An integrated decision making method for selecting machine tool guideways considering remanufacturability

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As one of the most important components of machine tool, guideway has an important driving-force to comprehensively improve the remanufacturability of machine tools. To select optimal guideway for machine tool remanufacturing, an integrated multi-criteria decision making (MCDM) approach that combines improved Analytic Hierarchy Process (AHP) and Connection Degree based Technique of ranking Preferences by Similarity to the Ideal Solution (CD-TOPSIS) method is proposed. The improved AHP is employed to calculate the weights of each criterion and the CD-TOPSIS is adapted to complete the task of sorting, finally, the comprehensive evaluation of the alternatives is carried out. A case study, i.e., eight types of guideways, is illustrated to verify the proposed MCDM method. In addition, comparison with existing methods are performed to validate the effective and reliability for the proposed hybrid approach. Also, sensitivity analysis is provided to evaluate the robustness of the method. The final result shows the method provides reliable decision support for the selection of machine tool guideways for remanufacturing.

Keywords: Multi-criteria decision making (MCDM); Machine Tool Guideway; Analytic hierarchy process (AHP); TOPSIS; Remanufacturability; Selection

1. Introduction

Due to increasing attention to environmental pollution and energy consumption, as well as the government's strict legislation, the disposal of EOL (End-of-Life) products has received considerable attention in the past few decades (Cai 2018; Liu 2018(157)). Remanufacturing, a process of bringing used products to 'like-new' functional state with a warranty (Wang 2018), is being regarded as one of the best environmental-friendly disposal ways for EOL products or parts and the important way of energy saving and emission reduction (Zhang 2015; Jing 2016).

Considering remanufacturing at the product design stage has become a significant competitive strategy that has attracted the attention of enterprises (Liu 2018(150); Wang 2017). As a typical production equipment, machine tools have high recycling value and potential for remanufacturing owing to high added value of steel products and large manufacturing costs of mechanical parts. Whether the EOL machine tools can be remanufactured successfully depends on the remanufacturability of its components. As one of the most important components of the machine tool, the guideway is the key to improve its remanufacturability. Therefore, remanufacturing oriented selection of guideway is an important approach to implement remanufacturing of machine tools. A large number of scholars have made extensive research about evaluation and selection of components for remanufacturing. Liu et al. (2017) proposed a selection method of engine crankshaft materials based on Quality Function Deployment (QFD) and AHP to improve their remanufacturing performance. To scientifically and objectively select materials for remanufacturing designs, Wei et al. (2018) presented a material multi-attribute decision-making method based on evidential reasoning. Moreover, Yang et al. (2015) utilized Fuzzy TOPSIS method to evaluate the performance of candidate materials for the first time in the early design stage of automobile products, and applied to the selection of automotive component materials to improve their remanufacturability. The shortcomings of aforementioned literature are that they only considered a feature of remanufacturing, and did not establish a complete evaluation system. In addition, their evaluation targets are usually automotive or engine parts. At present, it is still a brand-new field to evaluate the machine tool guide rails considering remanufacturability.

However, various selection criteria and complex relationships between them, which leads to the complexity and uncertainty in assessment process for remanufacturing and make it a challenging task. For instance, when considering remanufacturing characteristics, some criteria, e.g., disassemblability, assemblability, must be taken into account. As a consequence, a multi-criteria-decision-making (MCDM) method become a useful tool to deal with this problem. In general, there are many MCDM method have been developed to solve this. For example, AHP (Li 2016; Shi 2015) and fuzzy AHP (Zeng 2012; Kumar 2017), TOPSIS (Song 2013) and fuzzy comprehensive evaluation (FCE) (Zhou 2014). Additionally, some integrated methods have also been successfully proposed to compensate for the lack of a single method. For instance, Tian et al. (2018) proposed a MCDM approach based on AHP and grey correlation improved TOPSIS (GC-TOPSIS) for green decoration materials selection. In order to improve the prediction accuracy of remanufacturability evaluation for basic components of machine tools, a model for the remanufacturability evaluation using simulated annealing (SA) and genetic algorithm (GC) to optimize Back Propagation (BP) neural network was presented by Pan et al (2016).

Although each approach has its own advantages, these MCDM models share a similar assessment process (Yang 2016), mainly including the following four steps: 1) Determine the criteria and alternatives; 2) Construct a reasonable hierarchical structure according to different criteria; 3) Identify criteria weights; 4) Evaluate each of the alternatives and rank them. Among the above MCDM method, the AHP and TOPSIS hybrid approach is one of well accepted and practical MCDM approaches by the experts (Tian 2018). AHP is a kind of decision analysis method combining qualitative and quantitative analysis to solve complex problems which is usually used for comprehensive evaluation of multiple attributes and elements (Shi 2015; Chang 2017). TOPSIS is a method of ranking according to the degree of closeness between various schemes and idealized goals, which is widely used in product design, manufacturing systems (Enzhong 2015) and other multi-attribute program decision-making areas. It is a comparative evaluation of the relative merits of existing programs, it can make full use of the information of the original data of each scheme for evaluation (Zhao 2016). In fact, when evaluating the alternatives, whether it is index construction, weight calculation or ranking, it is not reasonable to deal with this complex strategic choice in one way.

The TOPSIS and AHP-TOPSIS method evaluates alternatives based on the distance relationship between the data sequences. However, the TOPSIS method has some shortcomings that cannot be ignored: the alternative closer to the Euclidean distance of ideal point may be closer to the Euclidean distance of the negative ideal point. The result of ranking the alternatives according to the relative Euclidean distance sometimes can not fully reflect advantages and disadvantages of each alternative. To ensure the rationalization and comprehensiveness of the final results, evaluation process should not only consider the location relationship among data sequences but also employs the relative distribution. Some experts have improved TOPSIS (Hua 2004; Wang 1999), but the proposed improvement methods still have some problems such as large amount of calculation and easy loss of information. Thus, in view of the shortcomings of TOPSlS method, this paper proposes a new limited scheme multi-attribute decision-making method based on the replacement of Euclidean distance: the improved TOPSIS method based on the connection degree.

