HYBRID UTILITY FUNCTION AND ENTROPY WEIGHTS MODEL FOR REMANUFACTURABILITY EVALUATION OF USED PARTS

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Remanufacturability of used parts is essential to determine whether and how the parts can be remanufactured, and it could be seen as a core precondition of remanufacturing. However, the current reliance on expert opinion for quantification and weight determination for each evaluation criterion makes the remanufacturability evaluation process complex and often unpractical. To fill this gap, a hybrid evaluation model is established to assess the remanufacturability of the used part. In this model, a remanufacturability evaluation criterion system is established by analyzing the factors which affect the remanufacturability of a used part. These factors can be classified into economic, technical, and environmental aspects, which can be condensed into eight specific criteria. Then, utility function is adopted to quantify each criterion by analyzing the relationship between the criterion and calculation parameters. On this basis, the entropy weight method is utilized to determine the weight of each criterion by information entropy of data. Finally, a used engine blade case is introduced to verify the feasibility and practicality of the proposed method. The result shows that the proposed model is feasible for the remanufacturability evaluation for a used part.

Key Words: *remanufacturability evaluation, utility function, entropy weights, used parts*

1. INTRODUCTION

Remanufacturability evaluation, a precondition to determine whether the used part can be remanufactured, has been considered as an important step in remanufacturing[1]. Within the parameters of remanufacturing, how one chooses the evaluation indicators and establishes a criteria system has became an important area in the remanufacturability evaluation of used parts.

There have been prior studies about the evaluation factors which influence the remanufacturability of used part. Fang et al. proposed an evaluation model of products, in which the remanufacturability was assessed by numerical metrics based on CAD information including disassembly accessibility, product complexity, and recoverability[2]. Shu san obtained the evaluation conclusion of used mobile phone by DEMATEL approach, and pointed out the innovation-rate and obsolescence were the main factors which have an impact on remanufacturability[3]. Karaulova et al. assessed the remanufacturability of used industrial equipment by LCA method, and the remanufacturability was divided into three aspects including technological aspects, economic aspects and ecological aspects[4]. In addition to establishing a comprehensive evaluation criterion system, how one quantifies and weights each criterion are also important tools to obtain a credible evaluation result. Omwando et al. presented a bi-level fuzzy method which combined qualitative and quantitative attributes of products to determine the remanufacturability of products[5]. Du et al. proposed an integrated method to evaluate the remanufacturability of used machine tool where the criteria were quantified by grading mathematical formula and weight of each criterion was calculated by AHP method[6]. Shi et al. proposed a three-dimensional method for remanufacturability for used engines, which adopted an life-cycle assessment (LCA) method to assess the environmental feasibility and AHP method to determine the weight of each criterion[7]. Otieno et al. applied fuzzy TOPSIS methodology to evaluate the remanufacturability of office furniture which clarified the evaluation criterion into three aspects including economic, social and environmental feasibility[8]. Zhang et al. adopted a fuzzy-EAHP method to quantify each evaluation criterion which was calculated by expert evaluation and a fuzzy comprehensive evaluation method[9].

The aforementioned studies provided valuable guidelines for the accurate remanufacturability evaluation of used parts. However, the quantification method and weight of each criterion are always determined by the evaluator's preference or expert' experience in most studies, which in turn affects the accuracy of the evaluation value and weight of each criterion. To this end, a hybrid remanufacturability evaluation model for used parts is proposed, which integrates utility function with entropy weight to obtain the quantification value and weight of each evaluation criterion in order to make the remanufacturability evaluation result more reasonable.

2. HYBRID REMANUFACTURABILITY EVALUATION MODEL FOR USED PARTS

In this section, a hybrid evaluation model that combines utility function with entropy weight is introduced for remanufacturability evaluation of used parts, as shown in Fig.1.

