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Multiplicative method of multi-criteria analysis based on expected criteria values

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ABSTRACT

When making a choice, there is a tendency to make the decision-making process as efficient as possible. The choice of method depends on the type of problem to be solved, but it also depends on the knowledge and experience of the decision maker in the field of multi-criteria analysis. The aim of this paper is to show how an additive multi-criteria decision-making model can be naturally converted into a multiplicative one. In this way, it is possible for the decision-maker to choose between additive and multiplicative approaches as suits him better. The paper introduces methodology and provides an algorithm for construction of multiplicative MCDM model based on aggregation function introduced by Žižović et al. (2016). The concept of ratio of the expected alternative value with respect to the ideal value and to anti-ideal value, for all criteria, are introduced and based on these relations, weighted coefficients for multiplicative method are given. Also, we provide a normalization method for multiplicative MCDM method based on values from decision matrix.

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1. Introduction

The problem of multi-criteria decision-making (MCDM) is based on the task of comparing a number of alternatives that need to be evaluated according to a large number of different criteria (most often of different relative importance for decision-making) with the aim of obtaining the best alternative choice. Some decisions may be relatively simple and resolved intuitively, while others can be very significant and involve complex mathematical models to determine the most suitable choice. Over the past decades, many studies have shown guidelines for the MCDM process and how to choose an appropriate MCDM method (Greco et. al. (2018), (Hwang & Yoon, 1981)). Nowadays, MCDM has been used in a wide variety of fields such as energy management, environmental planning, public services, healthcare, transportation, logistics, marketing, human resources management, finance, etc. (for example, see Mardani et al. (2015), Zardari et al. (2015), Zavadskas et al. (2016), Žižović et al. (2015)).

In structuring a decision-making problem, the first step is to identify the decision-maker's preferences and to build a model that is consistent with those preferences. Although multi-criteria decision problems could be very different in context, they share some common features. When working with multiple criteria, the difficulty arises because of many different criteria domains. Some criteria take qualitative values (described subjectively) while others take quantitative ones (measured numerically). Naturally, every criterion of qualitative type should be converted into a criterion of quantitative type, but even then a problem can arise because criteria can be assigned with different units. In order to have a valid comparison, all criteria units should be transferred into the basic unit interval [0, 1], i.e. they should be normalized. During normalization process it can happen that a criterion of the profit criteria category (that is to be maximized) is converted into a criterion of the cost criteria category (that is to be minimized) or vice versa. A detailed overview of various types of normalization can be found in Mukhametzyanov (2023) and Jahan and Edwards (2015).

An important part of any method for multi-criteria analysis is determination of weighted coefficients of the criteria in the model (Saaty, 1980; Keeney & Raiffa, 1976; Kiptum et al., 2023). Many weighting techniques are proposed in literature, and they can be divided into two groups: objective methods where weighted coefficients are calculated according to a pair-wise comparison of the alternatives in the model (Milićević & Župac, 2012; Žižović et al., 2020; Younis Al-Zibaree & Konur, 2023) and subjective methods where weighted coefficients are calculated based on data defined by the decision maker (Milićević & Župac, 2012a; Pamučar et al., 2018; Žižović et al., 2019, 2020a; Jafarzadeh Ghoushchi & Sarvi, 2023; Nezhad et al., 2023).

Each MCDM method uses appropriate mathematical calculus to determine the value of alternative choices. Clearly, such calculation is based on values of the alternatives according to the given criteria and includes weighted coefficients as degrees of importance of those criteria for the decision-making process, so the final ranking of the alternatives is obtained. Aggregation operators have been extensively adopted to handle MCDM problems for incorporating different values in one single function (Dubois et al., 2003; Grabisch et al., 2011; Vahidinia & Hasani, 2023).
For more on MCDM methods, we refer to Figueira et al. (2005) and for insight into the origins of decision-making, we refer to Köksalan et al. (2011).

In this paper, we will introduce an algorithm for converting additive MCDM method into multiplicative one. In Section 2, we will describe general approach to multi-criteria decision problem with an insight into aggregation theory and most commonly used aggregation functions. Also, here we recall on multiplicative aggregation function introduced by Žižović et al. (2016). In Section 3, an algorithm for converting additive data base into normalized decision matrix is given. This algorithm also provides weighted coefficients for multiplicative method which can be calculated starting from weighted coefficients in additive model. To illustrate the process, an adequate example will be provided.

2. Method description

Our focus will be on the typical multi-criteria decision problem. Let $A_1, A_2, \ldots, A_m$ be m alternatives to be assessed based on n criteria $C_1, C_2, \ldots, C_n$. A decision matrix is a $m \times n$ -matrix with each element a_{ij} being the j -th criterion performance value of the i -th alternative, i.e. a_{ij} is the degree in which alternative A_i satisfies criterion C_j.

