Aggregation operators on intuitionistic trapezoidal fuzzy number and its application to multi-criteria decision making problems

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(Received September 14, 2007)

Abstract: Intuitionistic trapezoidal fuzzy numbers and their operational laws are defined. Based on these operational laws, some aggregation operators, including intuitionistic trapezoidal fuzzy weighted arithmetic averaging operator and weighted geometric averaging operator are proposed. Expected values, score function, and accuracy function of intuitionistic trapezoidal fuzzy numbers are defined. Based on these, a kind of intuitionistic trapezoidal fuzzy multi-criteria decision making method is proposed. By using these aggregation operators, criteria values are aggregated and integrated intuitionistic trapezoidal fuzzy numbers of alternatives are attained. By comparing score function and accuracy function values of integrated fuzzy numbers, a ranking of the whole alternative set can be attained. An example is given to show the feasibility and availability of the method.

Keywords: intuitionistic trapezoidal fuzzy numbers, aggregation operators, multi-criteria decision making.

1. Introduction

There are several significant multi-criteria decision-making (MCDM) problems in social economics. At present, the methods of MCDM with certain criteria’s weight coefficients and criteria’s values have been relatively perfect. Ever since the fuzzy set theory was proposed and used to solve MCDM problems by Zadeh, fuzzy multi-criteria decision-making problems have received considerable attention[1−17]. The fuzziness in MCDM has the better character tool because of the proposal of fuzzy number[1]. There are several studies on the methods of multi criteria decision-making problems, in which the criteria’s weight coefficients are certain and the criteria’s values are certain or are fuzzy numbers in Ref. [2−4], and there are also some studies on multi-criteria decision making or multi-criteria group decision making in Ref. [5−6], in which the weight coefficients are incomplete and the criteria’s values are fuzzy numbers. The criteria’s fuzzy numbers and the criteria’s weight coefficients are aggregated to be fuzzy numbers using an aggregated function in those studies, and then the ranking or classification of alternatives can be attained by comparing with the fuzzy numbers. However, fuzzy numbers are used to character the fuzziness just by membership degree. Different from fuzzy set, there is another parameter: nonmembership degree in intuitionistic fuzzy set, which is used to describe and character the fuzzy essence of the objective world more exquisitely[7]; thus, there are some studies on it, however, the studies are focused on their characters, operations, relations, and so on [8−10], and there are few studies on multi-criteria intuitionistic fuzzy decision making. Multi-criteria decision making problems, in which the criteria’s weight coefficients and the criteria’s values are both intuitionistic fuzzy sets are studied in Ref. [11], and the corresponding methods to solve the problems are proposed. For multi-criteria decision making problems, in which the information on criteria’s weight coefficients is incomplete and the criteria’s values are intuitionistic fuzzy sets, the TOPSIS method and the VIKOR method are proposed in Ref. [12]. An evidential reasoning method for MCDM based on intuitionistic fuzzy sets is proposed in Ref. [13]. Interval intuitionistic fuzzy set is the extension

* This project was supported by the National Natural Science Foundation of China (70771115).
of intuitionistic fuzzy set, the membership degree and the nonmembership degree in interval intuitionistic fuzzy set are extended to interval values from real numbers, the multi-criteria decision making problems based on interval intuitionistic fuzzy set are studied in Ref. [14–15], and compounding decision methods are proposed. However, intuitionistic fuzzy sets and interval intuitionistic fuzzy sets are also the same as fuzzy sets, the domains of which are discrete sets, and intuitionistic fuzzy sets are used to indicate the extent to which the criterion does or does not belong to some fuzzy concepts. The intuitionistic triangular fuzzy numbers and their operations are defined in Ref. [14], which are also used in fault tree analysis. Intuitionistic trapezoidal fuzzy numbers are the extending of intuitionistic fuzzy sets in another way, which extends discrete set to continuous set, and they are the extending of fuzzy numbers. At present, there are few studies on intuitionistic trapezoidal fuzzy numbers, the multi-criteria decision making problems are extended to interval values from real numbers, the nonmembership degree in interval intuitionistic fuzzy set, the membership degree and accuracy function of intuitionistic trapezoidal fuzzy numbers. Thus, in this article, some aggregation operators of intuitionistic trapezoidal fuzzy numbers are defined, the expected values, the score function and accuracy function of intuitionistic trapezoidal fuzzy numbers are defined, and a simple ordering method of intuitionistic trapezoidal fuzzy numbers is proposed and used in multi-criteria decision making based on the score function and the accuracy function.