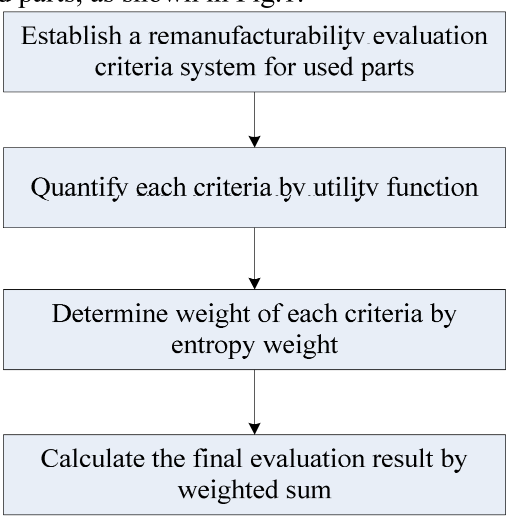

Fig. 1The remanufacturability evaluation process of used parts

After establishment of comprehensive remanufacturability evaluation criteria system for used part, the utility function is used to quantify each evaluation criteria. Then the entropy weight is adopted to calculate the weight of each evaluation criterion. Finally, the remanufacturability evaluation result can be obtained in a systematic way. The remanufacturability evaluation process in this paper will be illustrated step by step in the following.

(1) Establishment of remanufacturability evaluation criteria system

The remanufacturability evaluation refers to evaluating the feasibility of the used part to meet the remanufacturing requirements. In order to evaluate the remanufacturability of used part comprehensively and objectively, 28 papers mentioned in reference[10] are studied which are relate to remanufacturability evaluation and conclude a remanufacturability evaluation criteria system of used part in this paper, as shown in Figure 2.

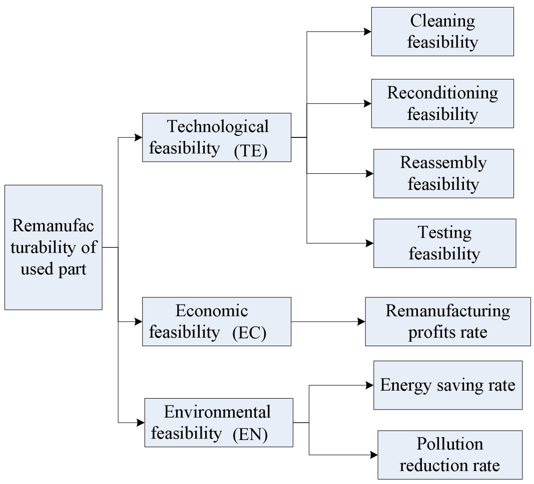

Fig.2 The remanufacturability evaluation criteria system of used part

a) Analysis of technological feasibility

Technological feasibility means it's capable for used part to be restored to like-new or upgraded conditions with the current capability and facility of the remanufacturing enterprises[11]. In order to comprehensively assess the technological feasibility of used part, the technological feasibility in this paper is divided based on the process of remanufacturing of used part. Firstly, technological feasibility on the preparation for remanufacturing process stage includes cleaning feasibility, noted as α_1; secondly, technological feasibility on the reconditioning stage, noted as α_2 ; then, technological feasibility on the end stage includes assembly and testing feasibility, noted as $\alpha_3 \sim \alpha_4$. There are many methods to represents technological feasibility like precision, reliability or processing efficiency, here, technological feasibility is represented by consumed time in each procedure in this paper as consumed time can comprehensively reflect technical difficulty and remanufacturing repair difficulty of each procedure like shot blast cleaning. The relation between technological feasibility and consumed time in four procedures can be expressed as function relation, as Equation (1).

$$TE(\alpha_1, \alpha_2, \alpha_3, \alpha_4) = (f_1 \sim f_4) \quad (1)$$

b) Analysis of economic feasibility

Economic feasibility means how much economic benefits the remanufacturing enterprises can get from remanufacturing a used part compared with manufacturing a new one. According to previous studies[12], the cost of remanufacturing of used part are usually less than 40% of that for manufacturing of new products and therefore remanufacturing enterprises are willing to take remanufacturing activity on this kind of used part. The economic feasibility of a used part is expressed as remanufacturing profits rate in this paper which calculated by cost in remanufacturing and manufacturing, noted as α_5 , because profits rate can practically reflect the economic benefits released by remanufacturing activities of used part. The relation between economic feasibility and cost in remanufacturing and manufacturing can be expressed as function relation, as in Equation (2).

