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Evaluation method of product configuration design integrated customer requirements and application

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Mass customization is an important production mode for the modern enterprise. Product configuration design is the core of mass customization. In the process of product configuration design, there are maybe many optional configuration schemes, but it needs the reasonable evaluation so as to scientifically and effectively select the optimal result from them. This paper takes the clear customer requirements as a part of the evaluation indexes into the evaluation system, and a novel fuzzy comprehensive evaluation method for configuration scheme integrated customer requirements is proposed by using the fuzzy set theory. This method takes the customer as the evaluation subject, and the customer’s maximum comprehensive satisfaction is the final evaluation target. The explicit customer requirements, the technical characteristics, economic characteristics and social characteristics of the product take as the specific evaluation indexes. The weights of customer requirements are determined with the standard weight matrix method and normalized as corresponding weights of evaluation indexes; in addition, the weights of other evaluation indexes are determined by using analytic hierarchy process (AHP) to construct the judgment matrix for sequencing and optimizing configuration scheme. Finally, a money-binding machine is taken as an example to validate the effectiveness of proposed method.

Key words: Customer requirements, fuzzy comprehensive evaluation, configuration design, money-binding machine.

INTRODUCTION

With the improvement of market competition and the customer individual requirements, more and more enterprises adopt the mass customization mode. Product configuration design is an important method and core to realize mass customization (Alexander et al., 2001; Kassi et al., 2008). Product configuration design must depend on customer requirements and the modular product model. It needs matching or changing the parts and components according to the certain configuration rules to quickly generate the satisfactory design solutions, so as to shorten the design time and cost savings (Burneika, 2008; Zhang et al., 2003; Wang et al., 2005). Because product configuration design has the characteristics of multiple restrictions, multiple solutions and relativity, the optimal configuration result should be selected from many optional design schemes, and the selecting process is based on the evaluation of configuration scheme. The evaluation process of configuration scheme is a complicated decision-making process, and needs to take into account many factors, such as product technical, economic, environmental impact and so on. Many scholars proposed some evaluation methods from

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different points. Fujita (2002) proposed through the whole life cycle of product cost optimization model to get the optimal modularized product configuration scheme. Gonzalez-Zugasti and Otto (2000) put forward the profit maximization and product diversification as the goal to deal with the problem of module configuration in conditions of uncertainty. Jiao and Tseng (1998) developed a fuzzy ranking methodology for conceptual evaluation in configuration design. The problem is defined as: given a set of design alternatives, evaluate and select a design alternative that can satisfy customer needs, meet design requirements and fit the technical capabilities of a company. Lu et al. (2006) proposed the customer-requirements weighted fuzzy integrated evaluation for product configuration, in which, the evaluation function was established with the weight value aggregate of requirement and the evaluation matrix. Wang et al. (2010) and Zhang et al. (2008) put forward the evaluation method for product configuration based on hierarchical grey relation analysis. This method took product performance index as criteria and established judgment matrix according to the analytical hierarchy process (AHP), and then took grey relational analysis for evaluation matrix to calculate the correlation degree of every configuration scheme, so as to obtain the scheduling of them. Wang et al. (2009) proposed evaluation method for product configuration based on the entropy technology and AHP, and the weight of evaluation index is determined by this method so as to select the configuration scheme. Yang (2011) and Yang et al. (2011) use an integration of Delphi and AHP methods to establish the assessment model and the evaluation system for configuration schemes. Meanwhile, a synthesized fuzzy judgment method is used to verify the practical example of highway maintenance machinery configuration. Golbabaie et al. (2012) employed analytical hierarchy process to evaluate each alternative layout with respect to each of the criterion in yard layout configuration. Zhu et al. (2012) use fuzzy analytic hierarchy process to calculate the evaluation index weight of the servo configuration and adopt technique for order preference by similarity to ideal solution (TOPSIS) to select the optimal scheme. Ullah et al. (2013) proposed an evaluation approach of multi-attributes decision making analysis. Based on performance parameters, program related issues and cost attributes, the decision matrixes of the candidate configuration schemes are constructed to obtain the positive ideal solution and the negative ideal solution, and the most promising scheme should have the shortest distance from the positive ideal solution and the longest distance from the negative-ideal solution.

In the above these evaluation methods, evaluation subject is the manufacturer rather than the customer. The evaluation process is mainly aimed at a certain aspect of product design, such as assembling of product, manufacturing, technology, maintainability, cost and so on, but less considers taking customization requirements and their weights directly as a part of the final evaluation criterions and according weights for product comprehensive evaluation. However, customization requirements are not only the starting point but also the end point of the configuration design. The final configuration scheme must meet customer requirements, and the configuration scheme that most satisfies customer requirements is the optimal result. So, this paper fully considers customer requirements and take the customer as evaluation subject in the evaluation process for configuration design. These explicit demands analyzed by the designer will become the part of the important evaluation indexes in configuration design, as well as comprehensively considering the technical characteristics of the product, economic factor and social factor, a novel fuzzy comprehensive evaluation method for configuration design integrated customer requirements is put forward. This method realizes the best matching and maximum satisfaction between the various performance indicators of the product and customer requirements, and explores a comprehensive optimal between product’s quality and customer’s satisfaction.

