Quantitative Evaluation of Heavy Duty Machine Tools Remanufacturing Based on Modified Catastrophe Progression Method

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Abstract: The result of remanufacturing evaluation is the basis for judging whether the heavy duty machine tool can remanufacture in the EOL stage of the machine tool lifecycle management. The objectivity and accuracy of evaluation is the key to the evaluation method. In this paper, the catastrophe progression method is introduced into the quantitative evaluation of heavy duty machine tools' remanufacturing, and the results are modified by the comprehensive adjustment method, which makes the evaluation results accord with the standard of human conventional thinking. Using the catastrophe progression method to establish the heavy duty machine tools' quantitative evaluation model, to evaluate the retired TK6916 type CNC floor milling-boring machine’s remanufacturing. The evaluation process is simple, high quantification, the result is objective.

1. Introduction

Heavy duty machine tools are products that consume a great deal of resources, such as: DL250 heavy horizontal lathe, only its machine tool bed used dozens of tons of gray cast iron [1]. The electrical components of heavy duty machine tools are updated speed, easy aging, but the iron castings which accounts for 60%~70% of the total weight of the machine tools is different [2,3]. Though remanufacturing, a great deal of casting and processing costs can be saved. Machine tool manufacturing enterprises can make the business from manufacture, sale and service to the EOL stage of the product life cycle management. Remanufacturing of heavy scrap machine tools save lots of resources and energy, reduce the environmental burden caused by the production of new machine tools [4].

Remanufacturability is the premise to evaluate whether the product can be remanufactured. Ghazall and Murat proposed an optimal decision model for the remanufacturing scheme of waste components and parts [5]. Some researchers from the residual life prediction of waste machine tool parts and the fatigue life [6]. Remanufacturing evaluation is a systematic evaluation process, a scientific quantitative research work. Commonly used evaluation methods are analytic hierarchy process (AHP), grey relational grade method, etc. AHP is widely used because of its simplicity, systematicness, practicability. However, AHP needs to give weight to the evaluation index, the quantitative data is few and the qualitative component is more. In this paper, the method of catastrophe progression is used to evaluate the remanufacturing performance of heavy duty machine tools which absorbs the advantages of AHP and combines qualitative and quantitative analysis on the basis of considering relative importance of evaluation indexes. In order to overcome the shortcomings of the catastrophe progression method, the evaluation results are too high, the results are modified to accordance with people's regular judgment thinking.
2 The remanufacturing evaluation of modified catastrophe progression method

2.1 Modified catastrophe progression method

The catastrophe progression method takes the catastrophe theory as the theoretical basis, and the research object of the catastrophe model is the potential function. The main feature of the catastrophe progression method is that it decomposes the system’s overall objectives at first, and then decomposes the fuzzy membership functions by combining the catastrophe theory with the fuzzy mathematics, the quantitative operation is performed by normalization formula, and finally normalized to a parameter, so as to evaluate[7]. Common types of mutant systems are cusp catastrophe, swallowtail catastrophe, and so on. The normalization formulas of their mathematical models are: cusp catastrophe: \( x_s = (u)^{0.85} \), swallowtail catastrophe: \( x_s = (u)^{0.75} \), \( x_s = (v)^{0.65} \), \( x_s = (w)^{0.55} \), \( T = \min \left( (x_s)^{0.85}, (x_s)^{0.75}, (x_s)^{0.65} \right) \).

Catastrophe progression method are widely applied in many fields such as natural science, mechanical engineering and so on[8]. In this paper, the method of comprehensive adjustment is used to modified the evaluation results. On the basis of understanding the evaluation system of catastrophe progression method, the underlying control variable \( X_i \) is set a certain value. \( Y_i \) is the superior evaluation index value. \( X, Y \) are as the rating scale. The scale is shown in Table 1.

| \( X_i \) | \( Y_0 \) | \( Y_1 \) | \( Y_2 \) | \( Y_3 \) | \( Y_4 \) | \( Y_5 \) | \( Y_6 \) | \( Y_7 \) | \( Y_8 \) | \( Y_9 \) | \( Y_{10} \) | \( Y_{11} \) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0.20 | 0.40 | 0.60 | 0.65 | 0.70 | 0.75 | 0.80 | 0.85 | 0.90 | 0.95 | 1 |