$$EC(\alpha_5) = f_5 \quad (2)$$

c) Analysis of environmental feasibility

Environmental feasibility means the impact of remanufacturing process of used part is less than minimum threshold of green remanufacturing. According to the previous study[13], the energy consumption of the remanufacturing of used parts can be reduced by 60% and the pollution can be reduced by 80% compared to the manufacturing of the new ones. Environmental feasibility is divided into two aspects this paper: energy saving rate and pollution reduction rate, noted as α_6 and α_7 . However, calculating the energy saving rate in the remanufacturing of used parts is difficult due to variations in energy resource such as fuel burning or electricity, therefore electric energy consumption is adopted as the basis for calculation and other kinds of energy consumption are converted into electric energy consumption. As for pollution reduction rate, in order to simplify the calculating process, this criterion can be assessed by CO_2 emission because it is the main polluting gases in the remanufacturing process of used parts and can be converted easily to measure other polluting gases. The relationship between environmental feasibility, electricity saving rate and CO_2 reduction rate can be expressed as function relation, as Equation (3)

$$EN(\alpha_6, \alpha_7) = (f_6, f_7) \quad (3)$$

(2) Hybrid remanufacturability quantification method of used part

a) Utility function method

For a comprehensive evaluation of the multiple criteria problem, a very concise evaluation method is to quantify each evaluation criteria according to a certain method and then it becomes a "quantified value" for the evaluation problem, i.e., the utility function value. Later, the total evaluation value is obtained by weighted sum according to a certain synthetic method, as in Equation (4). Therefore, under the situation that the comprehensive evaluation criteria system has been established as in section 2.1, the key component of the utility function method is the determination of the individual evaluation value (as called the utility function f_i), determination of the weight w_i and selection of the synthetic way ξ .

$$F = \xi(f_i(x_i), w_i), i = 1, 2 \dots n \quad (4)$$

Where, n represents the total numbers of evaluation criterion. In this paper, $n = 7$.

Usually, the relationship between x_i and $f_i(x_i)$ can be compared to the input and output of the system, and utility function f_i means a change in the value of x_i will cause a change in $f_i(x_i)$. Using the economic feasibility term in this paper as an example, x_1 represents how much cost can be saved by comparing remanufacturing a used part with manufacturing a new one where $f_1(x_1)$ represents remanufacturing profits rate. In previous studies, f_1 is usually described by a linear relationship, as Figure 3, however, as there is marginal benefit, the output will reach climax as input grows in a economic system and there is a point where output will grow rapidly, as x_M in Figure 4. So, the practical relationship between x_1 and $f_1(x_1)$ is not linear but shaped as “s”. Here, the utility function in economic feasibility f_1 is set as Equation (5) as suggested in a previous study[14].

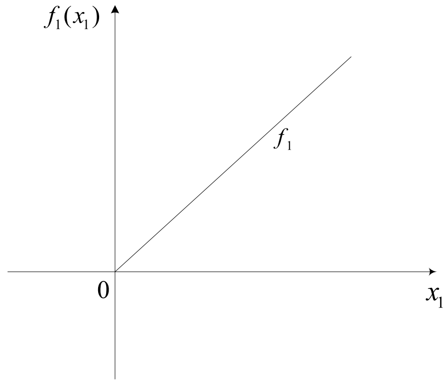

Fig. 3 The linear way between x_i and $f_i(x_i)$ from previous study

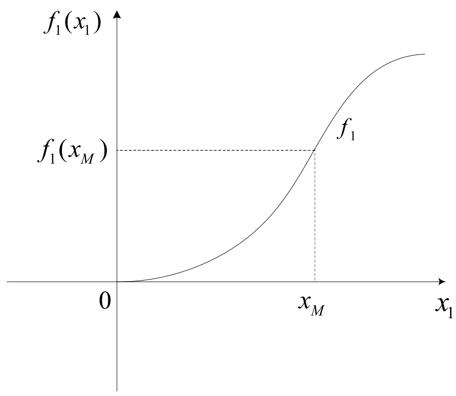

Fig.4 The non-linear way between x_i and $f_i(x_i)$ with marginal benefit

$$f_5 = \left(e^{-1} - e^{-e^{\frac{c_1 - c_{\min}}{c_{\max} - c_{\min}}}}\right) \Big/ \left(e^{-1} - e^{-e}\right) \quad (5)$$