2. Intuitionistic fuzzy numbers and intuitionistic trapezoidal fuzzy numbers

Definition 1 Let \( \tilde{a} \) be an intuitionistic fuzzy number in the set of real numbers, its membership function is defined as

\[
\mu_{\tilde{a}}(x) = \begin{cases} 
 f_{\tilde{a}}^L(x), & a \leq x < b \\
 \mu_{\tilde{a}}, & b \leq x \leq c \\
 f_{\tilde{a}}^R(x), & c < x \leq d \\
 0, & \text{otherwise}
\end{cases}
\]

Its nonmembership function is defined as

\[
\nu_{\tilde{a}}(x) = \begin{cases} 
 g_{\tilde{a}}^L(x), & a_1 \leq x < b \\
 \nu_{\tilde{a}}, & b \leq x \leq c \\
 g_{\tilde{a}}^R(x), & c < x \leq d_1 \\
 0, & \text{otherwise}
\end{cases}
\]

where \( f_{\tilde{a}}^L(x), g_{\tilde{a}}^L(x) \) are continuous monotone increasing functions, and \( f_{\tilde{a}}^R(x), g_{\tilde{a}}^R(x) \) are continuous monotone decreasing functions. \( f_{\tilde{a}}^L(x), f_{\tilde{a}}^R(x), g_{\tilde{a}}^L(x), g_{\tilde{a}}^R(x) \) are the left and the right basis functions of the membership function and the nonmembership function, respectively. The intuitionistic fuzzy number is denoted as \( \tilde{a} = ((a, b, c, d); \mu_{\tilde{a}}); ((a_1, b, c, d_1); \nu_{\tilde{a}}) \). Different from fuzzy numbers, intuitionistic fuzzy numbers have another parameter: nonmembership function, which is used to express the extent to which the decision makers think that the element does not belong to \( (a_1, b, c, d_1) \). When \( \mu_{\tilde{a}} = 1, \nu_{\tilde{a}} = 0 \), \( \tilde{a} \) is called normal intuitionistic fuzzy number, namely, traditional fuzzy number. When \( f_{\tilde{a}}^L(x) = \frac{x-a}{b-a} \mu_{\tilde{a}}, f_{\tilde{a}}^R(x) = \frac{d-x}{d-c} \mu_{\tilde{a}}, g_{\tilde{a}}^L(x) = \frac{b-x+\nu_{\tilde{a}}(x-a_1)}{b-a_1}, g_{\tilde{a}}^R(x) = \frac{x-c+\nu_{\tilde{a}}(d_1-x)}{d_1-c} \) \( (0 \leq \mu_{\tilde{a}} \leq 1, 0 \leq \nu_{\tilde{a}} \leq 1, \mu_{\tilde{a}} + \nu_{\tilde{a}} \leq 1, a, b, c, d \in R) \), the intuitionistic fuzzy number is called intuitionistic trapezoidal fuzzy number, denoted as \( \tilde{a} = ((a, b, c, d); \mu_{\tilde{a}}); ((a_1, b, c, d_1); \nu_{\tilde{a}}) \). When \( b = c \), the intuitionistic trapezoidal fuzzy number becomes intuitionistic triangle fuzzy number. Generally, there is \([a, b, c, d] = [a_1, b, c, d_1] \) in intuitionistic trapezoidal fuzzy number \( \tilde{a} \), here, denoted as \( \tilde{a} = ([a, b, c, d]; \mu_{\tilde{a}}, \nu_{\tilde{a}}) \). Without special declaration in this article, intuitionistic trapezoidal fuzzy numbers are all these fuzzy numbers. \( \pi_{\tilde{a}} = 1 - \mu_{\tilde{a}} - \nu_{\tilde{a}} \) denotes the hesitation of fuzzy number, the smaller the \( \pi_{\tilde{a}} \), the more certain is the fuzzy number.