In this paper, a hybrid MCDM method that combines improved AHP and connection-degree improved TOPSIS is presented to evaluate the selection problem of machine tool guideway considering remanufacturability. The objective of this work is to evaluate the guideway from the perspective of remanufacturing by considering the weight of the evaluation criteria, including factors, e.g., recyclability, disassembly and recoverability, so as to enable designers to better select the guideway and increase opportunities for product remanufacturing. Compared with existing research, this work has three unique contributions: 1) A hierarchical structure about evaluation criteria focusing on the characteristics of remanufacturability established, and the weights of each criterion could be calculated according to improved AHP method; 2) Aiming at the defects of general TOPSIS approach, a hybrid MCDM model combining improved AHP and CD-TOPSIS is proposed. This method makes full use of the characteristics of the quantitative analysis and weight distribution of AHP to reduce/avoid subjectivity and irrationality, and consider the distribution of sample total values via connection degree to make the result general relative; 3) Through the effective application of this method in the evaluation of guideway, it provides an important reference for the remanufacturing oriented selection of machine tool guideway. In addition, sensitivity analysis and comparison with existing methods are performed to validate the effective and reliability for the proposed hybrid approach.

2. A hybrid MCDM model

In this section, a decision method that integrates improved AHP, Connection Degree (CD) and TOPSIS is presented for multi-objective decision-making in complex systems. After identifying the criteria system of selecting machine tool guideway for remanufacturing, the AHP is firstly used to determine the hierarchy weight of the evaluation indicators/criteria under each feature. Then, the CD-TOPSIS method is utilized to select the optimal guideway scheme based on the comprehensive intimacy index. The proposed integrated approach will be explained step by step as follows.

2.1 Improved AHP approach

AHP (Chen 2000) is an effective MCDM method proposed by Thomas Saaty to quantitatively analyze qualitative problems. The theoretical core of AHP is to decompose the complex problem into different levels according to the nature of the problem and the overall goal, and forms a multi-level analysis structural model. The traditional AHP adopts the "1-9" scale to construct the index layer judgment matrix, the judgment scale is difficult to grasp and also has a high subjectivity. Moreover, if the constructed judgment matrix is not consistent, it needs to be reconstructed and calculated until passed, the amount of computation is also large (Jiang 2007). The improved AHP adopts the three-scale method, so the judgment matrix is easier to construct, and there is no need for the consistency test (Liu 2008). The specific implementation steps are as follows:

Step 1: *Establish a hierarchical structure.* The structure including different levels and various indexes/criteria. The first layer is the goal layer; the second is the criterion one, which is an evaluation index; the third is the sub-criteria one, which is the second layer of the refinement.

Step 2: *Create a 3-scale comparison matrix A.* The element of matrix A is r_{ij} , which is determined by Table 1, where r_{ij} is the factor i and the factor j relative importance, and $r_{ii}=1$.

Table 1 AHP scale for comparison

Numerical scale	Definition	Explanation
2	Strong importance	The factor i is more important than the factor j
1	Equal importance	The factor i is as important as the factor j
0	Less importance	The factor i is less important than the factor j

Step 3: *Calculate the importance of sorting index.* According to equation (1), calculating the sum of each row of the comparison matrix respectively, which is the sorting index r_i .

$$r_i=\sum_{j=1}^{n} r_{ij} \tag{1}$$

Step 4: *Construct judgment matrix.* The judgment matrix B is constructed according to the following equation.

$$b_{ij} = \begin{cases} \left(\dfrac{r_i - r_j}{r_{\max} - r_{\min}}\right) * (k-1) + 1 & r_i >= r_j \\ \left[\left(\dfrac{|r_i - r_j|}{r_{\max} - r_{\min}}\right) * (k-1) + 1\right]^{-1} & r_i < r_j \\ k = \dfrac{r_{\max}}{r_{\min}} \end{cases} \tag{2}$$

where, b_{ij} is the element of the judgment matrix B, r_i / r_j is the sorting index, k is a constant.

Step 5: *Find the optimal transfer matrix C of judgment matrix B.*

$$c_{ij} = \frac{1}{n} \sum_{t=1}^{n} \left(\lg \frac{b_{it}}{b_{jt}} \right) \tag{3}$$

where, c_{ij} is the element of the judgment matrix C, b_{it} / b_{jt} is the element of the judgment matrix B.

Step 6: *Calculate the pseudo-optimal consistent matrix D.* It is Calculated as follows:

$$d_{ij} = 10^{c_{ij}} \tag{4}$$

where, d_{ij} represents the element of matrix D and c_{ij} is the element of the judgment matrix C.

Step 7: *Solve the eigenvector corresponding to the largest eigenvalue of D, and normalize it to get the weight of each factor.*

2.2 CD-TOPSIS approach

TOPSIS is a comprehensive decision-making method that was first proposed by C. L. Hwang and K. Yoon in 1981 (Enzhong 2015). It constructs the positive and negative ideal points of multi-attribute problems, and shows the advantages and disadvantages of each solution by approaching positive ideal points and away from negative ideal points. The improved TOPSIS method based on the connection degree (CD-TOPSIS) is adopted in this paper. This method is based on the set pair idea, and the Euclidean distance can be replaced by the distance of the contact vector, which can satisfy the selected optimal scheme while being close to the ideal point and away from the negative ideal point (Wang 2010; Zhang 2008).

In view of the fuzziness of the definition of connection degree, this paper considers it necessary to discuss the relation degree before listing the steps of CD-TOPSIS method. Suppose that P and Q are two sets each containing n elements, and the elements of the two sets are compared one by one. Supposing there is a slight difference of s terms, a big difference of t terms, and difference of the remaining r terms between small and large, then the connection degree of the two sets is $U = a + bi + cj$, where $a = s / n$ indicates the same degree of the two sets, $b = r / n$ indicates the degree of difference of the two sets, and $c = t / n$ represents the degree of opposition of the two sets, with the obvious $a + b + c = 1$. According to the definition of the connection degree, when comparing two sets of elements, the degree of difference between the two corresponding elements is relatively vague, and there is no clear quantitative representation. Therefore, when determining the degree of difference between two elements, absolute comparisons cannot be made with numerical values. The comprehensive characteristics of all alternatives should be taken into account. Based on this, an interval measurement method based on sample distribution is proposed in this paper. Take one indicator of the sample as an example, other indicators are similar.

Let the value vector of m samples in index j be $X_j = (x_{1j}, x_{2j}, ..., x_{mj})$, where the optimal value is $x^+ = \max(x_{1j}, x_{2j}, ..., x_{mj})$.