**Establishing the evaluation index system**

There are many factors to affect the configuration design scheme, and each factor has a number of levels. Many factors have uncertainty and fuzziness (Sun, 2001). So, an evaluation index system, where evaluation indexes are related and restricted each other, must be established in order to reasonably and objectively evaluate the configuration examples and find the optimal configuration result. The evaluation system of configuration scheme is a multiple factors and multi-level structure. Establishing the evaluation index system should consider from two aspects, one is from the technical characteristics, economic characteristics and social characteristics of the product, and the other is from the point of the customer requirements to evaluate the quality of configuration scheme. The original fuzzy customer requirements will become some specific custom demands after analyzing by the designer. These specific custom demands are not only the basis of product configuration design, but also the important evaluation basis for the quality of configuration scheme, so they should be taken as part of the evaluation index in the evaluation index system. But customer requirements are put forward from the point of view of the user, after all, and it is impossible to measure comprehensively the quality of configuration result. As a result, the establishment of evaluation index system and determination of the specific evaluation index still need from the technical characteristics, economic characteristics and social characteristics of the product to comprehensively evaluate configuration scheme. For
example, the structure of evaluation index system with three layers for configuration scheme integrated customer requirements is shown in Figure 1. In Figure 1, \( U \) denotes the total factor set and means customer comprehensive satisfaction, \( U_i \) \( (i=1,2,\ldots,n) \) denotes the first \( i \) factor subset, \( u_{ij} \) \( (i,j=1,2,\ldots,n) \) expresses the first \( j \) influencing factor of the first \( i \) factor subset, \( R_i \) \( (i=1,2,\ldots,m) \) denotes the first \( i \) customer requirement, and \( \omega_i \) expresses the relative weight of \( R_i \).

### Evaluation mathematical model

In the evaluation index system of product configuration scheme, the influence factors of evaluation objects have multi-level, and each factor has the certain fuzziness, especially those factors related to human. In order to solve this kind of evaluation problem with multi-level and fuzzy influencing factors, this paper adopts multilevel fuzzy comprehensive evaluation method. Fuzzy comprehensive evaluation method could quantify fuzzy information by utilizing set and fuzzy mathematics to realize the quantitative evaluation (Huang et al., 2011). According to Figure 1, a secondary fuzzy comprehensive evaluation model is established to evaluate the configuration scheme.

### Evaluation index set

Evaluation index set (that is, factor set) is the content of evaluation index system of configuration scheme. The following gives the mathematical description of the factor set according to Figure 1. Supposing \( U \) is a total factor set, which can be defined as follows:

\[
U = \{U_1, U_2, \ldots, U_n\}
\]  

(1)

In Eqn. (1), \( U_i \) \( (i=1,2,\ldots,n) \) denotes any one of the factors subset corresponding secondary fuzzy comprehensive evaluation (that is, first level evaluation index in Figure 1). Among them,

\[
U_i = \{u_{i1}, u_{i2}, \ldots, u_{im_i}\} \ (i=1,2,\ldots,n)
\]  

(2)

That is, \( U \) contains \( m \) elements, and \( \sum_{i=1}^{n} m_i = K \) (K is the total number of second level evaluation index in Figure 1).

In Equation (2), \( u_{im_i} \) denotes any one of the influencing factors corresponding first level fuzzy comprehensive evaluation (that is, second level evaluation index in Figure 1).

### Evaluation set

In the evaluation model of product configuration scheme, evaluation set is described as follows. Supposing \( V \) is a total evaluation set, which can be defined as follows:

\[
V = \{v_1, v_2, \ldots, v_m\}
\]  

(3)

Among which, \( v_i \) denotes all kinds of possible general evaluation results, such as, better, good, medium, poor, poorer, higher, high, normal, low, lower. Here, taking \( m=5 \) (five rating), namely,

\[
V = \{v_1, v_2, v_3, v_4, v_5\}.
\]
Weight vector

In Figure 1, the specific customer requirements and their weights will be as part of the evaluation index and corresponding weights (after be normalized). The computing process of the weight of customer requirement will be described in next section. In addition, in the evaluation index system of configuration scheme, the weight of influencing factor and the weight of factor subset can be determined by using the analytic hierarchy process (AHP). The value of relative importance between various factors could be determined by comparing them one by one according to the ratio of 1 to 9 scale method.