Different from the definitions of intuitionistic fuzzy sets, intuitionistic fuzzy numbers are added to a trapezoidal fuzzy number \([a, b, c, d]\), which makes the membership degrees and the non-membership degrees no longer relative to a fuzzy concept “Excellent” or “Good”, but relative to the trapezoidal fuzzy number; then, the information of decision makers can be reflected exactly and can be expressed in different dimensions. For example, there is an intuitionis-
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tic trapezoidal fuzzy number \( \tilde{b} = ([4, 5, 7, 8]; 0.7, 0.2) \); then, when \( x = 5 \), its membership degree to be fuzzy number \( \tilde{b} \) is 0.7, and simultaneously, its non-membership degree to be fuzzy number \( \tilde{b} \) is 0.2, and its hesitation to be or not to be fuzzy number \( \tilde{b} \) is 0.1.

**Definition 2** Let \( \tilde{a}_1 = ([a_1, b_1, c_1, d_1]; \mu_{\tilde{a}_1}, \nu_{\tilde{a}_1}) \) and \( \tilde{a}_2 = ([a_2, b_2, c_2, d_2]; \mu_{\tilde{a}_2}, \nu_{\tilde{a}_2}) \) be two intuitionistic trapezoidal fuzzy numbers; then,

1. \( \tilde{a}_1 + \tilde{a}_2 = ([a_1 + a_2, b_1 + b_2, c_1 + c_2, d_1 + d_2]; \mu_{\tilde{a}_1} + \mu_{\tilde{a}_2}, \nu_{\tilde{a}_1} + \nu_{\tilde{a}_2}) \);
2. \( \tilde{a}_1 \cdot \tilde{a}_2 = ([\lambda a_1, \lambda b_1, \lambda c_1, \lambda d_1]; 1 - (1 - \mu_{\tilde{a}_1})^\lambda, (1 - \nu_{\tilde{a}_1})^\lambda) (\lambda \geq 0) \);
3. \( \tilde{a}_1^\lambda = ([\lambda a_1, b_1^\lambda, c_1^\lambda, d_1^\lambda]; \mu_{\tilde{a}_1}, 1 - (1 - \nu_{\tilde{a}_1})^\lambda) (\lambda \geq 0) \).

3. Aggregation operators on intuitionistic trapezoidal fuzzy numbers

**Definition 3** Let \( \tilde{a}_j (j = 1, \ldots, n) \) be a set of intuitionistic trapezoidal fuzzy numbers, and \( IT - WAA : \Omega^n \rightarrow \Omega \); if

\[
IT - WAA_\omega(\tilde{a}_1, \tilde{a}_2, \ldots, \tilde{a}_n) = \sum_{j=1}^{n} \omega_j \tilde{a}_j
\]

where \( \Omega \) is the set of all intuitionistic trapezoidal fuzzy numbers, and \( \omega = (\omega_1, \omega_2, \ldots, \omega_n)^T \) is the weight vector of \( \tilde{a}_j (j = 1, \ldots, n) \), \( \omega_j \in [0, 1] \), \( \sum_{j=1}^{n} \omega_j = 1 \), then, IT-WAA is called the weighted arithmetic average operator on intuitionistic trapezoidal fuzzy numbers. Specially, if \( \omega = \left( \frac{1}{n}, \frac{1}{n}, \ldots, \frac{1}{n} \right)^T \), IT-WAA is the arithmetic average operator (IT-WA) on intuitionistic trapezoidal fuzzy numbers.

**Theorem 1** Let \( \tilde{a}_j = ([a_j, b_j, c_j, d_j]; \mu_{\tilde{a}_j}, \nu_{\tilde{a}_j}) (j = 1, \ldots, n) \) be a set of intuitionistic trapezoidal fuzzy numbers; then, the results aggregated from Definition 3 are still intuitionistic trapezoidal fuzzy numbers, and even

\[
IT - WAA_\omega(\tilde{a}_1, \tilde{a}_2, \ldots, \tilde{a}_n) = \left( \sum_{j=1}^{n} \omega_j a_j, \sum_{j=1}^{n} \omega_j b_j, \sum_{j=1}^{n} \omega_j c_j, \sum_{j=1}^{n} \omega_j d_j \right)
\]

where \( \omega = (\omega_1, \omega_2, \ldots, \omega_n)^T \) is the weight vector of \( \tilde{a}_j (j = 1, \ldots, n) \), \( \omega_j \in [0, 1] \), \( \sum_{j=1}^{n} \omega_j = 1 \).