Where, c_1 means how much cost can be saved by comparing remanufacturing the used part compared with manufacturing a new one which can be calculated by Equation (6). $c_{\max}$ and $c_{\min}$ are the maximum and minimum of c_1 in collected cases.

$$c_1 = \frac{EcN - EcR}{EcN} \quad (6)$$

Where, ECR means the cost of remanufacturing of the used part and ECN means the cost of manufacturing the same new part.

As for criteria that can be divided into multiple secondary criteria like technological feasibility and environmental feasibility in this paper, logarithmic function is suggested as the tool since it can reflect the impact of the criteria changes on system evaluation so it's selected as the relationship between technological feasibility and consumed time. Also, it's the relationship between how much energy can be saved or how much pollution can be reduced in remanufacturing of used part compared with manufacturing a new one and environmental feasibility. The quantification method of technological feasibility and environmental feasibility can be expressed as Equation (7) and Equation (8).

$$TE(\alpha_1, \alpha_2, \alpha_3, \alpha_4) = \frac{\ln t_{i\max} - \ln t_i}{\ln t_{i\max} - \ln_{i\min}} \quad (7)$$

$$EN(\alpha_6, \alpha_7) = \frac{\ln en_i - \ln en_{i\min}}{\ln en_{i\max} - \ln en_{i\min}} \quad (8)$$

$$en_i = \frac{EnN_i - EnR_i}{EnN_i} \quad (9)$$

Where, t_i means the consumed time of i-th procedure in remanufacturing of used part, and $t_{i\max}$ and $t_{i\max}$ are the maximum and minimum of t_i in collected cases. EnR_i and EnN_i mean the energy consumption or pollution emission in remanufacturing process of a used part and manufacturing a new one. So, en_i means how much energy can be saved and pollution can be reduced compared remanufacturing a used part and manufacturing a new one. $en_{i\max}$ and $en_{i\min}$ are the maximum and minimum of en_i in collected cases.

After getting the individual evaluation value and weight of each criterion, the final evaluation result can be obtained from a synthetic way. The arithmetic mean composite way is selected as the synthetic way in this paper as it has the greatest average sensitivity to weights, which means the remanufacturability evaluation result is sensitive to the change of the weight determined by entropy weight.

$$F = \sum_{i=1}^{7} (\alpha_i \times w_i) \quad (10)$$

In order to illustrate the remanufacturability evaluation result, this paper gives a benchmark whose value is 60% of each interval length, which means that the benchmark for remanufacturability is exactly suitable for remanufacturing. When remanufacturability evaluation result of a used part is less than the benchmark, it's not suitable for remanufacturing but should be recycled into its component materials; otherwise, the used part is considered to have satisfied remanufacturability and it is deemed suitable to be remanufactured.

b) Entropy weight method

The calculation procedure of weighting by entropy weight method can be concluded as following steps:

Step 1: Establish an evaluation matrix between cases and criteria, as V. In this matrix, m is the number of criteria and n is the number of cases of same used part, where v_{ij} means the j-th case in the i-th evaluation criteria value.

$$V = (v_{ij})_{m\times n} = \begin{bmatrix} v_{11} & v_{12} & \cdots & v_{1n} \\ v_{21} & v_{22} & \cdots & v_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ v_{m1} & v_{m2} & v_{m3} & v_{mn} \end{bmatrix} \quad (11)$$

Step 2: Standardize the evaluation criteria. The criteria of the above-mentioned original data matrix V are divided into two categories: one is a positive criterion which means better with a larger value of criteria (such as α_5, α_6 and α_7 in this paper); the other is a negative indicator which means better with a smaller value of criteria (such as $\alpha_1 \sim \alpha_4$). For positive criteria, the standardized way is represented as Equation (12). For negative criteria, the standardized way is represented as Equation (13). After standardization, the standardized matrix $R = (r_{ij})_{m\times n}$ can be obtained.