Determining the weights of customer requirements

There are many methods to determine the weights of customer requirements, for example, Vanegas and Labib (2001) use quality attributes sorting method to determine the priority order of customer requirements. Mazur (1996), Park and Kim (1998) propose using AHP to calculate the relative importance of customer requirement in quality function development (QFD). Du et al. (1999) put forward a customer-oriented tree structural classification approach, and based on this, Chen et al. (2002) propose the growth tree algorithm to sort the importance of customer requirement. Che et al. (1999) use artificial neural network method to assess the importance of customer requirement in QFD. Kamara et al. (1999) propose criteria weighting matrix method to determine the weight of the customer requirement when they use QFD technology to solve the construction problems. This method is similar to the AHP thought, but it is simpler and more visual than AHP. It is more suitable for determining the weights of many requirement elements, so this method is adopted to determine the relative importance and weight of customer requirements in the paper. The calculation procedures are as follows:

(1) Decomposing customer requirements

The original customer requirements are decomposed into requirement elements and are respectively noted as $R_1$, $R_2$, ..., $R_n$. (2) Constructing requirement weighting matrix

Requirement weighting matrix is established by comparing requirement elements one to one. The relative importance of requirement element is marked with 1 to 4 scores, and 1, 2, 3, 4 score respectively means equal importance, weak importance, more importance and distinct importance. Vector of requirement element is marked as $R_{i*} = (R_{i1}, R_{i2}, ..., R_{in})$. Requirement weighting matrix is marked as $R_w$.

$$R_w = R \bullet R^{-1} \quad (4)$$

Because it is a symmetric matrix, $R_w$ could be simplified as upper triangular matrix as follows

$$R_w = \begin{bmatrix} R_{11} & R_{12} & \cdots & R_{1n} \\ R_{21} & R_{22} & \cdots & R_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ R_{n1} & R_{n2} & \cdots & R_{nn} \end{bmatrix}$$

In order to express definitely the relative importance between requirement elements and easy calculation, Equation (6) will be simplified as follows.

1) If two different requirement elements noted respectively as $R_i$ and $R_j$ have the same importance, they will be marked as $R_iR_j$ in Equation (6).
2) The items located diagonal line of Equation (6) could be fully marked as “1”, because they are self-comparison.
3) Except above-mentioned two situations, other items of Eqn. (6) will be marked as $R_{im}k(m=1,2,...,n)$, $(k=1,2,3,4)$, and among which $R_{mn}$ notes more important requirement element by comparing the importance between $R_i$ and $R_j$ and $k$ notes the score of $R_{im}$.

(3) Calculating absolute weight of any requirement element

Absolute weight of any requirement element is noted as $A_{\omega R}$ and calculated as follows

$$A_{\omega R_i} = \text{Row}(\omega R_i) + \text{Column}(\omega R_i) \quad (7)$$

In Equation (7), $\text{Row}(\omega R_i)$ denotes sum of weight of row vector for $R_i$ and $\text{Column}(\omega R_i)$ denotes sum of weight of column vector for $R_i$. But the weight located diagonal line only calculates one time in row vector or column vector for $R_i$. So, absolute weight of any requirement element equals the sum of weight of row vector adding that of column vector.

(4) Calculating relative weight of any requirement element

Relative weight of any requirement element could be calculated as follows:

$$R_{\omega R} = 10 \cdot (A_{\omega R}/A_{\omega R_{\text{max}}}) \quad (8)$$

In Equation (8), $A_{\omega R_{\text{max}}}$ denotes the maximum of absolute
weight of requirement element. For convenience of calculation, the maximum relative weight of requirement element is sets as “10”.

Membership vector set

Membership vector set is also known as fuzzy evaluation matrix. For example, in Figure 1, the first level fuzzy evaluation matrix and the second level fuzzy evaluation matrix are calculated. The membership of factors level of each influencing factor for a configuration example is noted as $r_{ijk}$ ($i$ means belonging to factor subset, $j$ means belonging to influencing factor, $k$ means the corresponding factor grade), that is, $R_j = (r_{i1}, r_{i2}, r_{i3}, r_{i4}, r_{i5})$. The first level fuzzy evaluation matrix can be express as

$$
R_i = \begin{bmatrix}
R_{i1} \\
R_{i2} \\
\vdots \\
R_{ij} \\
\vdots \\
R_{in}
\end{bmatrix}
$$

(9)

The element of the second level fuzzy evaluation matrix (namely corresponding to the factors of second layer in Figure 1) is the synthetic operation result on the weight set of factors located in the second layer with the corresponding first level fuzzy evaluation matrix.

$$
W_i = (\omega_{i1}, \omega_{i2}, \cdots, \omega_{in})
$$

Supposing $W_i$ is weight set of factor “$i$” located in the second layer, where $\omega_{ij}$ is the weight of the influencing factor “$j$” of the factor subset “$i$”, thus, $B_i = W_i \circ R_j$.

