Integrated Fuzzy Analysis and Group Decision Making Method for Collaborative Product Development

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Abstract. Group decision-making is one of the most important issues in product development. In order to tackle the vague and sometimes conflicting decision data, this paper presents a new approach based on fuzzy similarity and fuzzy compromise to deal with the fuzzy nature of group decisions. In the proposed method, a modified fuzzy Analytical Hierarchy Process method is used to get the criterion weights, a novel consensus aggregation algorithm is given to obtain the conflict-free results, and an improved compromise decision means is utilized to calculate the utilities of alternatives. Finally an integrated product development solution evaluation process is illustrated as a numerical example, and the corresponding software package is also developed.

Introduction

How to make the “best” decision when choosing from among a set of alternatives in a design process has been a common problem for research and application in product design. While there is not always sufficient information for design decisions, especially in the product planning and concept stages, the acquired information is often imprecise, incomplete and uncertain. In addition, the criteria for a decision are not always quantifiable or comparable, criteria may directly conflict or interact with one another, and multiple functional groups, each with different perspective and objectives, may all be involved in the design decision. So it is desirable to have an efficient approach capable of properly handling the multidimensional nature of the problem and adequately modeling the subjectiveness and imprecision of decision-making process.

Many methods and tools have been used to aid decision-making in product development. But the traditional techniques [1][2] were likely to use quantitative methods, such as optimal techniques, mathematical programming and utility models etc, which neglect the human behavior and only can be applied to the case if the required data are sufficient. Some researches have been concerned with multi-attribute decision in design under uncertain conditions. Pugh's concept selection methods were extended with fuzzy set theory to measure the quality of a chosen concept[3]. Wang[4] used fuzzy distance measure method for ranking fuzzy number of design concept. Lin [5] applied linguistic approximation and fuzzy arithmetic operations to aid new product go/no-go decisions. A novel method of operating on fuzzy numbers to obtain a fuzzy-weighted average of desirability levels during design evaluation was proposed in [6]. These methods still can’t adequately tackle the uncertainty and vagueness of the proposed decision problem, especially from the view of group consensus. This paper presents a new approach based on fuzzy similarity and compromise decision to deal with the fuzzy nature of group decisions.

The mathematical model and some preliminaries

The design decision problem mentioned in this research can be modeled as a multi-person multi-criteria decision making (MCDM) problem. In traditional MCDM, performance rating and weights are measured in crisp numbers. The application of fuzzy set theory to MCDM provides an
effective means of formulating decision problems in the environment where the information available is subjective and imprecise. Various methods such as Fuzzy TOPSIS [9], Compromise programming [10], Fuzzy preference [11] were proposed. They can be classified into two categories of defuzzification and fuzzy preference relation. But most of the work hasn’t adequately considered the multi DM effects of this problem. Usually, the aggregation is calculated based on simple weighted average means that can’t represent the consensus of DMs well. While on the other hand, other researches tried to draw consensus from opinions of experts [12]. Hsu [13] proposed a method called similarity aggregation method (SAMD) to aggregate individual opinions of experts based on measure near degree. Lee [14] presented a complex optimal aggregation method (OAM). Lo [15] proposed an Entropy method based on OAM. But they all have some limitations. In our view, transferring individual fuzzy opinions into a group consensus and aggregating weighted criterion fuzzy numbers are the two most important issues closely interrelated in group decision making, while most of the researches only consider one aspect of it. So we propose an integrated method for group decision support in product design environment.