$$R_{ij} = \frac{v_{ij} - v_i(\min)}{v_i(\max) - v_i(\min)} \quad (12)$$

$$R_{ij} = \frac{v_i(\max) - v_{ij}}{v_i(\max) - v_i(\min)} \quad (13)$$

$$v_i(\min) = \min_{1\le j\le n} v_{ij},\ v_i(\max) = \max_{1\le j\le n} v_{ij}$$

Step 3: Calculate the proportion of the j-th case in the i-th evaluation criteria value, noted as p_{ij}.

$$p_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}} \quad (14)$$

Step 3: Calculate the information entropy of the i-th criteria, noted as E_i.

$$E_i = -\frac{1}{\ln n}\sum_{j=1}^{n} p_{ij} \ln p_{ij} \quad (15)$$

Where, if $p_{ij} = 0$, then $p_{ij} \ln p_{ij} = 0$

Step 4: Calculate the entropy weight of the i-th criteria, noted as w_i.

$$w_i = \frac{1 - E_i}{m - \sum_{i=1}^{m} E_i} \quad (16)$$

3. CASE STUDY

In order to verify the feasibility and practicality of the above model, an engine blades case is presented as follow to validate it[15-20]. Three used blades called M, N, P are selected randomly to verify the above model. The fundamental information about theses blades are shown in Table 1. According to the defective characteristics of M, N, P, an initial remanufacturing process route can be chosen; thereby the remanufacturing data related to the remanufacturability evaluation criteria system of M, N, and P can be obtained or calculated, as shown in Table 2.

Table 1 The fundamental information of M, N and P

	M	N	P
Material	GGG40	GH4220	GH4049
Structure	Micro-arc	Micro-arc	Micro-arc
Failure type	Worn, Crack, Deformatio n	Corrosion, Erosion	Crack, Fracture, Corrosion
Failure degree	Severe	Medium	Severe

Table 2 Remanufacturing data of M, N and P

	M	N	P
Cleaning time (days)	1	0.9	0.9
Reconditioning time (days)	4.7	3.8	4.6
Reassembly time (days)	1.5	0.152	1.46
Testing time (days)	0.02	0.022	0.029
Remanufacturing cost reduction (%)	61.4	68.3	65
Remanufacturing energy reduction (%)	83.5	84.4	82.6
Remanufacturing pollution reduction (%)	38.4	43.5	35.3

(1) Remanufacturability evaluation result of M, N and P

According to historic data collection and literature review about the remanufacturing process of used blades, the maximum and minimum of the remanufacturability data of used engine in Table 1 can be obtained, as shown in Table 3.

According to Equation (5) ~ (9), the economic feasibility, technological feasibility and environmental feasibility of the three samples can be calculated into individual evaluation value by utility function, as shown in Table 4.

Table 3 The minimum and maximum of the remanufacturing data in Table 1

Criterion	Notation	[minimum, maximum]
Cleaning feasibility (days)	α_1	[0.9,1.3]
Reconditioning feasibility (days)	α_2	[3.5,5]
Reassembly feasibility (days)	α_3	[1.4,1.8]
Testing feasibility (days)	α_4	[0.01,0.04]
Remanufacturing cost reduction (%)	α_5	[58,70]
Remanufacturing energy reduction (%)	α_6	[80,90]
Remanufacturing pollution reduction (%)	α_7	[35,60]

Table 4 Remanufacturing feasibility of each criterion of M, N and P

Criterion	Notation	M	N	P
Cleaning feasibility	α_1	0.714	1	1
Reconditioning feasibility	α_2	0.173	0.770	0.234
Reassembly feasibility	α_3	0.725	0.673	0.833
Testing feasibility	α_4	0.5	0.431	0.232
Remanufacturing profits	α_5	0.340	0.906	0.667
Energy saving rate	α_6	0.364	0.455	0.272
Pollution reduction rate	α_7	0.172	0.403	0.011

After obtaining the individual remanufacturability evaluation value of each criterion of M, N and P, the next step is to determine weight of each criterion of M, N and P. According to Equation (11), the evaluation matrix V and R between evaluation criteria and cases of M, N, and P is presented as follow. According to Equation (12) ~ (16), the entropy information redundancy (IR) and weight of each criterion (W) can be calculated as shown in Table 5.