1) Find out the distance d_i between the index value x_{ij} and the optimum value x^+ of all samples:

$$d_i = x^+ - x_{ij}, i = 1,2,..., m \tag{5}$$

2) Sort all the distances in small to large order to get the vector $F = [f_1, f_2, ..., f_m]$

3) Divide the distance into three sections, including:

if $m = 3n$, where n is any positive integer, the ntervals are $[f_1, f_{m/3}]$, $[f_{m/3+1}, f_{2m/3}]$ and $[f_{2m/3+1}, f_{3m}]$;

if $m = 3n+1$, the ntervals are $[f_1, f_{(m-1)/3}]$, $[f_{(m-1)/3+1}, f_{2(m-1)/3}]$ and $[f_{2(m-1)/3+1}, f_m]$;

if $m = 3n+2$, the ntervals are $[f_1, f_{(m+1)/3}]$, $[f_{(m+1)/3+1}, f_{2(m+1)/3}]$ and $[f_{2(m+1)/3}+1, f_m]$.

4) Compare the difference between sample values and optimal values.

If the distance d_k between the index value x_{kj} of the sample A_k and the optimal value x^+ falls in the first interval, the difference is small, and so on. The method is the same when compared to the worst case. This method differentiates the differences based on the distance distribution between all samples and the optimal value (the worst value). The capacity of each nterval is 1/3 of the total capacity, which takes into account the distribution of the sample's overall index values, the results are relative. At the same time, it does not increase the amount of calculations and can be achieved by the program. The CD-TOPSIS method that combining CD and TOPSIS, which has the following steps:

Step 1: *Construct a characteristic matrix based on n quantitative index values of each evaluation target.* The characteristic matrix $C_1 = [x_{ij}]\ (i = 1,2,3...n;\ j = 1,2,3...m)$ can be collected by relevant expert scores or surveys in various fields. Among them, x_{ij} is the score of the i th alternative under the j th criterion; n is the total number of alternatives; and m is the total number of criteria in the hierarchy. Then, the canonical decision matrix Z is obtained by using the vector normalization method.

For the benefit factor, the normalized value z_{ij} is calculated as,

$$z_{ij} = x_{ij} / \max x_{ij}\ (i = 1,2,3...n;\ j = 1,2,3...m) \tag{6}$$

where, x_{ij} represents the elements of matrix C_1.

For the cost factor, the normalized value z_{ij} is calculated as,

$$z_{ij} = \min x_{ij} / x_{ij}\ (i = 1,2,3...n;\ j = 1,2,3...m) \tag{7}$$

Step 2: *Construct the normalized-weighted matrix.* By calculating the normalized weights, a weight normalization matrix is established, that is $A = a_{ij} = w_j * z_{ij}\ (i = 1,2,3...n;\ j = 1,2,3...m)$. Moreover, the weight vector for each criterion $w_j = [w_1, w_2, ...w_k]$ is obtained through improved AHP.

Step 3: *Determine positive ideal point* $A^+ = \{a_1^+, a_2^+, ..., a_m^+\}$ *and negative ideal point* $A^- = \{a_1^-, a_2^-, ..., a_m^-\}$, *they are calculated as*

$$\begin{cases} a_j^+ = \{< \max\limits_{1\le i\le n} a_{ij} \mid j \in j^+, < \min\limits_{1\le i\le n} a_{ij} \mid j \in j^- >\} \\ a_j^- = \{< \min\limits_{1\le i\le n} a_{ij} \mid j \in j^+, < \max\limits_{1\le i\le n} a_{ij} \mid j \in j^- >\} \end{cases} \tag{8}$$

where, J^+ denotes the benefit indicator, that is the greater the value of the better; J^- denotes the cost indicator which the smaller the better.

Step 4: *Calculate the connection degree between each alternative and the positive/negative ideal points.*

$$\begin{cases} U_k^+ = a_k^+ + b_k^+ i + c_k^+ j \\ U_k^- = a_k^- + b_k^- i + c_k^- j \end{cases} \quad k = 1,2,...,n \tag{9}$$

where, a_k^+ / a_k^- , b_k^+ / b_k^- , c_k^+ / c_k^- represent the similarity degree, difference degree, contrast degree of the index vector of the alternative A_k and positive/negative ideal point vector respectively.

Step 5: *Calculate the contact vector distance between each alternative and the positive/negative ideal points, they are calculated as*

$$d_k^+ = \sqrt{(1-a_k^+)^2 + (b_k^+)^2 + (c_k^+)^2}, \quad k = 1,2,...,n \tag{10}$$

$$d_k^- = \sqrt{(1-a_k^{--})^2 + (b_k^-)^2 + (c_k^-)^2}, \quad k = 1,2,...,n \tag{11}$$

where, d_k^+, d_k^- represents the contact vector distance.

Step 6: *Calculate the comprehensive closeness index (CCI) between each alternative and the optimal solution, it is expressed as* C_k .

$$C_k = \frac{d_k^-}{d_k^+ + d_k^-}, k = 1,2,...n \tag{12}$$

Step 7: *Rank each alternative by the size of the CCI value. The lager value of* C_k *, the greater the closer to the optimal scheme.*

2.3 The comprehensive evaluation process for machine tool guideway

In this paper, the integrated MCDM method of combining AHP and CD-TOPSIS is proposed. The index weight is determined by the AHP method, the evaluation hierarchy structure is established considering the remanufacturability characteristics, and the evaluation value of the alternative schemes is mapped to the membership degree of (0, 1) interval. The proposed method can not only overcome the subjectivity of AHP in the index that is not easy to quantify, but also avoid defect of that TOPSIS can not completely reflect the advantages and disadvantages of each scheme. The proposed method can be divided into two stages, as shown in Fig. 1.