The general group decision making problem usually consists of a number of alternatives \( A_i (i = 1, 2, ..., n) \) to be evaluated against a set of criteria \( C_j (j = 1, 2, ..., m) \) by a group of DMs \( D_k (k = 1, 2, ..., s) \). Subjective assessments are often required for determining the performance of each alternative \( A_i (i = 1, 2, ..., n) \) with respect to each criterion \( C_j (j = 1, 2, ..., m) \), denoted as \( \tilde{A}_{ij}^k \), and the relative importance of each criterion, represented as \( w_j \), with respect to the overall objective of the problem. As a result, a decision matrix for the group decision-making problem can be obtained as:

\[
\tilde{D}^k = \begin{bmatrix}
\tilde{A}_{11}^k & \tilde{A}_{12}^k & \ldots & \tilde{A}_{1m}^k \\
\tilde{A}_{21}^k & \tilde{A}_{22}^k & \ldots & \tilde{A}_{2m}^k \\
\vdots & \vdots & \ddots & \vdots \\
\tilde{A}_{nl}^k & \tilde{A}_{n2}^k & \ldots & \tilde{A}_{nm}^k
\end{bmatrix}
\]

To facilitate the making of subjective assessments, predefined linguistic terms can be used. Here, triangle fuzzy numbers are used to approximate these linguistic terms. The proposed method can also be extended to other kinds of L/R fuzzy numbers.

A linguistic term \( \tilde{a} \) is denoted by \((a, b, c)\). Where \( a \leq b \leq c \), a and c stand for the lower and upper values of the support of the linguistic term \( \tilde{a} \), respectively, and b denotes the modal value. The relation of linguistic variables used for alternative performance evaluation and their corresponding fuzzy numbers are shown in table 1.

<table>
<thead>
<tr>
<th>Linguistic Variables</th>
<th>Very Poor (VL)</th>
<th>Poor (L)</th>
<th>Medium Poor (MP)</th>
<th>Faire (F)</th>
<th>Medium Good (MG)</th>
<th>Good (G)</th>
<th>Very Good (VG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuzzy Numbers</td>
<td>(0,0,0.1)</td>
<td>(0, 0.1, 0.3)</td>
<td>(0.1, 0.3, 0.5)</td>
<td>(0.3, 0.5, 0.7)</td>
<td>(0.5, 0.7, 0.9)</td>
<td>(0.7, 0.9, 1.0)</td>
<td>(0.9, 1.0, 1.0)</td>
</tr>
</tbody>
</table>

**Fuzzy Analysis and Group Decision Making Method**

To a given design decision problem, the evaluating criteria hierarchy structure is first built. Then a modified triangular fuzzy AHP method in terms of ratio scale is employed to proceed with relative importance of pair wise comparison among every criterion and calculate the triangular fuzzy weights of the evaluating attributes.

DM \( d_i \) evaluates the significance among criterion with the fuzzy linguistic terms given in table 2. Then the importance evaluation results can be translated into a reciprocal fuzzy matrix as follow:
\[ \tilde{T}^k = \begin{bmatrix} \tilde{t}_{11}^k & \tilde{t}_{12}^k & \ldots & \tilde{t}_{1m}^k \\ \tilde{t}_{21}^k & \tilde{t}_{22}^k & \ldots & \tilde{t}_{2m}^k \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{t}_{m1}^k & \tilde{t}_{m2}^k & \ldots & \tilde{t}_{mm}^k \end{bmatrix} \]

For each value of \( i \) and \( j \), \( \tilde{t}_{ij}^k = (a_{ij}, b_{ij}, c_{ij}) \) is the relative importance of criterion \( i \) to criterion \( j \) represented by a triangular fuzzy number. Because of the reciprocal characteristic of this matrix, the linguistic variables used are different from the aforementioned rating variables in Table 1.

\[ \tilde{t}_{ij}^k = (\tilde{t}_{ij}^k)^{-1} = (c_{ij}^{-1}, b_{ij}^{-1}, a_{ij}^{-1}) \] has the opposite meaning of \( \tilde{t}_{ij}^k \), e.g. Little Unimportant (1/5, 1/3, 1) can be represented as (-LI).