Table 1. Decision matrix.

	C_1	C_2	$\ldots$	C_n
A_i	a_{11}	a_{12}	$\cdots$	a_{1n}
A_2	a_{21}	a_{22}	$\cdots$	a_{2n}
$\vdots$	$\vdots$	$\vdots$	$\ldots$	$\vdots$
A_m	a_{m1}	a_{m2}	$\cdots$	a_{mn}

Let $w_1, w_2, \ldots, w_n$ denote the weights assigned to criteria $C_1, C_2, \ldots, C_n$. The natural assumption is that the weights are normalized, i.e., they sum add up to 1:

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

The overall value of alternative A_i is given by function $V(A_i)$ which is the result of the aggregation of the value functions $V_j(a_{ij})$ assigned to each criterion C_j. This can be expressed as

$$V(A_i) = A_g\left(V_1(a_{i1}), V_2(a_{i2}), \ldots, V_n(a_{in}) \right), \tag{2}$$

where A_g is feasible aggregation operator. The most commonly used aggregation function is the weighted sum

$$V(A_i)=\sum_{j=1}^{n} w_j \cdot V_j(a_{ij}), \tag{3}$$

which is attractive due to its low complexity, but other aggregation functions can also be applied such as weighted product

$$V_{\Pi}(A_i)=\prod_{j=1}^{n} w_j V_j(a_{ij}), \tag{4}$$

or product of exponents

$$V_E(A_i)=\prod_{j=1}^{n}\left(V_j\left(a_{ij}\right)\right)^{w_j} . \tag{5}$$

Finally, a rank of alternatives is defined in the following way. We say that alternative A_{i_1} is preferred over alternative A_{i_2} if and only if $A_{i_1} > A_{i_2}$.

Some applications of aggregation functions (3)-(5) can be seen in Yazdani et al. (2019), (Brauers & Zavadskas, 2010), Zavadskas et al. (2012) and Stanujkić et al. (2013). For more details on aggregation functions and their properties we refer to Grabisch et al. (2011).

In this article, we will use aggregation function of multiplicative multi-criteria decision introduced in Žižović et al. (2016). This function is dependent on some additional piece of information on the preference relation of the decision-maker, and it is usually given by specifying a reference point, co called hypothetical alternative $A(a_1,a_2,\dots,a_n)$, where $a_1,a_2,\dots,a_n$ are degrees in which hypothetical alternative A satisfies criteria $C_1,C_2,\dots,C_n$, respectively. So, for alternative A_i we have

$$v_n(A_i)=\left(1+\frac{a_{i1}-a_1}{a_1}\cdot w_1\right)\cdot\left(1+\frac{a_{i2}-a_2}{a_2}\cdot w_2\right)\cdots\left(1+\frac{a_{in}-a_n}{a_n}\cdot w_n\right). \tag{6}$$

Let us note that multiplicative multi-criteria decision model introduced in Žižović et al. (2016) is released from the condition (1).

3. Definition of the problem and its solution

In this section, we will provide a methodology and an algorithm for converting given additive MCDM model into corresponding multiplicative MCDM model. For that purpose, we will suppose that we have n criteria $C_1,C_2,\dots,C_n$ which are sorted by importance and which are associated with additive and normalized weights $k_1 \ge k_2 \ge \cdots \ge k_n$, $\sum_{j=1}^{n} k_j = 1$. Let there are m alternatives $A_1,A_2,\dots,A_m$ represented by the matrix given by Table 2.

Table 2. Evaluation of alternatives by criteria in additive MCDM model.

A	C_1	C_2	$\dots$	C_n
A_1	X_{11}	X_{12}	$\cdots$	X_{1n}
A_2	X_{21}	X_{22}	$\cdots$	X_{2n}
$\vdots$	$\vdots$	$\vdots$	$\dots$	$\vdots$
A_m	X_{m1}	X_{m2}	$\cdots$	X_{mn}

In order to construct a multiplicative aggregation function using this database, it is necessary to introduce new weighting coefficients that would describe the importance of the criteria in the multiplicative model and to normalize that model. The process is described in the following steps.

Step 1. For each criterion $C_i \ \ (i = 1, 2, \dots, n)$, we choose three points from interval of criteria:

X_{I_i} - the ideal value of interval of criteria C_i (any value better than this one would be treated equally);

X_{N_i} - normal value of interval of criteria C_i;

X_{A_i} - the anti-ideal value of interval of criteria C_i, i.e. barely acceptable value (alternatives which have performance values less than this are rejected).