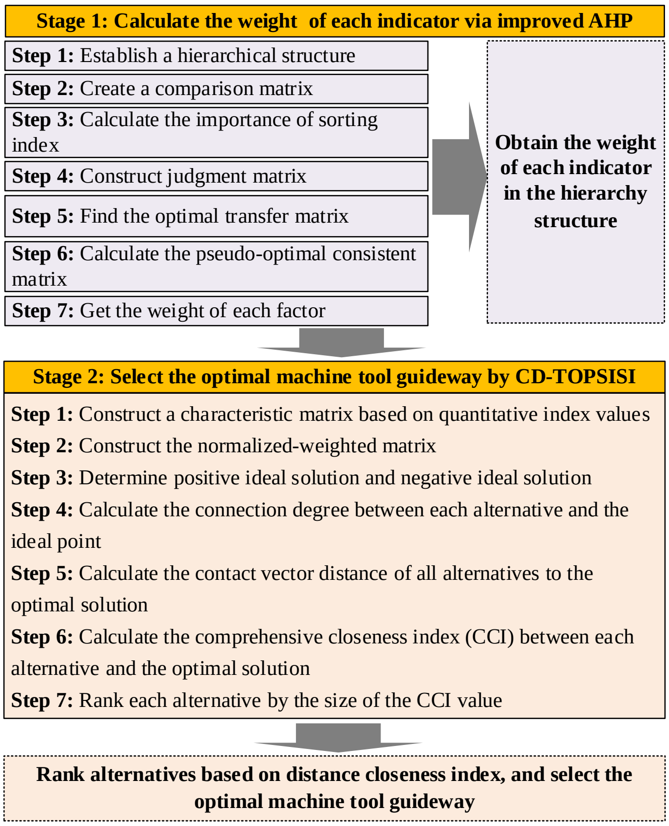

Fig.1. The framework of integrated MCDM method

Stage 1: Calculate the weight of the hierarchical structure/criteria based on the improved AHP. According to the value rules shown in Table 1, a comparison of the importance of each factor in the index layer was made by two or more related fields experts and a judgment matrix was generated. It is noteworthy that the final comparison matrix is established by calculating the average of the evaluation values obtained from each expert. Therefore, after a series of calculations, it can get the weight of each criterion that meets the requirements.

Stage 2: Select the optimal machine tool guideway by CD-TOPSISI. By calculating the average of the quantitative values of the matrixes acquired by each expert, the decision matrix for schemes is established. The final value of CCI for each alternative can be obtained through the CD-TOPSIS calculation process. Then the optimal machine tool guideway is selected based on the ranking of CCI. In addition, the difference in remanufacturability of machine tool guideways can be determined by the magnitude of the CCI value C_i , and the higher the value C_i , the better the remanufacturability.

3. Case Study

In this section, an empirical research is utilized to illustrate the application of the proposed hybrid MCDM method to evaluate machine tool guideways considering remanufacturability and select the optimal one. Additionly, comparison with existing methods are performed to validate the effectiveness and reliability for this approach. It will benefit machine tool design from the perspective of helping enterprises select the right parts.

The guideway is one of the most important components of machine tool. Due to its diversified structure and complex manufacturing process, the remanufacture of EOL guideways can save cost and resources effectively. Therefore, from the point of view of machine tool design, the requirements in terms of remanufacturability for guideway is very high. After preliminary screening and taking into account the characteristics of environment, economy and technology, eight kinds of common guideways are treated as alternatives, which is demonstrated in Table 2.

Table 2 Eight kinds of common guideway for alternatives

Alternatives	Machine tool guideway
a	Linear Motion Guideway of Ttriangle-Rectangular Combination
b	Linear Motion Guideway of Double Rectangular
c	Linear Rolling Guideway
d	Hydrostatic Guideway
e	Roller Guideway
f	Spherical Guideway
g	Plastic Guideway
h	Injection Molding Guideway

3.1 Hierarchical structure of machine tool guideway evaluation

From the review of the literature, many researches have been conducted on the issue of remanufacturability evaluation. More than 20 characteristics have been identified as criteria that must be considered in the evaluation of remanufacturing, they involve technology, environment and economy field. In light of this, the hierarchy of evaluation criteria for remanufacturing is presented in Table 3. However, for different types of products, the evaluation emphasis should also be different. Take the guideways as an example, its material type is relatively single, but its structure is diverse. It is of great significance to consider the technical characteristics caused by structure in the remanufacturing evaluation of guideway.

Table 3 List of various remanufacturability evaluation as proposed by previous researches

First-level indicators	Environmental criteria (E)	Technical criteria (T)	Economic criteria (C)
Secondary indicators	Consumption of raw material Energy consumption Waste-gas production Waste quantity Material recyclability Material separability Material reusability	Disassemblability Assemblability Cleanability Restorability Complexity Durability Abrasion resistance Service life	Economic benefits Remanufacturing cost Remanufacturing time Cost of raw material Direct cost Processing cost of EoL
References	Gang 2018; LU 2018; YAO 2010; Zhao 2016; Liu 2017; Yan-bin 2015; Liu 2014	Yang 2016; Liu 2017; Gang 2018; Yang 2015; Liu 2014; LU 2018; Liu 2017; Li 2016 ; Yan-bin 2015; Liu 2014	Liu 2017; LU 2018; Zhao 2016; Liu 2017; Liu 2014; Wang 2012; Zhang 2015

As shown in Table 3, many quantitative and qualitative criteria should be considered/added into the hierarchical structure, which is used to evaluate the remanufacturability of a product. Based on the related literature (Liu 2014; Liu 2017) and expert interview, combining with the characteristics of machine tool guideway selection, the paper thinks that the main factors influencing the choice of guideways are in the aspects of environment, technology and economy. Hierarchical structure shown in Fig. 2.

Many quantitative/qualitative criteria such as remanufacturing cost, process complexity, etc. have been considered in the established three-level hierarchy structure to determine the optimal alternative. The goal layer (G) is evaluation on machine tool guideway for remanufacturing; the criterion layer (C) is environmental characteristic (C_1), technical characteristic (C_2) and economic characteristic (C_3); environmental characteristic includes material saving (S_1), energy consumption (S_2) pollution index (S_3) and material reproducibility (S_4); technical characteristic includes five criteria, i.e., recyclability (S_5), disassembly (S_6), recoverability (S_7), processing complexity (S_8), service life (S_9); economic characteristic includes recycling cost (S_{10}), cost of cleaning (S_{11}) replacement cost of parts (S_{12}) and remanufacturing cost (S_{13}). The sub-criteria layer is consist of these eleven criteria.

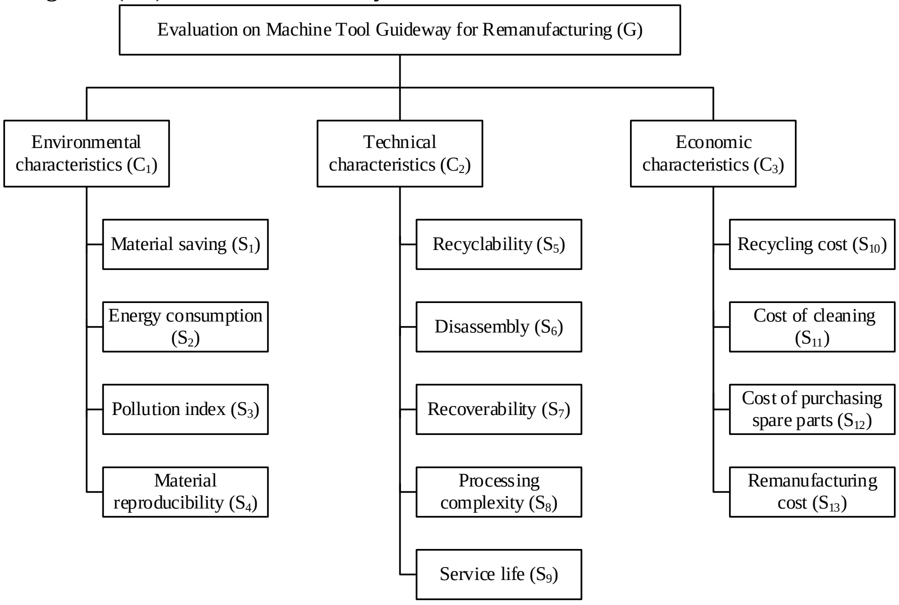

Fig. 2. Hierarchical structure for evaluation on machine tool guideway for remanufacturing