<table>
<thead>
<tr>
<th>Linguistic Variables</th>
<th>Same Important (SI)</th>
<th>Little Important (LI)</th>
<th>Medium Important (MI)</th>
<th>Very Important (VI)</th>
<th>Extreme Important (EI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuzzy Numbers</td>
<td>(1, 1, 1)</td>
<td>(1, 3, 5)</td>
<td>(3, 5, 7)</td>
<td>(5, 7, 9)</td>
<td>(7, 9, 10)</td>
</tr>
</tbody>
</table>

Then the consistency of \( \tilde{T}^k \) can be checked through a defuzzification method. For each \( \tilde{t}_{ij}^k \), we can get \( t_{ij}^k \in \ker(\tilde{t}_{ij}^k) = \{x \mid \tilde{t}_{ij}^k (x) = 1\}, i,j = 1,2,\ldots,m \). Then it can be used as the representative value of \( \tilde{t}_{ij} \) to calculate the consistency of \( T^k \).

The calculation is conducted on the following matrix \( T^k = [t_{ij}^k]_{m \times m} \). We can get \( \lambda_{\max}^k \) through solving the equation \( |\lambda_{\max}^k - T^k| = 0 \). Then if \( C(T^k) = \frac{\lambda_{\max}^k - m}{m - 1} \leq 0.1 \), the \( \tilde{T}^k \) is consistency, or the \( \tilde{T}^k \) must be adjusted for further consistency checking.

Thus, the corresponding weight \( \tilde{t}_{ij}^k \) can be obtained as follow:

Denoted \( a_i = \left[ \prod_{j=1}^{m} a_{ij} \right]^{1/m} \), \( b_i = \left[ \prod_{j=1}^{m} b_{ij} \right]^{1/m} \), \( c_i = \left[ \prod_{j=1}^{m} c_{ij} \right]^{1/m} \)

\[ a = \sum_{i=1}^{m} a_i \), \( b = \sum_{i=1}^{m} b_i \), \( c = \sum_{i=1}^{m} c_i \)

Then the weight factor of criterion \( i \) can be got as \( \tilde{t}_{ij}^i = \left( \frac{a_i}{c_i} \right) \), \( i = 1,2,\ldots,m \).

Design decision-making is always conducted by a group of multidisciplinary stakeholders. Opinions from different DMs should be properly and accurately aggregated into a group consensus to avoid opinion conflict. This problem can be formed as \( \tilde{O} = \{\tilde{\alpha}_1, \tilde{\alpha}_2, \ldots, \tilde{\alpha}_k\} \), \( \tilde{\alpha}_k \) \( k = 1,2,\ldots,s \) is the kth DM’s Opinion represented as a fuzzy triangular number. The key problem is to get the aggregation weight \( g_k \) \( k = 1,2,\ldots,s \), and \( \sum_{k=1}^{s} g_k \otimes \tilde{\alpha}_k \) will be the ultimate aggregation opinion. We present a new

**Fuzzy Consensus Aggregation Algorithm – FCAA below:**

First, the similarity of \( \tilde{\alpha}_i \) and \( \tilde{\alpha}_j \) should be considered, Hsu [18] have proposed a similarity measure function:

\[ S(\tilde{\alpha}_i, \tilde{\alpha}_j) = \frac{1}{2} (\min \mu_{\tilde{\alpha}_i}(x), \mu_{\tilde{\alpha}_j}(x)) dx \], but when the two fuzzy numbers don’t intersect, the value will be 0. And this function is hard to calculate. From the practicability and maneuverability point of view, we give two factors of \( m(\tilde{\alpha}) \) and \( \sigma(\tilde{\alpha}) \) to form an integrated index for the similarity measure.

Definition 1: Let \( \tilde{A} \) be a fuzzy number that is defined in real number field, its membership function
is $\mu_{\tilde{A}}(x)$. Then we define the fuzzy mean value of $\tilde{A}$ as $m(\tilde{A}) = \frac{\int_{S(\tilde{A})} x \mu_{\tilde{A}}(x)dx}{\int_{S(\tilde{A})} \mu_{\tilde{A}}(x)dx}$, and the fuzzy standard deviation of $\tilde{A}$ as $\sigma(\tilde{A}) = \left( \frac{\int_{S(\tilde{A})} x^2 \mu_{\tilde{A}}(x)dx}{\int_{S(\tilde{A})} \mu_{\tilde{A}}(x)dx} - m^2(\tilde{A}) \right)^{1/2}$.