When the mutation series obtained comprehensive evaluation index \( Y \in (Y_i, Y_{i+1}) \), the evaluation of the modified \( X' \) should meet \( X' \in (X_i, X_{i+1}) \). \( X' \) can be obtained as in equation (1):

\[
X' = \frac{X_{i+1} - X_k}{Y_{k+1} - Y_k}
\]  

(1)

2.2 The model of remanufacturing evaluation

The second class indicator of remanufacturing assessment model is divided into the environmental index \( (T_e) \), the economic index \( (T_i) \) and the technical index \( (T_t) \). \( T_e \) can be thought over from the material recycling rate, the type of material and so on. \( T_i \) should include the machine tool manufacturers purchase profit, economic benefits, environmental and social aspects. But because the difficulty in obtaining data and other factors, only consider the first two items. \( T_t \) is based on the process of remanufacturing. In fact, the index of disassemble closes to 1 and is discarded. Construct a remanufacturing evaluation model for heavy duty machine tools, as shown in Fig 1. The importance of the control variables is different in the mutation model, which is determined by itself.

Fig 1. The remanufacturing evaluation model of heavy duty machine tools

2.3 The index of remanufacturing evaluation

2.3.1 The environmental index

Compared with the new manufacturing machine tools, the more materials can be saved, the more feasible the remanufacture is. And the quality and the type of materials will affect the environmental
feasibility. So $T_e$ can be obtained through the following process. The index ($D_j$) is mainly affected by the ratio of the total abandon parts quality ($M_e$) and the machine tool weight ($M$), as in equation (2).

$$D_j = 1 - \frac{m_q}{M}$$  \hspace{1cm} (2)

The ecological index reflects the environment effects of the materials. Components and parts with the different materials can influence the energy consumption, discharge, reuse, etc. The ecological index of heavy duty machine tools common using materials is shown in Table 2 [9]. Through the resuing weight of different materials ($m_i$) and its ecological index ($EI_i$) to get the ecological index of the whole machine ($D_2$). $M_i$ is the weight of the whole machine parts using the material $i$.

**Table 2. The main ecological index of heavy duty machine tools**

| Materials          | Aluminium alloy | Copper alloy | Carbon steel | Cast iron | Plastic |
|--------------------|-----------------|--------------|--------------|-----------|---------|
| Ecological index   | 10.0-18.0       | 60.0-85.0    | 4.0-4.3      | 3.0-10.0  | 4.2-4.3 |

$$D_2 = \min \left( \sum \frac{EI_{\max i} m_i}{EI_{\max i} M_i}, \sum \frac{EI_{\min i} m_i}{EI_{\min i} M_i} \right)$$  \hspace{1cm} (3)

2.3.2 The economic index

This paper use the manufacturers profitability index ($D_3$) and users’ benefit index ($D_4$) to evaluate the economic feasibility of heavy duty machine tools. Remanufacturing cost mainly consists of three parts: recycling cost ($C_1$), remanufacturing cost ($C_2$), other cost ($C_3$). If the price of remanufactured products is the 40%-70% of the new products with the same performance, the manufacturers will profit [10]. Therefore, we can determine the price of remanufacturing heavy duty machine tools ($C$). The manufacturer profitability index ($D_3$) is obtained as in equation (4).

$$D_3 = \frac{C - \sum_{j=1}^{3} C_j}{\sum_{j=1}^{3} C_j}$$  \hspace{1cm} (4)

The users’ benefits index ($D_4$) is influenced by the price of remanufacturing heavy duty machine tools ($C$), the price of new machine ($C_0$), the service life of remanufacturing heavy duty machine tools ($N$), and the service life of new machine ($N_0$). The users’ benefits index ($D_4$) is obtained as in equation (5).

$$D_4 = \left( 1 - \frac{C}{C_0} \right) \times \frac{N}{N_0}$$  \hspace{1cm} (5)