$$V=(v_{ij})_{7\times 3}=\begin{bmatrix} 1 & 1.2 & 0.9 \\ 4.7 & 4.3 & 4.6 \\ 1.5 & 1.52 & 1.46 \\ 0.02 & 0.03 & 0.029 \\ 61.4 & 68.3 & 65 \\ 83.5 & 83.1 & 82.6 \\ 38.4 & 40.5 & 35.3 \end{bmatrix}$$

$$R=(r_{ij})_{7\times 3}=\begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 0.11 \\ 0.33 & 0.33 & 1 \\ 1 & 0.78 & 0 \\ 0 & 1 & 0.52 \\ 0.5 & 1 & 0 \\ 0.38 & 1 & 0 \end{bmatrix}$$

Table 5 Entropy information redundancy and weight of each criterion

	α_1	α_2	α_3	α_4	α_5	α_6	α_7
IR	0.631	0	0.865	0.624	0.585	0.579	0.535
W	0.116	0.314	0.0424	0.118	0.130	0.132	0.1476

The remanufacturability evaluation result of M, N and P can be calculated by Equation (10). Here, the technological feasibility, economic feasibility and environmental feasibility of the benchmark in this paper is calculated and shown in Table 6. The remanufacturability evaluation result of M, N, P and benchmark is shown in Table 7.

Table 6 Remanufacturing feasibility of each criterion of the benchmark

	α_1	α_2	α_3	α_4	α_5	α_6	α_7
Individual evaluation value	0.357	0.358	0.370	0.257	0.683	0.614	0.662

Table 7 Remanufacturability evaluation result of M, N, P and benchmark

	M	N	P	Benchmark
F	0.467	0.674	0.376	0.467

(2) Result discussion

The remanufacturability evaluation result of used engine blades called M, N and P are 0.467, 0.674 and 0.376. Compared with the benchmark, that is 0.467, the remanufacturability of case N is satisfied while the remanufacturability of case M and P are not acceptable for remanufacturing. The information from the remanufacturing enterprise about these engine blades have proved that the blade called N can remain at good performance after remanufacturing for about one year, which also indicates that the remanufacturability evaluation model in this paper is effective and feasible for used blades.

After analysing the relationship between the individual evaluation values of criteria, weight of criteria and finally the evaluation result of M, N, and P, it's concluded that the reason why case N is satisfied for remanufacturing is that the economic feasibility (0.906) and reconditioning feasibility (0.770) are much higher than other two samples, besides, the weight of these two evaluation criteria is dominant as they accounted for more than 45%. The reason why case M is not suitable for remanufacturing may be its low economic feasibility (0.340) and low reconditioning feasibility (0.173), while the reason why case P is not suitable could be low reconditioning feasibility (0.234).

From an overall viewpoint, the environmental feasibility of these three cases (less than 0.5) is less than benchmark (more than 0.6), which means that remanufacturing these three engine blades would not bring benefits in energy saving or pollution reduction from remanufacturing. The reason why environmental feasibility of these three engine blades is low may attribute to reconditioning feasibility as the fact that the current remanufacturing technology takes much time to fix the defects like wear and deformation on these three engine blades, so, the energy consumption and pollution emission in remanufacturing process is higher than benchmark.

4. CONCLUSION

A hybrid remanufacturability evaluation model for used parts is proposed in this paper, which could make the quantification and weight determination of each evaluation criterion more accurate and the remanufacturability evaluation result more reasonable. There are two contributions that this work has made: (1) a remanufacturability evaluation criteria system is established for used parts which comprehensively takes technological feasibility, economic feasibility, and environmental feasibility into consideration. (2) A hybrid quantification method of remanufacturability assessment of used parts combined with utility function and entropy weight is introduced.

Further development can be made in the future study focus in the following two aspects: (1) Consider factors such as costumer's requests which limit the data interval of the remanufacturability evaluation criteria of the used part to make the remanufacturability evaluation criteria system more practical. (2) Construct the utility function to be more reasonable by applying least squares method for data simulation to make the quantification of each evaluation criterion more accurate.

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