For decision-maker, these three points are connected in the sense that X_{I_i} is better than X_{N_i} in the same proportion as X_{A_i} is weaker than X_{N_i}.

Step 2. Decision-maker defines number θ_1 such that $\theta_1 > 1$ represents how many times X_{I_i} is better than X_{N_i}.

Step 3. We calculate parameter λ (parameter of connection between additive and multiplicative coefficients) by formula

$$1 + \lambda k_1 = \theta_1 \ , \tag{7}$$

i.e. λ is given by

$$\lambda = \frac{\theta_1 - 1}{k_1}. \tag{8}$$

Step 4. For $i = 2, 3, \dots, n$, we calculate how many times X_{I_i} is better than X_{N_i} using obtained parameter λ in the following way:

$$1 + \lambda k_i = \theta_i, \qquad (i = 2, 3, ..., n), \tag{9}$$

Symmetric values η_i of θ_i are determined to represent how many times X_{A_i} is weaker than X_{N_i}:

$$\eta_i = \frac{1}{\theta_i}, \qquad (i = 1, 2, \dots, n). \tag{10}$$

Clearly, since $k_1 \ge k_2 \ge \dots \ge k_n$ and $\theta_1 > 1$, we have

$$\theta_1 \ge \theta_2 \ge \dots \ge \theta_n > 1 > \eta_n \ge \dots \ge \eta_2 \ge \eta_1 > 0. \tag{11}$$

Step 5. Multiplicative weighted coefficients are obtained by formula

$$\rho_i = 1 - \eta_i \qquad (i = 1, 2, \dots, n). \tag{12}$$

Clearly, for each $i = 1, 2, \dots, n$ holds $0 < \rho_i < 1$ and

$$1 > \rho_1 \ge \rho_2 \ge \dots \ge \rho_n > 0. \tag{13}$$

Step 6. Calculation of normalized normal values for each criterion C_i, $i = 1, 2, \dots, n$:

$$a_i = \frac{1 - \eta_i}{\theta_i - \eta_i} \qquad (i = 1, 2, \dots, n). \tag{14}$$

Clearly, for each $i = 1, 2, \dots, n$ holds $0 < a_i < 1$, and moreover

$$0 < a_1 \le a_2 \le \dots \le a_n < 1. \tag{15}$$

Step 7. [Normalization of decision matrix] For each $i=1,2,\dots,n$, the part of the criteria interval $\left[X_{A_i}, X_{N_i}\right]$ is mapped on the interval $\left[0,a_i\right]$ using function $f_{1i}:\left[X_{A_i}, X_{N_i}\right]\to\left[0,a_i\right]$, and the part of the criteria interval $\left[X_{N_i}, X_{I_i}\right]$ is mapped on the interval $\left[a_i,1\right]$ using function $f_{2i}:\left[X_{N_i}, X_{I_i}\right]\to\left[a_i,1\right]$. In this way, initial decision matrix is transformed to new matrix.

Table 3. Normalized decision matrix for multiplicative MCDM model.

A'	C_1	C_2	$\cdots$	C_n
A_1	a_{11}	a_{12}	$\cdots$	
A_2	a_{21}	a_{22}	$\cdots$	a_{2n}
$\vdots$	$\vdots$	$\vdots$	$\cdots$	$\vdots$
A_m	a_{m1}	a_{m2}	$\cdots$	a_{mn}

In this matrix, all performance values a_{ij} satisfy condition $0\le a_{ij}\le 1$ and all criteria are transformed to maximization type.

Step 8. In this step we will apply multiplicative method proposed in Žižović et al. (2016), so the alternatives are evaluated by the formula

$$v_n(A_j)=\prod_{i=1}^{n}\left(1+\frac{a_{ji}-a_i}{a_i}\cdot\rho_i\right). \tag{16}$$

Remark 1: If for some $i=1,2,\dots,n$, criterion C_i is of the minimization type, then functions f_{1i} and are monotonically decreasing, and if criterion C_i is maximization type criterion, then functions f_{1i} and f_{2i} are monotonically increasing.

Remark 2: By the construction of the model we obtain that the ideal value of the alternative according to the given criterion C_i $(i=1,\dots,n)$ is exactly θ_i times better than the normally expected value, that is, that the anti-ideal value of the alternative is exactly η_i times weaker than the normally expected value. Due to this condition, it must be $\eta_i=1/\theta_i$. Hence, it is natural to require that the value of an alternative with a normal expected value be one.

4. Example

Let us consider example from the monograph (Nikolić & Borović, 1996, pp. 4-214) given by following table.

Table 4. Decision matrix of example.