4. Expected values of intuitionistic trapezoidal fuzzy numbers and comparison between them

For intuitionistic trapezoidal fuzzy numbers, \( f_\lambda^L(x) \) is strictly linear increasing function, and \( f_\lambda^R(x) \) is strictly linear decreasing function in Definition 1. Their in-
verse functions are respectively

\[ p^L_\alpha(x) = a + \frac{y}{\mu_a} \times (b - a), \quad y \in (0, \mu_a); \]

\[ p^R_\alpha(x) = d + \frac{y}{\mu_a} \times (c - d), \quad y \in (0, \mu_a); \]

The trust degree of intuitionistic trapezoidal fuzzy number \( \tilde{a} \) is between \([\mu_\tilde{a}, 1 - \nu_\tilde{a}]\).

**Definition 5** \( I_\tilde{a}(\tilde{a}) = \frac{1}{2} \times \left( \int_0^{1-\nu_\tilde{a}} \left\{ (1 - \lambda) \times g^L_\tilde{a}(x) + \lambda \times g^R_\tilde{a}(x) \right\} \right) + \int_0^{\mu_\tilde{a}} \left\{ (1 - \lambda) \times g^L_\tilde{a}(x) + \lambda \times g^R_\tilde{a}(x) \right\} \right) \)

is called the expected value of intuitionistic trapezoidal fuzzy number \( \tilde{a} \).

Where \( \lambda \in [0, 1] \) expresses the decision makers’ risk preference; if \( \lambda > 0.5 \), then, it is the decision makers’ love risk, and if \( \lambda < 0.5 \), then, it is the decision makers’ hate risk, and if \( \lambda = 0.5 \), then, they have indifferent risk reference.

**Theorem 3** For the intuitionistic trapezoidal fuzzy number \( \tilde{a} = ([a, b, c, d]; \mu_\tilde{a}, \nu_\tilde{a}) \), its expected value is \( I(\tilde{a}) = \frac{1}{8} \times [a + b + c + d] \times (1 + \mu_\tilde{a} - \nu_\tilde{a}) \).

The score function and accuracy function of intuitionistic trapezoidal fuzzy numbers are introduced below.

**Definition 6** Let \( \tilde{a} = ([a, b, c, d]; \mu_\tilde{a}, \nu_\tilde{a}) \) be an intuitionistic trapezoidal fuzzy number; then, \( S(\tilde{a}) = I_\tilde{a} \times (\mu_\tilde{a} - \nu_\tilde{a}) \) is called the score function of \( \tilde{a} \), where \( I_\tilde{a} \) is the expected value of intuitionistic trapezoidal fuzzy number \( \tilde{a} \).

**Definition 7** Let \( \tilde{a} = ([a, b, c, d]; \mu_\tilde{a}, \nu_\tilde{a}) \) be an intuitionistic trapezoidal fuzzy number; then, \( H(\tilde{a}) = I_\tilde{a} \times (\mu_\tilde{a} + \nu_\tilde{a}) \) is called the accuracy function of \( \tilde{a} \), where \( I_\tilde{a} \) is the expected value of intuitionistic trapezoidal fuzzy number \( \tilde{a} \).

**Definition 8** If \( \tilde{a}_1 \) and \( \tilde{a}_2 \) are two random intuitionistic trapezoidal fuzzy numbers, then,

1. If \( S(\tilde{a}_1) > S(\tilde{a}_2) \), then, \( \tilde{a}_1 > \tilde{a}_2 \);
2. If \( S(\tilde{a}_1) = S(\tilde{a}_2) \), and
   1. if \( H(\tilde{a}_1) = H(\tilde{a}_2) \), then, \( \tilde{a}_1 = \tilde{a}_2 \);
   2. if \( H(\tilde{a}_1) > H(\tilde{a}_2) \), then, \( \tilde{a}_1 > \tilde{a}_2 \).