3.2 Determination of weights of evaluation index by improved AHP approach

Weight is a measure of the importance of a goal. It comprehensively reflects the importance of the decision makers on the goal, the degree of difference in the value of each target attribute, and the degree of reliability of each target attribute value. The weights of index affects the final evaluation of the machine tool guideway, so the improved AHP is employed to determine its value. In order to ensure the generality and availability of the weight, this paper obtains data through expert scoring method, and the specific steps for determining the weights are as follows.

(1) Construct comparison matrix

An expert decision-making group is composed of three authoritative experts in the related field, three technicians with extensive experience in workshop of remanufacturing, and two company managers. According to the indicators of evaluation model for machine tool guideway and the principle of 1-3 scale method, experts construct the judgment matrix of each criterion by pairwise comparison.

It is worth noting that this paper cannot show the specific scores of each expert due to space limitations. As shown in Table 3-6, the pairwise comparison matrix is the final result based on the average calculation. The comparison matrix from the viewpoint of remanufacturing-oriented evaluation， from environmental characteristic perspective, from technical characteristic perspective and from economic characteristic perspective are demonstrated in Table A1-A4, respectively.

(2) Calculate weights of each indicator

According to the given comparison matrix, the weight value of each indicator can be obtained via the improved AHP method proposed. Base on the process of steps 2-7 in section 2.1, the weights of the indicators at all levels can be calculated. The weights of the first-level indicators and weights of secondary indicators for environment, technology and economy, are shown in the Table A5-A8 respectively. The data shown in the tables is the ultima result calculated by using MATLAB.

Additionally, the weights of the criterion at all levels on the overall goal can be obtained based on the above results, which is presented in Table 4.

Table 4 Weights of the criterion at all levels on the overall goal

Criterion	Sub-criterion	Overall weights	Rank
C_1 (0.2583)	S_1 (0.0528)	0.0136	11
	S_2 (0.1715)	0.0443	7
	S_3 (0.4649)	0.1201	3
	S_4 (0.3108)	0.0803	4
C_2 (0.6370)	S_5 (0.1233)	0.0785	5
	S_6 (0.2743	0.1747	2
	S_7 (0.5065)	0.3226	1
	S_8 (0.0327)	0.0208	10
	S_9 (0.0632)	0.0403	8
C_3 (0.1047)	S_{10} (0.2045)	0.0214	9
	S_{11} (0.0955)	0.0100	12
	S_{12} (0.0456)	0.0048	13
	S_{13} (0.6545)	0.0685	6

3.3 Comprehensive evaluation of alternatives for machine tool guideway

After determining the weights of each indicator, the next step is to comprehensively rank the alternatives by using the TOPSIS method. Table 12 shows the scores of all alternatives for the machine tool guideways under each indicator. The scores are the comprehensive values obtained by referring to the relevant documents and scoring by experts. Based on the methods mentioned in section 2.2, the specific steps for evaluating machine tool guideway are as follows:

1) According to Table A9, the characteristic matrix $C = [x_{ij}]$ ($i = 1,2,3...n;\ j = 1,2,3...m$) for alternatives is established as

$$C = \begin{bmatrix} 4 & 6 & 4 & 4 & 8 & 8 & 3 & 2 & 5 & 4 & 5 & 2 & 4 \\ 4 & 5 & 4 & 6 & 9 & 9 & 5 & 2 & 6 & 4 & 5 & 2 & 3 \\ 3 & 6 & 5 & 4 & 8 & 7 & 4 & 4 & 5 & 6 & 4 & 2 & 6 \\ 2 & 7 & 7 & 5 & 4 & 5 & 2 & 5 & 7 & 7 & 6 & 6 & 7 \\ 2 & 4 & 5 & 3 & 4 & 5 & 3 & 4 & 4 & 6 & 6 & 4 & 5 \\ 6 & 4 & 5 & 4 & 7 & 6 & 4 & 2 & 4 & 6 & 6 & 4 & 4 \\ 5 & 5 & 6 & 7 & 8 & 7 & 4 & 3 & 7 & 7 & 5 & 4 & 5 \\ 6 & 4 & 6 & 7 & 6 & 6 & 2 & 3 & 7 & 7 & 5 & 5 & 5 \end{bmatrix}$$

2) In order to make each index comparable, the normalized decision matrix $Z = [z_{ij}]$ calculated according to the Eqs. (5) and (6) is shown in Table A10.

3) Calculate weighted normalization matrix $A = [a_{ij}] = w_j \cdot z_{ij}$, as shown in Table A11. Then, positive-ideal and negative-ideal points can be obtained, which are presented in Table A12.

4) Calculate the connection degree between each alternative and the positive ideal points according to Eqs (9) are:

$$U_a^+ = 0.3846 + 0.3846i + 0.2308j$$

$$U_b^+ = 0.3077 + 0.4615i + 0.2308j$$

$$U_c^+ = 0.2308 + 0.3846i + 0.3846j$$

$$U_d^+ = 0.2308 + 0.0769i + 0.6923j$$

$$U_e^+ = 0.1538 + 0.4615i + 0.3846j$$

$$U_f^+ = 0.5385 + 0.3077i + 0.1538j$$

$$U_g^+ = 0.4615 + 0.4615i + 0.0769j$$

$$U_h^+ = 0.3846 + 0.1538i + 0.4615j$$

5) The connection degree between each alternative and the negative ideal points are:

$$U_a^- = 0.3846 + 0.4615i + 0.1538j$$

$$U_b^- = 0.3077 + 0.4615i + 0.2308j$$

$$U_c^- = 0.2308 + 0.3077i + 0.4615j$$
$$U_d^- = 0.3077 + 0.0000i + 0.6923j$$
$$U_e^- = 0.1538 + 0.5385i + 0.3077j$$
$$U_f^- = 0.5385 + 0.2308i + 0.2308j$$
$$U_g^- = 0.3846 + 0.5385i + 0.0769j$$
$$U_h^- = 0.3846 + 0.2308i + 0.3846j$$

6) The contact vector distance of each alternative from the positive-ideal points d_i^+ and negative-ideal points d_i^-, and the CCI C_i can be calculated by Eqs (10), (11), (12), respectively. The final results are shown in Table 5.