Among which, “$\circ$” denotes a certain synthetic operation. So, the second level fuzzy comprehensive evaluation matrix can be defined as

$$
R = \begin{bmatrix}
B_1 \\
B_2 \\
\vdots \\
B_n
\end{bmatrix}
$$

(10)

Multi-grade fuzzy comprehensive evaluation

The configuration examples could be compared and optimized by solving their values. Evaluation process can be described as follow.

1) The first level fuzzy comprehensive evaluation according to each factor grade

The first level fuzzy comprehensive evaluation set $B_i = W_i \circ R_j$, $W_i = (\omega_{i1}, \omega_{i2}, \cdots, \omega_{ij})$ is $\sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \sim \si...
a money-binding machine’s configuration scheme is established as shown in Figure 2, that takes the maximum of customer’s comprehensive satisfaction as the overall evaluation target as well as considers technical characteristics, economic characteristics and social characteristics of product. In Figure 2, the clear corresponding relationship between the specific customer requirements and evaluation indexes is given.

The evaluation of configuration example for a money-binding machine

(1) Configuration example of a money-binding machine
The two configuration examples that meet customer requirements are obtained after configuration solving. The configuration result and the corresponding technical indexes are shown in Table 2.

(2) Determining factor set
The factor, factor subset and factor grade are introduced into the evaluation index system of a money-binding machine (as shown in Figure 2). The evaluation indexes are divided into four factor subsets (namely the first level evaluation index in Figure 2) and 21 influencing factors (namely the second level evaluation index in Figure 2), and each factor is divided into five grades. The factor subset, factor and factor grade of configuration evaluation for a money-binding machine is shown in Table 3.

(3) Determining the membership of each factor grade for configuration scheme
According to the configuration results of example I and example II, the membership of factor grade for every configuration example could be given by the expert scoring and as shown in Table 4.

(4) Determining the weight set

The weight of each factor in each factor subset

It is known from the Figure 2 that part of the influencing factors comes from the specific customer requirements, and their weights can directly use the weights of customer requirements (normalized value). In addition, the weights of other influencing factors can be
Table 1. Requirements and their weights for money-binding machine.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
<th>R6</th>
<th>R7</th>
<th>R8</th>
<th>R9</th>
<th>R10</th>
<th>R11</th>
<th>R12</th>
<th>R13</th>
<th>R14</th>
<th>R15</th>
<th>R16</th>
<th>R17</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binding adjustability</td>
<td>R1</td>
<td>R2</td>
<td>R3-R4</td>
<td>R1-2</td>
<td>R1-2</td>
<td>R1-2</td>
<td>R1-4</td>
<td>R1-3</td>
<td>R1-3</td>
<td>R1-2</td>
<td>R1-4</td>
<td>R1-3</td>
<td>R1-4</td>
<td>R1-3</td>
<td>R1-4</td>
<td>R1-3</td>
<td></td>
</tr>
<tr>
<td>Binding tightly</td>
<td>R2</td>
<td>1</td>
<td>R2-R3</td>
<td>R2-R4</td>
<td>R2-2</td>
<td>R2-2</td>
<td>R2-4</td>
<td>R2-3</td>
<td>R2-3</td>
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<td>R2-4</td>
<td>R2-3</td>
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<td>R2-4</td>
<td>R2-3</td>
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<tr>
<td>High binding efficiency</td>
<td>R3</td>
<td>1</td>
<td>R3-R4</td>
<td>R3-R5</td>
<td>R3-2</td>
<td>R3-2</td>
<td>R3-3</td>
<td>R3-2</td>
<td>R3-2</td>
<td>R3-2</td>
<td>R3-4</td>
<td>R3-3</td>
<td>R3-4</td>
<td>R3-2</td>
<td>R3-3</td>
<td>R3-2</td>
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<tr>
<td>Operational safety</td>
<td>R4</td>
<td>1</td>
<td>R4-R5</td>
<td>R4-R6</td>
<td>R4-2</td>
<td>R4-2</td>
<td>R4-3</td>
<td>R4-2</td>
<td>R4-2</td>
<td>R4-2</td>
<td>R4-4</td>
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<td>R4-4</td>
<td>R4-2</td>
<td>R4-3</td>
<td></td>
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<tr>
<td>Running safety</td>
<td>R5</td>
<td>1</td>
<td>R5-R6</td>
<td>R5-2</td>
<td>R5-3</td>
<td>R5-2</td>
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<td>R5-3</td>
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<tr>
<td>Operation reliability</td>
<td>R6</td>
<td>1</td>
<td>R6-R7</td>
<td>R6-3</td>
<td>R6-2</td>
<td>R6-2</td>
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<tr>
<td>Longer life</td>
<td>R7</td>
<td>1</td>
<td>R7-R9</td>
<td>R7-10</td>
<td>R7-2</td>
<td>R7-2</td>
<td>R7-2</td>
<td>R7-2</td>
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<tr>
<td>Small pollution</td>
<td>R10</td>
<td>1</td>
<td>R10-2</td>
<td>R10-3</td>
<td>R10-3</td>
<td>R10-2</td>
<td>R10-2</td>
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<tr>
<td>Compact structure</td>
<td>R13</td>
<td>1</td>
<td>R12-R13</td>
<td>R12-R14</td>
<td>R13-R15</td>
<td>R13-R16</td>
<td>R13-R17</td>
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<tr>
<td>Light weight</td>
<td>R14</td>
<td>1</td>
<td>R13-R14</td>
<td>R13-R15</td>
<td>R13-R16</td>
<td>R13-R17</td>
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<tr>
<td>Fine appearance</td>
<td>R15</td>
<td>1</td>
<td>R15-2</td>
<td>R14-R16</td>
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<tr>
<td>Moderate cost</td>
<td>R16</td>
<td>1</td>
<td>R15-2</td>
<td>R14-R16</td>
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<td>Intelligent control</td>
<td>R17</td>
<td>1</td>
<td>R15-2</td>
<td>R14-R16</td>
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<tr>
<td>Absolute weight</td>
<td>Aω</td>
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<td>37</td>
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<td>7</td>
<td>5</td>
<td>10</td>
<td>5</td>
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<tr>
<td>Relative weight</td>
<td>Rω</td>
<td>10</td>
<td>10</td>
<td>8.6</td>
<td>8.6</td>
<td>7.2</td>
<td>6.7</td>
<td>4.2</td>
<td>1.4</td>
<td>4.2</td>
<td>5.3</td>
<td>4.4</td>
<td>0.9</td>
<td>1.6</td>
<td>1.2</td>
<td>2.3</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 2. The configuration results of money-binding machine.