	C_1	C_2	C_3	C_4	C_5	C_6
A_1	4	45	50	90	40	30
A_2	3	30	50	70	40	50
A_3	2	20	30	10	20	60
Relative importance	4	3	2	5	1	7
Type of criterion	min	min	max	max	max	max

For relative importance of criteria given in Table 4, we obtain additive normalized weighted coefficients by Table 5.

Table 5. Additive weighted coefficients.

k_1	k_2	k_3	k_4	k_5	k_6
$\frac{4}{22}$	$\frac{3}{22}$	$\frac{2}{22}$	$\frac{5}{22}$	$\frac{1}{22}$	$\frac{7}{22}$

Clearly, criterion C_6 is the most important criterion, so we have:

$$X_{I_6} = 60, \quad X_{N_6} = 40, \quad X_{A_6} = 20 \qquad \text{and} \qquad \theta_6 = 3,$$

and from (9) and (10) we have that

$$k_6 = 0{,}3182, \quad \lambda = \frac{\theta_6 - 1}{k_6} = 6{,}2854 \qquad \text{and} \qquad \eta_6 = \frac{1}{\theta_6} = 0{,}3333.$$

In a similar way, we obtain the specified values for the remaining criteria, presented in the following table.

Table 6. Criteria values obtained based on the presented algorithm.

C_i	C_1	C_2	C_3	C_4	C_5
k_i	0,1818	0,1364	0,0909	0,2273	0,0454
θ_i	2,143	1,857	1,571	2,429	1,285
η_i	0,467	0,539	0,637	0,412	0,778

Further, from (12), we have

$$\rho_6 = 0{,}667;\ \rho_4 = 0{,}588;\ \rho_1 = 0{,}533;\ \rho_2 = 0{,}461;\ \rho_3 = 0{,}364;\ \rho_5 = 0{,}222,$$

and from (14), we have

$$a_6 = 0{,}25;\ a_4 = 0{,}292;\ a_1 = 0{,}318;\ a_2 = 0{,}35;\ a_3 = 0{,}389;\ a_5 = 0{,}438.$$

Now can we define ideal, normal and anti-ideal values for the rest of the criteria:

Table 7. Ideal, normal and anti-ideal values for the criteria $C_i \quad (i = 1, 2, \dots, 5)$.

C_i	C_1	C_2	C_3	C_4	C_5
X_{Ii}	2	20	50	90	40
X_{Ni}	3	30	30	40	20
X_{Ai}	4	45	10	10	10

The normalization is in accordance with Step 7. of the mentioned algorithm. So, for criterion C_6, we have

$$f_{11} : [20, 40] \to [0; 0{,}25] \qquad \text{and} \qquad f_{21} : [40, 60] \to [0{,}25; 1].$$

From $f_{16} = \frac{0.25}{40 - 20}(x - 20)$ we have $f_{16}(30) = 0{,}125$, and from $f_{26} - 0{,}25 = \frac{0{,}75}{60 - 40}(x - 40)$ we have $f_{26}(60) = 1$.

In a similar way, we repeat the process for other criteria. So, the new decision matrix is presented by Table 8.

Table 8. Normalized matrix of example.

	C_1	C_2	C_3	C_4	C_5	C_6
A_1	0	0	1	1	1	0,125
A_2	0,318	0,35	1	0,7168	1	0,375
A_3	1	1	0,389	0	0,438	1

Now, using the multiplicative method we have that $v(A_1) = 0,82$, $v(A_2) = 5,00$ and $v(A_3) = 4,92$. So, the rang of alternatives is

$$A_2 \to A_3 \to A_1,$$

and the obtained result is compatible with (Nikolić & Borović, 1996).

5. Conclusion

In this paper, a specific procedure for calculating weighted coefficients for the method of multi-criteria analysis of the multiplicative type is given based on aggregation function proposed by Žižović et al. (2016). Given algorithm have several important features that distinguish it from the already known methods (AHP method, for example). Optimal values of weighted coefficients are obtained in a simpler and more effective way compared to other methods. The algorithm does not become more complex with the increase of the number of criteria, so it is easy for understanding and it can effectively be handled by a decision maker. It can be noticed that many multi-criteria decision methods which are based on an additive aggregation function allow some kind of compensation between criteria. The low performance of an important criterion can be redeemed in the overall aggregation by the good performance of a few other less important criteria. The main advantage of multiplicative method is that it recognizes when an absolutely important criterion is not fulfilled. Namely, if an alternative does not satisfy an absolutely important criterion, then its overall aggregation value is zero. Also, advantage of multiplicative method is that it does not allow manipulating alternative ranking, i.e. no alternative can be favored by the addition of new alternatives. In our further research, we will study parameters and properties of multiplicative and similar aggregation functions such as product of exponents, and corresponding weighting techniques and normalization process.

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