7) Based on the size of the CCI, rank the all alternatives, as shown in Fig. 3.

Based on the above calculation, the best choice is Alternative b, as shown in Fig. 3. According to the final ranking of CCI, the priority of selecting remanufacturing oriented machine tool guideway are shown in follows: Linear Motion Guideway of Double Rectangular > Plastic Guideway > Linear Rolling Guideway > Roller Guideway > Linear Motion Guideway of Ttriangle-Rectangular Combinatio > Spherical Guideway > Injection Molding Guideway > Hydrostatic Guideway. When designing a green/remanufactured machine tool, this can be used as a guide for selecting a guideway.

3.4 Comparison of the obtained results

In this work, both AHP-TOPSIS and AHP-CD (Xuan 2009; Wang 2003) methods were used to compare the results of the proposed method. It should be known that the same criteria/factor weight is applied when using three MCDM methods. The final rank of each alternative from three decision approaches are presented in Table 5. It is worth noting that both C_i and D_i represent the comprehensive closeness index. For AHP-CD method, TL denotes tendency and level of the evaluated schemes, which is a comprehensive evaluation result based on connection degree, S/U/O indicates the Similar/Uniform/Opposite tendency respectively, the number represents the level. Its comparison rules are shown in follows: the similar tendency takes precedence over the uniform tendency, the uniform tendency takes precedence over the opposite tendency, and low level take precedence over high one.

Table 5 Comparison results obtained from three approaches.

Alternative	The proposed method		AHP-TOPSIS method		AHP-CD method	
	C_i	Rank	D_i	Rank	TL	Rank
a	0.5000	5	0.3968	5	S5	3
b	0.5352	1	0.7591	1	S1	1
c	0.5017	3	0.6225	3	S4	2
d	0.4855	8	0.2593	8	O5	8
e	0.5027	4	0.3089	6	U3	5
f	0.4955	6	0.5650	4	U1	4
g	0.5074	2	0.6642	2	O3	7
h	0.4926	7	0.2684	7	O1	6

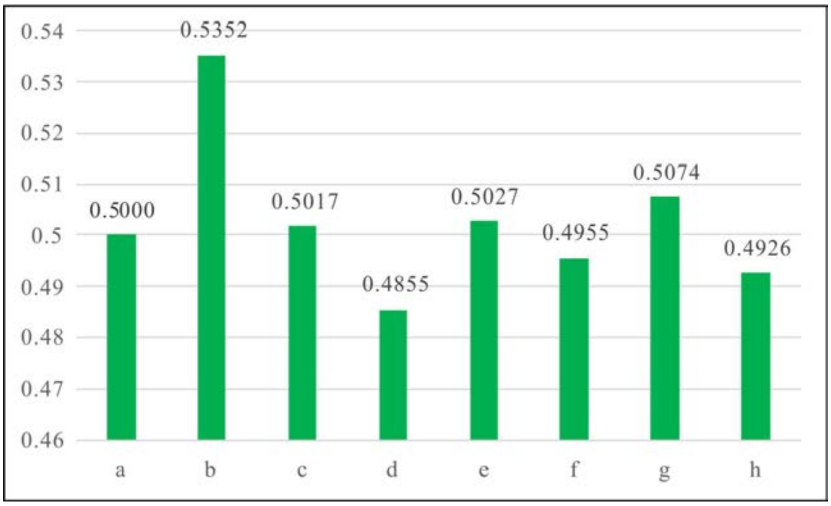

Fig. 3. Ranking the alternatives according to CCI

As can be seen from Table 5, the results of the three decision methods are basically consistent and close. This shows that the proposed hybrid MCDM method combined with the improved AHP method and CD-TOPSIS method is a reasonable and feasible to select optimal remanufacturing oriented machine tool guideway. According to the results, Linear Motion Guideway of Double Rectangular is an optimal machine tool guide considering remanufactured characteristics as a hierarchical structure, and Hydrostatic Guideway is most not optimistic. In addition, the rank obtained by the proposed CD-TOPSIS method are highly consistent with the results obtained by AHP-TOPSIS method, only the positions of *Alternative e* and *Alternative f* are exchanged with each other. There are some differences in the results obtained by the AHP-CD method. The main reasons for these differences are as follows: 1) different information aggregation methods have different degrees of information utilization, and it is easy to lose a great deal of information during the aggregation process; 2) the theoretical basis of the general TOPSIS method is the distance of the positive/negative ideal solution, the results of sorting alternatives according to the relative Euclidean distance sometimes do not fully reflect the advantages and disadvantages of each solution; 3) similarly, the CD method can not make full use of the existing information. From Table 5, some finding can be summarized that the distribution of CCI obtained by proposed method is concentrated and has relative discrimination, while the range of CCI of AHP-TOPSIS method fluctuates greatly, and the result of AHP-CD method can not be quantified well. In short, CD-TOPSIS overcomes the one-sidedness of AHP-TOPSIS and AHP-CD; and makes the evaluation results more objective and more realistic. Therefore, the CD-TOPSIS method is feasible and effective to evaluate the the performance of machine tool guideway.

3.5. Sensitivity analysis

A sensitivity analysis is conducted to monitor the robustness of alternative ranking to changes. Sixteen experiments are conducted to investigate the impact of criterion weights for the ultimate results (denoted by ω_{Si} for criterion Si where i = 1, 2, …, n). Table 6 presents the detail of the experiment at result. Fig. 4 presents the results of sensitivity analysis for the sixteen experiments, and note that comprehensive closeness index Ci scores can be seen in Table 6.

As can be seen from Table 6 and Fig. 4, that out of 16 experiments, *alternative b* (Linear Motion Guideway of Double Rectangular) has the highest score in 12/16 experiments. So it can be said that based on the obtained evaluation, the proposed decision process is relatively robust to the criterion weights. The results showed that the proposed method was feasible, effective and robust. In addition, the results of sensitivity analysis in different cases show that the optimal alternative may change when different weights are assigned to the evaluation criteria. This finding means that establishing a qualified group of experts and determining weights of the criteria reasonably are important for selecting the optimal remanufacturable components.