<table>
<thead>
<tr>
<th>Configuration result</th>
<th>Technical parameters</th>
<th>Configuration result</th>
<th>Technical parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>- A-type Pressuring Mechanism</td>
<td>Type of Bundling Paper Money: Double Cross 5 Point Type</td>
<td>- B-type Pressuring Mechanism</td>
<td>Type of Bundling Paper Money: Double Cross 5 Point Type</td>
</tr>
<tr>
<td>- A-type Transmitting Belt Mechanism</td>
<td>Bundling Speed: 25s/bundle</td>
<td>- B-type Transmitting Belt Mechanism</td>
<td>Bundling Speed: 30s/bundle</td>
</tr>
<tr>
<td>- Mechanism of Sticking and Cutting Belt with Double Cross 5 Point Type</td>
<td>External Dimensions: 0.6m×0.55m×1.3m</td>
<td>- Mechanism of Sticking and Cutting Belt with Double cross 5 Point Type</td>
<td>External Dimensions: 0.6m×0.45m×1.3m</td>
</tr>
<tr>
<td>- Dust removal Mechanism with External type</td>
<td>Design Life: 3 Year</td>
<td>- Dust removal Mechanism with Internal type</td>
<td>Design Life: 3 Year</td>
</tr>
<tr>
<td>- A-type Control System</td>
<td>Rated Voltage: 220V</td>
<td>- B-type Control System</td>
<td>Rated Voltage: 220V</td>
</tr>
<tr>
<td>- A Series Cover</td>
<td>Rated Power: 600W</td>
<td>- B Series Cover</td>
<td>Rated Power: 550W</td>
</tr>
<tr>
<td></td>
<td>Total Weight: 115kg</td>
<td></td>
<td>Total Weight: 100kg</td>
</tr>
<tr>
<td></td>
<td>Operating Mode: full-automatic</td>
<td></td>
<td>Operating Mode: Semi-automatic</td>
</tr>
<tr>
<td></td>
<td>Range of Bundling Paper Money: ¥0.1-¥100</td>
<td></td>
<td>Range of Bundling Paper Money: ¥0.1-¥100</td>
</tr>
</tbody>
</table>
determined by using AHP method.