2.3.3 The technical index

Common cleaning methods are blowing, wiping, baking, chemical cleaning, ultrasonic cleaning, etc. The degree of difficulty in the distribution of these cleaning methods is \{0.2, 0.4, 0.5, 0.7, 0.9\} [7]. $\theta_j$ is the degree of the cleaning method $j$. $N_j$ is the number of the cleaning method $j$ is used. $D_5$ is the index of cleaning. As shown in equation (6).

$$D_5 = 1 - \frac{\sum_{j=1}^{5} N_j \theta_j}{N_j} \hspace{1cm} (j=1,2,3,4,5)$$  \hspace{1cm} (6)

The smaller the ratio of $m_d$ and $M$ is, the greater the index of test will be. $m_d$ is weight of the non reusable class. $M$ is the weight of the whole. The index of test ($D_6$) is obtained as in equation (7).

$$D_6 = 1 - \frac{m_d}{M}$$  \hspace{1cm} (7)

Different types of components, because of using environment, load and other factors, will lead to a different rate of repair. $D_7$ is the index of repair, and can be calculated by formula (8). $m_r$ is the weight of components and parts with no value of remanufacturing. $M_r$ is the weight of being tested.
\[ D_5 = 1 - \frac{m_r}{M_r} \]  

2.4 Comprehensive evaluation

\( D_1 \) and \( D_2 \) constitute cusp catastrophe model, \( D_3 \) and \( D_4 \) constitute cusp catastrophe model, and \( D_5, D_6 \) and \( D_7 \) constitute swallowtail catastrophe model. \( T_e, T_i \) and \( T_i \) constitute swallowtail catastrophe model. Indicators at each level can not be complementary between each other, combining the dovetail catastrophe model, the normalized formula and select the minimum. \( T \) is the comprehensive evaluation index of heavy duty machine tool remanufacturing which needs to be modified by (1) to obtain the regular evaluation results \( T' \). At present, the regular scoring standard is 1, and the pass is 0.6. According to the value of \( T' \), make the following judgement: when \( T' \geq 0.6 \), retired heavy duty machine tool is can be remanufactured. And the greater the \( T' \) is, the more the heavy duty machine tool can be remanufactured.

3 Example analysis

This paper studies an TK6916 type CNC floor milling-boring machine with a service life of more than 10 years in Wuhan heavy duty machine tool group corporation. Obtaining the relevant data from the manufacturers and according to assessment process, we get the following values in Table 3.

**Table 3. Remanufacturing evaluation index**

| Secondary indicators | Environmental feasibility | Economic feasibility | Technical feasibility |
|----------------------|---------------------------|----------------------|----------------------|
| Thridary indicators  | \( D_1 \)                 | \( D_2 \)             | \( D_3 \)             |
| Value                | 0.841                     | 0.910                | 0.692                |

According to the normalization formula of the catastrophe progression method, \( T_e \) is 0.917, \( T_i \) is 0.832, \( T_i \) is 0.867, \( T \) is 0.941. According to the correction principle and formula (1), the \( T \) is modified, and \( T' \) is 0.773. That is to say, the CNC floor milling-boring machine has higher manufacturability.

4 Summary

This paper uses catastrophe progression method to comprehensive quantitative evaluate the remanufacturing of heavy duty machine tools. Reduce the qualitative components caused by artificial weighting, the quantitative component of the synthetic analysis was increased. Considering that the catastrophe progression method can lead to larger evaluation result in the normalization process, comprehensive evaluation method is used to modify the evaluation results, to conform the habits of people's assessment of the pros and cons. Based on catastrophe theory, the remanufacturing evaluation model of heavy duty machine tools is established, and calculates the various levels of the remanufacturing evaluation model according to the characteristics of heavy duty machine tools. The remanufacturing performance of the retired TK6916 type CNC floor milling-boring machine is evaluated by using the modified catastrophe progression method proposed in this paper. The evaluation of the remanufacturing is affected by various uncertainties, but the evaluation results of the method proposed in this paper can provide a decision basis for the remanufacturing process of heavy duty machine tools, and the evaluation results are within the acceptable range.

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