5. Multi-criteria decision making method based on intuitionistic trapezoidal fuzzy numbers

For some fuzzy multi-criteria decision making problem, assume that there are \( m \) alternatives \( A = \{a_1, a_2, \ldots, a_n\} \), \( l \) decision criteria \( C = \{c_1, c_2, \ldots, c_l\} \), and the corresponding weight coefficients are \( \omega = \{\omega_1, \omega_2, \ldots, \omega_l\} \), \( \omega_j \in [0, 1] \), \( \omega_1 + \omega_2 + \ldots + \omega_l = 1 \). The value of alternative \( a_i \) on the criteria \( c_j \) is intuitionistic trapezoidal fuzzy number \( \tilde{a}_{ij} = ([m_{ij}(a_i), m_{ij}(a_i), m_{ij}(a_i), m_{ij}(a_i)]; \mu_{ij}(a_i), \nu_{ij}(a_i)) \), where, \( \mu_{ij}(a_i) \) denotes the extent to which alternative \( a_i \) belongs to trapezoidal fuzzy number \([m_{ij}(a_i), m_{ij}(a_i), m_{ij}(a_i), m_{ij}(a_i)]\) on the criteria \( c_j \), \( \nu_{ij}(a_i) \) denotes the extent to which alternative \( a_i \) does not belong to trapezoidal fuzzy number \([m_{ij}(a_i), m_{ij}(a_i), m_{ij}(a_i), m_{ij}(a_i)]\) on the criteria \( c_j \), \( 0 \leq \mu_{ij}(a_i) \leq 1, 0 \leq \nu_{ij}(a_i) \leq 1, \mu_{ij}(a_i) + \nu_{ij}(a_i) \leq 1 \), and the constructed decision matrix denotes \( D = (\tilde{a}_{ij})_{n \times l} \). Assuming decision makers have indifferent risk preference, the ranking of alternatives is required.

The familiar types of criteria are benefit and cost in multi criteria decision making problems. To eliminate the effect from different physical dimensions to decision results, the matrix \( T = (t_{ij})_{m \times n} \), \( t_{ij} = [m_{ij}(a_i), m_{ij}(a_i), m_{ij}(a_i), m_{ij}(a_i)] \) composed by trapezoidal fuzzy numbers of fuzzy decision matrix \( D = (\tilde{a}_{ij})_{n \times l} \) is translated into standardized matrix \( R = (r_{ij})_{n \times l}, r_{ij} = [r^1_{ij}, r^2_{ij}, r^3_{ij}, r^4_{ij}] \) using formulas to standardize the fuzzy decision matrix.

For cost criteria:

\[ r^k_{ij} = \frac{\max_j(m_{ij}(a_i)) - m_{kj}(a_i)}{\max_j(m_{ij}(a_i)) - \min_j(m_{ij}(a_i))}, \quad k = 1, \ldots, 4 \]

For benefit criteria:

\[ r^k_{ij} = \frac{m_{kj}(a_i) - \min_j(m_{ij}(a_i))}{\max_j(m_{ij}(a_i)) - \min_j(m_{ij}(a_i))}, \quad k = 1, \ldots, 4 \]

Decision steps:

1. Standardize decision matrix
2. Using weighted arithmetic average operator

\[ \tilde{a}_i = IT - WAA_\omega(c_1(a_i), c_2(a_i), \ldots, c_l(a_i)), \quad i = 1, 2, \ldots, n \]

or using weighted geometric average operator

\[ \tilde{a}_i = IT - WGA_\omega(c_1(a_i), c_2(a_i), \ldots, c_l(a_i)), \quad i = 1, 2, \ldots, n \]

Aggregate criteria’s weights and values to attain the integrated intuitionistic trapezoidal fuzzy numbers \( \tilde{a}_i \), \( i = 1, 2, \ldots, n \) of alternative \( a_i \).
(3) Calculate the score value and the accuracy value using the score function and the accuracy function, respectively.

(4) Rank the alternatives by Definition 8.

6. Example

There are 5 alternatives $a_1, a_2, \ldots, a_5$ and 5 criteria $c_1, c_2, \ldots, c_5$ in a multi-criteria decision making problem; the weight vector of criteria is $\omega = (0.20, 0.15, 0.25, 0.10, 0.30)$, and the decision information is given as Table 1 by decision makers, trying to get ranking of the 5 alternatives.