(i) The weights of influencing factor $u_{11}$, $u_{12}$, $u_{13}$
Their weights are determined by using AHP method, and
the calculation process can be described as follow.
a) The judgment matrix of $u_{11}$, $u_{12}$, $u_{13}$ is shown in Table 5.
b) Calculating the all elements' geometric mean of each
row in judgment matrix as follow
\[
\bar{\sigma}_i = \sqrt[3]{\prod_{j=1}^{3} \mu_{ij}} \quad (i = 1, 2, 3)
\]
then $\bar{\sigma}_1 = 3.979$, $\bar{\sigma}_2 = 0.754$, $\bar{\sigma}_3 = 0.333$
c) Normalizing $\bar{\sigma}_i$ as follow
\[
\omega_i = \bar{\sigma}_i / \sum_{j=1}^{3} \bar{\sigma}_j \quad (i = 1, 2, 3)
\]
(12)
Thus, $\omega = (\omega_1, \omega_2, \omega_3)^T$ is the approximation of feature
vector, and it is also the relative weight of each factor,
then $\omega = (\omega_1, \omega_2, \omega_3)^T = (0.785, 0.149, 0.066)^T$
d) Calculating the maximum eigenvalue of judgment
matrix as follow
\[
\lambda_{max} = \frac{\sum_{i=1}^{3} (A\omega)_i}{3\omega_i}
\]
(13)
where $(A\omega)_i$ is the first i element of $A\omega$ vector, then
$\lambda_{max} = \sum_{i=1}^{3} \frac{(A\omega)_i}{3\omega_i} = \frac{(A\omega)_1}{3\omega_1} + \frac{(A\omega)_2}{3\omega_2} + \frac{(A\omega)_3}{3\omega_3} = 3.081$
e) Testing the consistency index of the judgment matrix
as follow
\[
CR = \frac{CI}{RI} = \frac{\lambda_{max} - n}{n-1} / RI
\]
(14)
where $RI$ is the correction factor for the dimension of
judgment matrix, and its value can be obtained in reference (Qian, 1990). If $CR < 0.1$, that the

<table>
<thead>
<tr>
<th>Factor subset</th>
<th>Influencing factor</th>
<th>Factor grade</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>$U_1$ Price</td>
<td>$u_{11}$ Product cost</td>
<td>Lower</td>
</tr>
<tr>
<td></td>
<td>$u_{12}$ Consumable cost</td>
<td>Lower</td>
</tr>
<tr>
<td></td>
<td>$u_{13}$ Transport cost</td>
<td>Lower</td>
</tr>
<tr>
<td></td>
<td>$u_{21}$ Binding efficiency</td>
<td>Higher</td>
</tr>
<tr>
<td></td>
<td>$u_{22}$ Binding tightly</td>
<td>Better</td>
</tr>
<tr>
<td>$U_2$ Performance</td>
<td>$u_{23}$ Operational reliability</td>
<td>Better</td>
</tr>
<tr>
<td></td>
<td>$u_{24}$ Binding adjustability</td>
<td>Better</td>
</tr>
<tr>
<td></td>
<td>$u_{25}$ Service life</td>
<td>Longer</td>
</tr>
<tr>
<td></td>
<td>$u_{26}$ Intelligent control</td>
<td>Better</td>
</tr>
<tr>
<td>$U_3$ Service</td>
<td>$u_{31}$ Delivery time</td>
<td>Shorter</td>
</tr>
<tr>
<td></td>
<td>$u_{32}$ Warranty period</td>
<td>Longer</td>
</tr>
<tr>
<td></td>
<td>$u_{41}$ Operational safety</td>
<td>Better</td>
</tr>
<tr>
<td></td>
<td>$u_{42}$ Running safety</td>
<td>Better</td>
</tr>
<tr>
<td></td>
<td>$u_{43}$ Energy consumption</td>
<td>Smaller</td>
</tr>
<tr>
<td></td>
<td>$u_{44}$ Noise</td>
<td>Lower</td>
</tr>
<tr>
<td></td>
<td>$u_{45}$ Pollution</td>
<td>Less</td>
</tr>
<tr>
<td></td>
<td>$u_{46}$ Simple operation</td>
<td>Better</td>
</tr>
<tr>
<td></td>
<td>$u_{47}$ Convenient carrying</td>
<td>Better</td>
</tr>
<tr>
<td></td>
<td>$u_{48}$ Compact structure</td>
<td>Better</td>
</tr>
<tr>
<td></td>
<td>$u_{49}$ Weigh</td>
<td>Lighter</td>
</tr>
<tr>
<td></td>
<td>$u_{410}$ Appearance</td>
<td>Better</td>
</tr>
</tbody>
</table>

Table 3. The factor subset, factor and factor grade of configuration scheme evaluation.
Table 4. The membership degree of factor grade for example I and example II.

<table>
<thead>
<tr>
<th>Factor subset</th>
<th>Influencing factor</th>
<th>Factor grade</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Name</td>
<td>Weight</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Price</td>
<td>Product cost</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>Consumable cost</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>Transport cost</td>
<td>0.06</td>
</tr>
<tr>
<td>Performance</td>
<td>Binding efficiency</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>Binding tightly</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>Operational reliability</td>
<td>0.15</td>
</tr>
<tr>
<td>Service</td>
<td>Delivery time</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>Warranty period</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Human-machine-environment</td>
<td>Operational safety</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>Running safety</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>Energy consumption</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>Noise</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pollution</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>Simple operation</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>Conventional carrying</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>Compact structure</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>Weigh</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>Appearance</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Note:</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: The italics values is the membership of each factor grade for configuration example II.