On above of these two factors, a comprehensive index can be obtained as follow:

$$F(\tilde{A}) = \beta m(\tilde{A}) + (1 - \beta)[1 - \sigma(\tilde{A})]$$

In it, $\beta \in [0,1]$ is some chosen believed level among $m$ and $\sigma$.

Then, the disagreement between $\tilde{A}$ and $\tilde{B}$ can be calculated through equation

$$D(\tilde{A}, \tilde{B}) = F(\tilde{A}) - F(\tilde{B}).$$

Further, $d_{\text{max}} = \sup_{\forall \tilde{A}, \tilde{B} \in \text{DomainA}} D(\tilde{A}_i, \tilde{A}_j)$ can be deduced as the measure level of the distance in certain environment.

Thus, the similarity between $\tilde{A}$ and $\tilde{B}$ can be defined as follow:

$$S(\tilde{A}, \tilde{B}) = 1 - \frac{D(\tilde{A}, \tilde{B})}{d_{\text{max}}}.$$  

It can be seen, $0 \leq S(\tilde{A}, \tilde{B}) \leq 1$, $S(\tilde{A}, \tilde{B}) = S(\tilde{B}, \tilde{A})$. The larger the S, the nearer among opinions between $\tilde{A}$ and $\tilde{B}$.

For each DM, the average of agreement with others, i.e. the agreement coefficient, can be represented by:

In practical product design decision-makings, DMs often come from different disciplines. They have different background and experience, and some of them may be more familiar with the decision problem than others, so the degree of importance of DM should also be considered in opinion aggregation. The weight of each DM could be captured through method such as AHP or entropy sum. The normalized weights can be represented as $v = (v_1, v_2, \ldots, v_r)$, so the coefficient $h_k$ can be formed as follow:

$$h_k = \gamma E_k + (1 - \gamma)v_k$$

$\gamma$ is determined according to the characteristic of the problem, i.e. which aspect is important, the opinion agreement aspect or the experience important aspect.

Then $g_k$ can be normalized as $g_k = h_k / \sum_{k=1}^{s} h_k$

For the arithmetic operation between fuzzy numbers, the Bonissone[20] approximate operation method is used, especially for multiplication. It can give adequate accuracies.

Definition II: For two triangular fuzzy number $\tilde{M} = (a; \alpha, \beta)$ and $\tilde{N} = (c; \gamma, \delta)$, the multiplication of the two fuzzy numbers can be calculated as:

$$\tilde{M} \otimes \tilde{N} = (ac; a\gamma + c\alpha - \alpha\gamma, a\delta + c\beta - \beta\delta).$$

Then, by integrating above proposed method, a new fuzzy group decision-making algorithm can be represented by the following steps:

1. Get the fuzzy criterion comparative judgment matrix $\tilde{D}^k$. Use fuzzy AHP method to calculate the corresponding weights $\tilde{t}_j^k$ (k=1,2,...s; j=1,2,...m).

2. Get the performance rating matrix for each DM, i.e. $\tilde{A}_{ij}^k$.

3. Use FCAA to make a consensus among different DMs, first on $\tilde{t}_j^k$ to get $\tilde{t}_j^k$, and then on $\tilde{A}_{ij}^k$ to get $\tilde{A}_{ij}^k$. 

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4. Use Bonissone fuzzy operation method to get the weighted matrix $\tilde{A}^0_{ij}$.

5. Get the compromise utility of alternative $i$ by the following steps. Because of page limitation, it won’t be illustrated in great detail.

