Saaty scale.

1. The results of experts' assessments are shown in Table IV. In literature, Table IV is commonly called *a pairwise comparison matrix*. The number in cell a_{ij} at the intersection of the i-th row and the j-th column of Table IV represents the degree of importance of criterion c_i relative to criterion c_j, expressed on the Saaty scale.

TABLE IV

RESULTS OF PAIRWISE COMPARISON OF CRITERIA BY IMPORTANCE EXPRESSED ON THE SAATY SCALE

	c_1	c_2	c_3
c_1	1	$\frac{1}{3}=0.333$	$\frac{1}{6}=0.167$
c_2	3	1	$\frac{1}{4}=0.250$
c_3	6	4	1
Sums by columns	10.000	5.333	1.417

In the cell at the intersection of the j-th row and the i-th column, a number $\frac{1}{a_{ij}}$ is written that expresses the degree of importance of criterion c_j relative to criterion c_i. In the diagonal cells of Table IV, 1 is recorded because these cells represent the results of comparing each of the criteria with itself. The last row of Table IV shows the sums of values in the columns of that table.

2. Normalisation of initial values. The initial values in the columns of Table IV are divided by the sums of values in the corresponding columns. The results of that procedure are presented in the 2nd, 3rd and 4th columns of Table V.

TABLE V

NORMALISED VALUES OF THE INITIAL NUJMBERS FROM TABLE IV AND RESULTS OF FOLLOW-UP PROCEDURES

	c_1	c_2	c_3	Sums by rows	Sums by rows/3
1	2	3	4	5	6
c_1	0.100	0.062	0.118	0.280	0.093
c_2	0.300	0.188	0.176	0.644	0.221
c_3	0.600	0.750	0.706	2.056	0.685
Sums by columns	1.000	1.000	1.000		1.000

3. Calculation of sums of values in the rows of Table V. The results of calculation are shown in the 5th column of Table V.
4. Calculation of resulting values. The sums of values by rows in the 5th column of Table V have to be divided by the number of pairwise comparisons n ($n = 3$ in this example). The resulting values are shown in the 6th column of Table V.

Vector W of resulting values from the 6th column of Table V is called *the normalised eigenvector* of pairwise comparison matrix. In the example under consideration

$$W = \begin{bmatrix} 0.093 \\ 0.221 \\ 0.685 \end{bmatrix}.$$

Elements of vector W are the saught weights of criteria: $w_1 = 0.092$, $w_2 = 0.221$, $w_3 = 0.685$. Then, the results of pairwise comparisons in Table IV have to be checked for their consistency. To that end, these procedures are performed.

5. Calculation of the *principal eigenvalue* of pairwise comparison matrix λ_{max}. This value is calculated as the sum of products of each element of the matrix eigenvector by the sum of values in the corresponding column of the initial matrix of pairwise ciomparisons (Table IV).

In our example, we have

$$\lambda_{max} = 0.093 \cdot 10 + 0.226 \cdot 5.333 + 0.685 \cdot 1.417 = \\ = 0.930 + 1.178 + 0.971 = 3.079.$$

6. Calculation of *the consistency index* of pairwise comparisons by (7):

$$CI = \frac{\lambda_{max} - n}{n-1}, \tag{7}$$

where n – the number of pairwise comparisons.

In the example under consideration,

$$CI = \frac{3.079-3}{3-1} = \frac{0.079}{2} = 0.039.$$

7. Calculation of *consistency ratio* (CR) by expression (8):

$$CR = \frac{CI}{RI}. \tag{8}$$

The value of the consistency index by itself says nothing about the degree of actual consistency of pairwise comparisons. It is necessary to compare this index with some reference value. The so-called *random consistency index (RI)*, whose value depending on the number of pairwise comparisons was calculated on the basis of a large number of randomly generated matrices of pairwise comparisons, is used as such a value. The values of *RI* are given in Table VI.

TABLE VI

VALUES OF RANDOM CONSISTENCY INDEX (*RI*) FOR DIFFERENT NUMBERS OF PAIRWISE COMPARISONS

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

The value of CR is a finite measure of the consistency of pairwise comparisons. At a value $CR \leq 10$ % the results of pairwise comparisons are considered to be acceptably consistent. At values $CR > 10$ % the experts making pairwise comparisons may be asked to refine all or some results of their pairwise comparisons.

In the above example,

$$CR = \frac{0.039}{0.58} = 0.069 = 6.9\ \%.$$

Since the value $CR < 10$ %, the results of pairwise comparisons can be considered to be acceptably consistent. If pairwise comparison of criteria by importance is made by a group of experts, the task is to aggregate the results of their comparison. Some approaches to solving the task are discussed in [18], [19]. It seems preferable to perform a group pairwise comparison based on the consensus of all experts. If it is impossible to reach a consensus, then the values of criteria weights can be obtained through performing all the above procedures for each of the experts. The resulting criteria weights can be obtained by averaging the resulting estimates of individual experts.

It should be admitted that the AHP-based approach to criteria weight determination has found widespread use in multicriteria decision-making tasks.

IV. Conclusion

In the literature related to MCDM, very little attention has been paid to the problems of criteria weight determination. As a rule, in publications on specific approaches to multicriteria decision choice the values of criteria weights are set arbitrarily. Most attention has been paid to the methods and their practical applications. The paper has presented basic practical approaches to determine decision weights. These techniques can be divided into two large groups.

1. Criteria weight determination based only on an ordinal sequence of criteria ranked by importance. These techniques are simple and easy to execute in practice. However, the results obtained are rather crude, and their reliability does not appear to be high.
2. Determination of criteria weights based on the assessment of their relative importance. These techniques require a lot of effort but produce more reliable results.

Finally, it should be noted that all the techniques described in the paper can also be applied in risk analysis tasks to assess the importance of outcomes of unfavourable events (hazards).

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