Consistency of the judgment matrix can be accepted, Otherwise recounting the judgment matrix. After
Table 5. The judgment matrix of $u_{11}$, $u_{12}$, $u_{13}$

<table>
<thead>
<tr>
<th></th>
<th>Product cost ($u_{11}$)</th>
<th>Consumable cost ($u_{12}$)</th>
<th>Transport cost ($u_{13}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product cost</td>
<td>1</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>Consumable cost</td>
<td>1/7</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Transport cost</td>
<td>1/9</td>
<td>1/3</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 6. Weight result on factor set of performance

<table>
<thead>
<tr>
<th>Influencing factor ($u_{2i}$ ($i=1,2,\ldots,6$))</th>
<th>Weight</th>
<th>Normalizing</th>
<th>Normalized weight ($\omega_{2i}$ ($i=1,2,\ldots,6$))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binding efficiency</td>
<td>8.4</td>
<td></td>
<td>0.19</td>
</tr>
<tr>
<td>Binding tightly</td>
<td>10</td>
<td></td>
<td>0.23</td>
</tr>
<tr>
<td>Operational reliability</td>
<td>6.6</td>
<td>$\sum_{i=1}^{6} u_{2i}$</td>
<td>0.15</td>
</tr>
<tr>
<td>Binding adjustability</td>
<td>10</td>
<td></td>
<td>0.23</td>
</tr>
<tr>
<td>Service life</td>
<td>4.1</td>
<td></td>
<td>0.09</td>
</tr>
<tr>
<td>Intelligent control</td>
<td>4.3</td>
<td></td>
<td>0.11</td>
</tr>
</tbody>
</table>

Table 7. Weight result on factor set of human-machine-environment

<table>
<thead>
<tr>
<th>Influencing factor ($u_{4i}$ ($i=1,2,\ldots,10$))</th>
<th>Weight</th>
<th>Normalizing</th>
<th>Normalized weight ($\omega_{4i}$ ($i=1,2,\ldots,10$))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational safety</td>
<td>8.4</td>
<td></td>
<td>0.23</td>
</tr>
<tr>
<td>Running safety</td>
<td>7</td>
<td></td>
<td>0.19</td>
</tr>
<tr>
<td>Energy consumption</td>
<td>1.4</td>
<td></td>
<td>0.04</td>
</tr>
<tr>
<td>Noise</td>
<td>4.1</td>
<td></td>
<td>0.11</td>
</tr>
<tr>
<td>Pollution</td>
<td>5.2</td>
<td>$\sum_{i=1}^{10} u_{4i}$</td>
<td>0.14</td>
</tr>
<tr>
<td>Simple operation</td>
<td>4.3</td>
<td></td>
<td>0.12</td>
</tr>
<tr>
<td>Convenient carrying</td>
<td>0.9</td>
<td></td>
<td>0.02</td>
</tr>
<tr>
<td>Compact structure</td>
<td>1.6</td>
<td></td>
<td>0.05</td>
</tr>
<tr>
<td>Weight</td>
<td>1.1</td>
<td></td>
<td>0.03</td>
</tr>
<tr>
<td>Appearance</td>
<td>2.3</td>
<td></td>
<td>0.07</td>
</tr>
</tbody>
</table>

The weight of factor subset

After determining the weight of influencing factor, the requirements, and the calculation results are shown in Table 6. So,

$$W_2 = (\omega_{21}, \omega_{22}, \omega_{23}, \omega_{24}, \omega_{25}, \omega_{26}) = (0.19, 0.23, 0.15, 0.23, 0.09, 0.11)$$

(price subset). Similarly, the weights of $u_{41}$, $u_{42}$, $u_{43}$, $u_{44}$, $u_{45}$, $u_{46}$, $u_{47}$, $u_{48}$, $u_{49}$, $u_{410}$ are shown in Table 7. So,

$$W_4 = (\omega_{41}, \omega_{42}, \omega_{43}, \omega_{44}, \omega_{45}, \omega_{46}, \omega_{47}, \omega_{48}, \omega_{49}, \omega_{410}) = (0.23, 0.19, 0.04, 0.11, 0.14, 0.12, 0.02, 0.05, 0.03, 0.07)$$

(service subset)

(human-machine-environment subset)
weight of factor subset (price, performance, service, human-machine-environment) can be obtained by using AHP method, and the normalized calculation results are shown in Table 4, that is,

\[ W = (\omega_1, \omega_2, \omega_3, \omega_4) = (0.08, 0.48, 0.15, 0.29) \] (the weight of factor subset)