   Calculate the positive fuzzy ideal solution as:
   $$\tilde{M}^+ = (\tilde{M}^+_1, \tilde{M}^+_2, ..., \tilde{M}^+_n), \tilde{M}^+_j = \max \{\tilde{a}_{ij}, \tilde{a}_{2j}, ..., \tilde{a}_{mj}\}.$$

   And the negative fuzzy ideal solution as: $\tilde{M}^- = (\tilde{M}^-_1, \tilde{M}^-_2, ..., \tilde{M}^-_n), \tilde{M}^-_j = \min \{\tilde{a}_{ij}, \tilde{a}_{2j}, ..., \tilde{a}_{mj}\}$

   Calculate the distance between alternative $i$ and positive ideal:
   $$D^+_i = \sqrt{\sum_{j=1}^{m} [(\tilde{M}^+_j - \tilde{\tilde{M}}^+_j)^{\mu} + (\tilde{\tilde{M}}^+_j - \tilde{\tilde{M}}^+_j)^{\mu} j^2}$$

   Here, a distance different from traditional Hamming distance is proposed. Where, $\tilde{M}^+_j = \min_{\mu(z)>\alpha} (z), \tilde{M}^+_j = \max_{\mu(z)>\alpha} (z)$

   Due to page limitation, the detail meaning and proof will not been given in this paper. It can better support the L/R characteristics of fuzzy numbers.

   Also calculate the distance between alternative $i$ and negative ideal:
   $$D^-_i = \sqrt{\sum_{j=1}^{m} [(\tilde{M}^-_j - \tilde{\tilde{M}}^-_j)^{\mu} + (\tilde{\tilde{M}}^-_j - \tilde{\tilde{M}}^-_j)^{\mu} j^2}$$

6. Ranking the alternatives according to $r_i$.

**Numerical Example**

In this section, we give an example for evaluating a machine tool mechanical design solution to illustrate our proposed method. A software package is also developed to support this fuzzy design decision-making environment. For simplicity, we only give the one layer criterion evaluation for example.

Four criteria are used for decision-making, they are $C_1$=Cost, $C_2$=Energy consumption, $C_3$=Ease of Manufacture, $C_4$=Reliability. Three decision makers from Customer, Design, and Manufacture discipline give their ratings respectively. First they give their criterion comparative judgment matrix as below. They are represented by linguistic variables that are then transformed into triangular fuzzy numbers for computing.

$$D^1 = \begin{bmatrix} 1 & MI & LI & SI \\ MI & 1 & -MI & -VI \\ LI & -MI & 1 & -LI \\ SI & -LI & LI & 1 \end{bmatrix}, D^2 = \begin{bmatrix} 1 & VI & SI & LI \\ VI & 1 & -LI & SI \\ SI & LI & 1 & -LI \\ LI & SI & LI & 1 \end{bmatrix}, D^3 = \begin{bmatrix} 1 & LI & -LI & -LI \\ LI & 1 & -MI & -MI \\ -LI & MI & 1 & LI \\ -LI & SI & LI & 1 \end{bmatrix}$$

By using the fuzzy AHP method mentioned above, we can obtain the three fuzzy weight vectors as follows:

$\tilde{\tilde{t}}^1_1 = (0.187, 0.375, 0.673) \quad \tilde{\tilde{t}}^1_2 = (0.031, 0.0524, 0.1067) \quad \tilde{\tilde{t}}^1_3 = (0.0837, 0.1645, 0.4496) \quad \tilde{\tilde{t}}^1_4 = (0.2126, 0.408, 0.7158)

$\tilde{\tilde{t}}^2_1 = (0.2393, 0.4646, 0.8046) \quad \tilde{\tilde{t}}^2_2 = (0.0618, 0.1014, 0.2078) \quad \tilde{\tilde{t}}^2_3 = (0.107, 0.217, 0.4645) \quad \tilde{\tilde{t}}^2_4 = (0.107, 0.217, 0.4645)

$\tilde{\tilde{t}}^3_1 = (0.0549, 0.1465, 0.5163) \quad \tilde{\tilde{t}}^3_2 = (0.031, 0.0655, 0.1994) \quad \tilde{\tilde{t}}^3_3 = (0.1616, 0.4995, 1.2558) \quad \tilde{\tilde{t}}^3_4 = (0.1081, 0.2884, 0.8398)$
The DMs also give their ratings for the three alternatives as follow:

<table>
<thead>
<tr>
<th></th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>DM1</td>
<td>DM2</td>
<td>DM3</td>
<td>DM1</td>
</tr>
<tr>
<td>60</td>
<td>G</td>
<td>VG</td>
<td>F</td>
<td>G</td>
</tr>
<tr>
<td>A2</td>
<td>30</td>
<td>VG</td>
<td>VG</td>
<td>G</td>
</tr>
<tr>
<td>A3</td>
<td>40</td>
<td>MG</td>
<td>G</td>
<td>VG</td>
</tr>
</tbody>
</table>

The ratings of cost criterion are also represented in fuzzy numbers. E.g. for the DM1, the ratings are ((0.5, 0.5, 0.5), (1, 1, 1), (0.75, 0.75, 0.75)).

Calculate the consensus weight $\tilde{t}_j$ (j=1…m), and calculate the consensus performance rating matrix $(\tilde{D})_{mon}$. Here, we don’t take the importance degree of DM into consideration, and we make $\beta=0.5$.

Thus, we can get the weight vector: $\tilde{t}_1=(0.17, 0.454, 0.6618), \tilde{t}_2=(0.041, 0.0728, 0.1712), \tilde{t}_3=(0.1099, 0.2578, 0.6287), \tilde{t}_4=(0.14029, 0.3026, 0.68)\quad(\text{notation})$

Also, we can get the aggregated performance rating matrix as follow:

<table>
<thead>
<tr>
<th></th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>(.574,.574,.574)</td>
<td>(.66,.825,.918)</td>
<td>(.592,.792,.919)</td>
<td>(.763,.931,1)</td>
</tr>
<tr>
<td>A2</td>
<td>(1,1,1)</td>
<td>(.9,.1,.1)</td>
<td>(.7,.9,1)</td>
<td>(.7,.9,1)</td>
</tr>
<tr>
<td>A3</td>
<td>(.795,.795,.795)</td>
<td>(.702,.87,.968)</td>
<td>(.702,.87,.968)</td>
<td>(.837,.969,1)</td>
</tr>
</tbody>
</table>

Though fuzzy multiplication, we can get $\tilde{A}_j^m = \tilde{t}_j \otimes \tilde{A}_j$ as follow:

<table>
<thead>
<tr>
<th></th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>(.1413,.26,.424)</td>
<td>(.0169,.06,.09)</td>
<td>(.067,.204,.335)</td>
<td>(.057,.282,.443)</td>
</tr>
<tr>
<td>A2</td>
<td>(.246,.454,.738)</td>
<td>(.023,.0728,.1046)</td>
<td>(.079,.232,.3761)</td>
<td>(.052,.272,.432)</td>
</tr>
<tr>
<td>A3</td>
<td>(.196,.361,.587)</td>
<td>(.018,.0633,.095)</td>
<td>(.0779,.224,.364)</td>
<td>(.063,.293,.455)</td>
</tr>
</tbody>
</table>

$\tilde{M}^+ =((.246,.454,.738), (0.023, 0.0728, 0.1046), (0.079, 0.232, 0.3761), (0.063, 0.293, 0.455)\quad D_1^+=0.408, D_2^+=0.038, D_3^+=0.194.$

$\tilde{M}^-=((.1413,.26,.424), (0.0169, 0.06, 0.09), (0.067, 0.204, 0.335), (0.052, 0.272, 0.432)\quad D_1^- =0.018, D_2^- =0.408, D_3^- =0.128.$

$r_j=D_j^-/(D_j^-+D_j^+)=0.0423$

$r_j=D_j^-/(D_j^-+D_j^+)=0.915$

$r_j=D_j^-/(D_j^-+D_j^+)=0.398$

Finally, we can get the order as $A2>A3>A1$.

Conclusions

Multi expert and multi criterion decision-making is an important issue for facilitating efficient product design. This paper presents a novel integrated fuzzy analysis and group decision-making approach to solve this problem. It integrates the method such as fuzzy AHP, similarity based consensus aggregation and compromise decision-making. A mechanical design solution evaluation example is also illustrated for verification. It shows that the underlying concept of the approach developed is transparent and comprehensible, sufficiently efficient in solving this kind of problems.

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