Steps using the method in this article are as follows

1. Standardize data in Table 1;
2. Aggregate all the elements $a_{ij}$ ($j = 1, \ldots, 5$) in the ith row of decision matrix $D$ using IT-WAA; then, the integrated intuitionistic trapezoidal fuzzy numbers $\tilde{a}_i$, $i = 1, 2, \ldots, 5$ of alternative $a_i$ are attained.

$$
\tilde{a}_1 = ([0.407, 0.539, 0.683, 0.814]; 0.727, 0.216)
\tilde{a}_2 = ([0.547, 0.679, 0.810, 0.942]; 0.705, 0.230)
\tilde{a}_3 = ([0.424, 0.572, 0.704, 0.868]; 0.697, 0.252)
\tilde{a}_4 = ([0.392, 0.557, 0.724, 0.902]; 0.639, 0.280)
\tilde{a}_5 = ([0.411, 0.555, 0.699, 0.831]; 0.812, 0.137)
$$

3. Calculate the score values $S(\tilde{a}_i)$ of $\tilde{a}_i$:

$$
S(\tilde{a}_1) = 0.236, S(\tilde{a}_2) = 0.261, S(\tilde{a}_3) = 0.206,
S(\tilde{a}_4) = 0.153, S(\tilde{a}_5) = 0.353.
$$

4. Rank alternatives by Definition 2; the result obtained is as follows

$$
a_5 \succ a_2 \succ a_1 \succ a_3 \succ a_4
$$

If all elements $a_{ij}$ ($j = 1, \ldots, 5$) in the ith row of decision matrix $D$ are aggregated using IT-WGA, the integrated intuitionistic trapezoidal fuzzy numbers $\tilde{a}_i$, $i = 1, 2, \ldots, 5$ of alternative $a_i$ are as follows

$$
\tilde{a}_1 = \langle 10^{-5} \times \langle 0.198 4, 0.991 2, 3.645 8, 8.888 9; 0.717, 0.245 \rangle,
\tilde{a}_2 = \langle 10^{-5} \times \langle 0.714 3, 2.430 6, 6.349 2, 14.062 5; 0.684, 0.248 \rangle,
\tilde{a}_3 = \langle 10^{-5} \times \langle 0.198 4, 1.190 5, 3.645 8, 11.111 1; 0.673, 0.276 \rangle,
\tilde{a}_4 = \langle 10^{-5} \times \langle 0.198 4, 1.071 4, 4.050 9, 13.333 3; 0.626, 0.294 \rangle,
\tilde{a}_5 = \langle 10^{-5} \times \langle 0.238 1, 1.240 1, 4.166 7, 9.722 2; 0.803, 0.146 \rangle.
$$

The score values are: $S(\tilde{a}_1) = 1.192 9 \times 10^{-5}$, $S(\tilde{a}_2) = 1.839 2 \times 10^{-5}$, $S(\tilde{a}_3) = 1.121 7 \times 10^{-5}$, $S(\tilde{a}_4) = 1.032 0 \times 10^{-5}$, $S(\tilde{a}_5) = 2.091 2 \times 10^{-5}$.

The ranking is $a_5 \succ a_2 \succ a_1 \succ a_3 \succ a_4$.

The results attained using the above two methods are consistent. By analyzing the data in Table 1, we know that the results are rational.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Criterion values of alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_1$</td>
<td>$c_1: ([1,2,3,4]; 0.7,0.3)$</td>
</tr>
<tr>
<td>$a_2$</td>
<td>$c_2: ([5,6,7,8]; 0.7,0.3)$</td>
</tr>
<tr>
<td>$a_3$</td>
<td>$c_3: ([3,4,5,6]; 0.7,0.3)$</td>
</tr>
<tr>
<td>$a_4$</td>
<td>$c_4: ([4,5,7,8]; 0.6,0.3)$</td>
</tr>
<tr>
<td>$a_5$</td>
<td>$c_5: ([4,5,7,8]; 0.8,0.0)$</td>
</tr>
</tbody>
</table>

7. Conclusion

Aggregation methods on intuitionistic trapezoidal fuzzy numbers are discussed in this article, based on the definitions of intuitionistic fuzzy numbers and intuitionistic trapezoidal fuzzy numbers. A method to compare intuitionistic trapezoidal fuzzy numbers is given and applied to decision making. An efficient method to solve fuzzy multi-criteria decision making problems based on intuitionistic trapezoidal fuzzy numbers is provided.

References


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