(5) Fuzzy comprehensive evaluation

(i) the first level fuzzy comprehensive evaluation

According to the configuration example I and example II in Table 4, the first level fuzzy comprehensive evaluation matrix of the first influencing factor (price factor) can be described as \( R_{II} \) and \( R_{III} \) respectively, that is,

\[
R_{II} = \begin{pmatrix}
0 & 0.125 & 0.5 & 0.375 & 0 \\
0.125 & 0.375 & 0.5 & 0 & 0 \\
0.125 & 0.375 & 0.5 & 0 & 0
\end{pmatrix}
\]

\[
R_{III} = \begin{pmatrix}
0.125 & 0.5 & 0.375 & 0 & 0 \\
0.25 & 0.5 & 0.25 & 0 & 0 \\
0.25 & 0.5 & 0.25 & 0 & 0
\end{pmatrix}
\]

so, the result of the first level fuzzy comprehensive evaluation for each factor subset (price, performance, service, human-machine-environment) of configuration example I and example II can be expressed as

\[
B_{II} = W_1 \circ R_{II}
\]

\[
= (0.79, 0.15, 0.06) \circ \begin{pmatrix}
0 & 0.125 & 0.5 & 0.375 & 0 \\
0.125 & 0.375 & 0.5 & 0 & 0 \\
0.125 & 0.375 & 0.5 & 0 & 0
\end{pmatrix}
\]

\[
= (0.026, 0.178, 0.5, 0.296, 0)
\]

\[
B_{III} = W_1 \circ R_{III}
\]

\[
= (0.79, 0.15, 0.06) \circ \begin{pmatrix}
0.125 & 0.5 & 0.375 & 0 & 0 \\
0.25 & 0.5 & 0.25 & 0 & 0 \\
0.25 & 0.5 & 0.25 & 0 & 0
\end{pmatrix}
\]

\[
= (0.151, 0.5, 0.349, 0, 0)
\]

(ii) the second level fuzzy comprehensive evaluation

According to the above calculation results, the first level fuzzy comprehensive evaluation matrix of them can be described as \( R_I \) and \( R_{II} \) respectively, that is,

\[
R_I = \begin{pmatrix}
B_{II} \\
B_{III}
\end{pmatrix}
\]

\[
= \begin{pmatrix}
B_{II} \\
B_{III}
\end{pmatrix} = \begin{pmatrix}
(0.026, 0.178, 0.5, 0.296, 0) \\
(0.151, 0.5, 0.349, 0, 0)
\end{pmatrix}
\]

\[
R_{II} = \begin{pmatrix}
B_{II} \\
B_{III}
\end{pmatrix}
\]

\[
= \begin{pmatrix}
(0.026, 0.178, 0.5, 0.296, 0) \\
(0.151, 0.5, 0.349, 0, 0)
\end{pmatrix}
\]

So, the general comprehensive evaluation result for configuration example I and example II can be described as

\[
B_I = W \circ R_I = (0.338, 0.422, 0.202, 0.035, 0.003)
\]

According to the principle of the maximum membership degree, two schemes all belong to the better grade and can not be distinguished which one is better.

(6) Calculating the comprehensive evaluation value (marked as \( E \))

Taking \( b_i \) as weight, the value of the weighted average for \( v_i \) is acted as the final evaluation result and can be expressed as follow

\[
v = \frac{\sum_{i=1}^{5} b_i v_i}{\sum_{i=1}^{5} b_i}
\]

\[
\sum_{i=1}^{5} b_i = 1
\]

and

\[
v = \sum_{i=1}^{5} b_i v_i
\]

The evaluation set of configuration result (marked as \( V \)) is expressed as \( V=\{\text{better, good, normal, bad, worse}\} \). If the value of \( V \) is marked with number, it can be described as \( V=\{5,4,3,2,1\} \). So, the comprehensive evaluation values of configuration example I and example II are

\[
E_I = B_I \cdot V^T = 4.1 \quad E_{II} = B_{II} \cdot V^T = 3.6
\]

respectively.

Because of \( E_I > E_{II} \), the configuration example I is better than the configuration example II according to the principle of selecting the best qualified, and it also commendably accords with the practical situation.
Conclusion

The evaluation of configuration scheme is an important section in configuration design. This paper puts forward a new fuzzy comprehensive evaluation method on the basis of fully considering the customer requirement. In the process of evaluation, customer is the evaluation body, and the specific customer requirements are taken as the part of material evaluation indexes to evaluate, sort and optimize the configuration scheme. As a result, it could realize the best matching and maximum satisfaction between the various performance indicators of product and customer requirements. This method utilizes fuzzy mathematics theory to quantify the fuzzy information in the process of evaluation, and makes the evaluation result more scientific and objective. So that the optimal product configuration scheme that meets customer requirements maximally could be chosen, and it also could provide the base for the product optimization design. After the practical application of the configuration design for a money-binding machine, it proves that the proposed method has the better effectivity and feasibility.

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