Table 6 Experiments for sensitivity analysis.

Exp. No.	Weights	Comprehensive Closeness Index C_i							
		a	b	c	d	e	f	g	h
1	$\omega_{S1}=0.7$, $\omega_{S2-S13}=0.025$	0.4444	**0.5455**	0.4286	0.4500	0.4737	0.3889	0.4167	0.2857
2	$\omega_{S2}=0.7$, $\omega_{S1,\ S3-S13}=0.025$	0.4545	0.4667	0.4167	0.4118	0.5385	0.5833	0.2857	0.4375
3	$\omega_{S3}=0.7$, $\omega_{S1-S2,\ S4-S13}=0.025$	0.4375	**0.6250**	0.5294	0.5000	0.4375	0.5714	0.4615	0.4118
4	$\omega_{S4}=0.7$, $\omega_{S1-S3,\ S5-S13}=0.025$	0.3750	**0.5789**	0.4545	0.4926	0.4762	0.5238	0.5200	0.5455
5	$\omega_{S5}=0.7$, $\omega_{S1-S4,\ S6-S13}=0.025$	0.4286	0.4615	0.2941	0.5217	0.5500	0.5000	0.4286	0.5217
6	$\omega_{S6}=0.7$, $\omega_{S1-S5,\ S7-S13}=0.025$	0.5294	**0.7059**	0.5882	0.3889	0.4286	0.6250	0.5714	0.4286
7	$\omega_{S7}=0.7$, $\omega_{S1-S6,\ S8-S13}=0.025$	0.4118	**0.5714**	0.5385	0.3529	0.4211	0.5500	0.5417	0.3636
8	$\omega_{S8}=0.7$, $\omega_{S1-S7,\ S9-S13}=0.025$	0.6842	**0.7273**	0.5714	0.5263	0.6667	0.2308	0.4500	0.6000
9	$\omega_{S9}=0.7$, $\omega_{S1-S8,\ S10-S13}=0.025$	0.4762	0.5238	0.6000	0.3636	0.5455	0.2857	0.5263	0.4706
10	$\omega_{S10}=0.7$, $\omega_{S1-S9,\ S11-S13}=0.025$	0.5217	**0.5882**	0.3750	0.4615	0.5455	0.2778	0.4118	0.4667
11	$\omega_{S11}=0.7$, $\omega_{S1-S10,\ S12-S13}=0.025$	0.4211	**0.6316**	0.3571	0.4286	0.4375	0.5909	0.5333	0.5294
12	$\omega_{S12}=0.7$, $\omega_{S1-S11,\ S13}=0.025$	0.4444	**0.6471**	0.5625	0.2778	0.4615	0.5417	0.5833	0.5238
13	$\omega_{S13}=0.7$, $\omega_{S1-S12}=0.025$	0.4706	0.5455	0.5263	0.4286	0.3889	0.6429	0.5714	0.2857
14	$\omega_{S1-S13}=0.025$	0.4615	**0.6429**	0.6316	0.6111	0.4375	0.4545	0.4783	0.4286
15	$\omega_{S1-S8}=0.125$, $\omega_{S9-S13}=0$	0.2308	**0.5352**	0.2308	0.2308	0.2308	0.2308	0.2308	0.2308
16	$\omega_{S1-S8}=0$, $\omega_{S9-S13}=0.25$	0.4286	**0.5714**	0.3077	0.4211	0.5385	0.4737	0.4375	0.4667

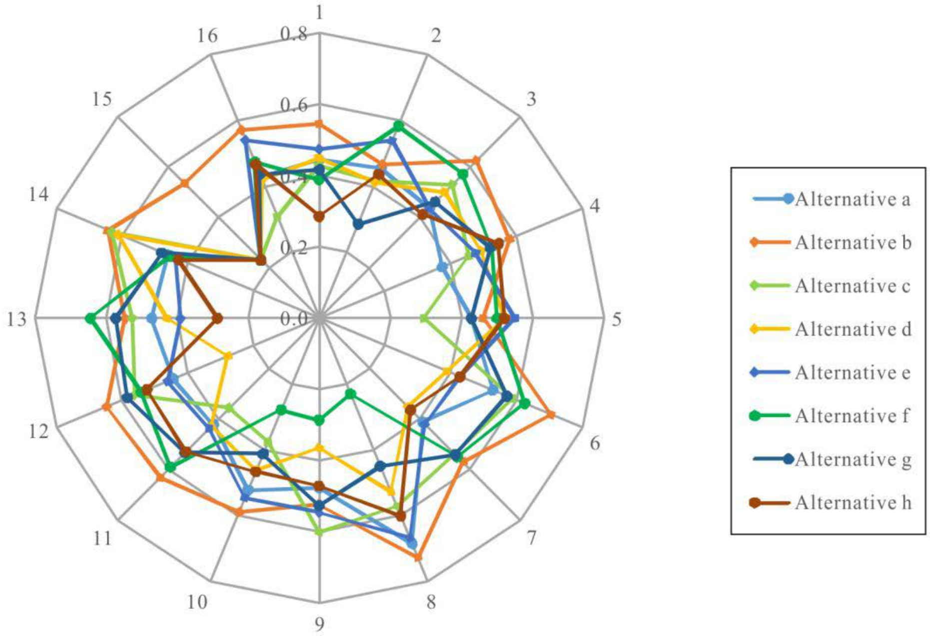

Fig. 4. The results of sensitivity analysis.

4. Conclusions

The selection of components and parts with good remanufacturability is critical to product development for remanufacturing. In terms of index construction, weight calculation or ranking, it is impossible to solve this complex decision problem with one method. Therefore, this paper proposes a hierarchical structure with the characteristics of environment, technology and economy. An integrated MCDM method is presented, which combines the improved AHP with the CD-TOPSIS method, they completed the task of calculating weights and ranking respectively, and finally evaluated the alternatives comprehensively. An empirical application of eight kinds of guideways was illustrated. Also, sensitivity analysis was carried out to judge the robustness of the proposed method. Compared with the results of the existing methods (i.e., AHP-TOPSIS and AHP-CD), the results show that the method is feasible and effective for product evaluation. The results can be used to provide the optimal scheme for decision makers to select remanufactured machine tool guideway.

The main contribution of this work is to identify and develop an effective evaluation framework to guide designers in evaluating product options. To the best of our knowledge, this study is the first time on devising a integrated MCDM method combing with improved AHP, TOPSIS and CD is used to solve the problem of parts selection for remanufacturing in product development. The research results show that the method overcomes the shortcomings of conventional AHP and TOPSIS, and makes the evaluation result more objective and more realistic. In addition， this study provides a more accurate, effective and systematic decision support tool for product development, which will be beneficial to to evaluate complex products in future. In the same way, it is propitious to better understand remanufacturing design issues for researchers and provide a reference for developing a better remanufacturability evaluation systems. However, this research also has some defects. For instance, it has a strong subjectivity when using the AHP to determine the weights and it depends on the expert score when constructing the evaluation matrix. These problems will be solved in further studies.

Future research will focus on three aspects: 1) develop a more comprehensive hierarchical structure of product selection for remanufacturing considering other key factors such as environment, technology, and economy; 2) construct reasonable judgment matrix by applying big data technology to analyze existing data, which reduces the dependence on scoring evaluation; 3) since the information of experts in the decision matrix is uncertain and ambiguous, the uncertainty theory will be integrated into the MCDM method to fill this gap.

Acknowledgements

The work described in this paper was supported by the National Natural Science Foundation of China (51675388, 51605347). These financial contributions are gratefully acknowledged.

Appendix

See Tables A1–A12.

Table A1 Comparison matrix from the viewpoint of remanufacturing-oriented evaluation (G-C)

G	C_1	C_2	C_3
C_1	1	0	2
C_2	2	1	2
C_3	0	0	1

Table A2 The comparison matrix from environmental characteristic perspective (C1-S)

C_1	S_1	S_2	S_3	S_4
S_1	1	0	0	0
S_2	2	1	1	0
S_3	2	1	1	2
S_4	2	2	0	1

Table A3 The comparison matrix from technical characteristic of view (C2-S)

C_2	S_5	S_6	S_7	S_8	S_9
S_5	1	0	0	2	2
S_6	2	1	0	2	2
S_7	2	2	1	2	2
S_8	0	0	0	1	0
S_9	0	0	0	2	1

Table A4 The comparison matrix from economic characteristic perspective (C3-S)

C_3	S_{10}	S_{11}	S_{12}	S_{13}
S_{10}	1	2	2	0
S_{11}	0	1	2	0
S_{12}	0	0	1	0
S_{13}	2	2	2	1

Table A5 The criterions weight from the viewpoint of remanufacturing-oriented evaluation(G-C)

Criterions	Weight	Rank
Environmental characteristics (C_1)	0.2583	2
Technical characteristics (C_2)	0.6370	1
Economic characteristics (C_3)	0.1047	3

Table A6 The weight of secondary indicators for environment (C1-S)

Indicators	Weight	Rank
S_1	0.0528	4
S_2	0.1715	3
S_3	0.4649	1
S_4	0.3108	2

Table A7 The weight of secondary indicators for technology (C2-S)

Indicators	Weight	Rank
S_5	0.1233	3
S_6	0.2743	2
S_7	0.5065	1
S_8	0.0327	5
S_9	0.0632	4

Table A8 The weight of secondary indicators for economy (C3-S)

Indicators	Weight	Rank
S_{10}	0.2045	2
S_{11}	0.0955	3
S_{12}	0.0456	4
S_{13}	0.6545	1

Table A9 Scores of all alternatives on each indicator

Alternative	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}
a	4	6	4	4	8	8	3	2	5	4	5	2	4
b	4	5	4	6	9	9	5	2	6	4	5	2	3
c	3	6	5	4	8	7	4	4	5	6	4	2	6
d	2	7	7	5	4	5	2	5	7	7	6	6	7
e	2	4	5	3	4	5	3	4	4	6	6	4	5
f	6	4	5	4	7	6	4	2	4	6	6	4	4
g	5	5	6	7	8	7	4	3	7	7	5	4	5
h	6	4	6	7	6	6	2	3	7	7	5	5	5

Table A10 Normalized decision matrix Z

Alternative	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}
a	0.67	0.67	1.00	0.57	0.89	0.89	0.60	1.00	0.71	1.00	0.80	1.00	0.75
b	0.67	0.80	1.00	0.86	1.00	1.00	1.00	1.00	0.86	1.00	0.80	1.00	1.00
c	0.50	0.67	0.80	0.57	0.89	0.78	0.80	0.50	0.71	0.67	1.00	1.00	0.50
d	0.33	0.57	0.57	0.71	0.44	0.56	0.40	0.40	1.00	0.57	0.67	0.33	0.43
e	0.33	1.00	0.80	0.43	0.44	0.56	0.60	0.50	0.57	0.67	0.67	0.50	0.60
f	1.00	1.00	0.80	0.57	0.78	0.67	0.80	1.00	0.57	0.67	0.67	0.50	0.75
g	0.83	0.80	0.67	1.00	0.89	0.78	0.80	0.67	1.00	0.57	0.80	0.50	0.60
h	1.00	1.00	0.67	1.00	0.67	0.67	0.40	0.67	1.00	0.57	0.80	0.40	0.60

Table A11 Weighted normalization matrix A

	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}
a	0.009	0.030	0.120	0.046	0.070	0.155	0.194	0.021	0.029	0.021	0.008	0.005	0.051
b	0.009	0.035	0.120	0.069	0.079	0.175	0.323	0.021	0.035	0.021	0.008	0.005	0.069
c	0.007	0.030	0.096	0.046	0.070	0.136	0.258	0.010	0.029	0.014	0.010	0.005	0.034
d	0.005	0.025	0.069	0.057	0.035	0.097	0.129	0.008	0.040	0.012	0.007	0.002	0.029
e	0.005	0.044	0.096	0.034	0.035	0.097	0.194	0.010	0.023	0.014	0.007	0.002	0.041
f	0.014	0.044	0.096	0.046	0.061	0.116	0.258	0.021	0.023	0.014	0.007	0.002	0.051
g	0.011	0.035	0.080	0.080	0.070	0.136	0.258	0.014	0.040	0.012	0.008	0.002	0.041
h	0.014	0.044	0.080	0.080	0.052	0.116	0.129	0.014	0.040	0.012	0.008	0.002	0.041

Table A12 The positive-ideal and negative-ideal points

	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}
A^+	0.014	0.025	0.069	0.080	0.079	0.175	0.323	0.008	0.040	0.012	0.007	0.002	0.029
A^-	0.005	0.044	0.120	0.034	0.035	0.097	0.129	0.021	0.023	0.021	0.010	0.005	0.069

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