Research on Timing Decision of Active Remanufacturing Based on 3E Analysis of Product Life Cycle

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Active remanufacturing is an important technique that is used to reduce the uncertainty of the quality of remanufactured cores. However, the implementation of active remanufacturing too early or late will lead to a reduction in economic benefits and an increase in environmental impact during the whole life cycle of the product. To this end, an active remanufacturing timing decision method is proposed based on economic, energy and environmental (3E) analysis of product life cycle. In this method, the quantitative function of the cost, energy consumption and environmental emissions of used products in the manufacturing stage, service stage, and remanufacturing stage are firstly constructed based on LCA and LCC. Then, a multi-objective optimization method and the particle swarm algorithm are utilized to obtain active remanufacturing timing with the optimal economic and environmental benefits of remanufacturing. Finally, a case study on remanufacturing on used engines is demonstrated to validate the proposed method.

Key Words : *Active remanufacturing, 3E analysis, LCA and LCC, Multi-objective optimization*

1. INTRODUCTION

Remanufacturing is a green manufacturing technology that can effectively utilize used products and has become an important contributor to the development of circular economy [1]. The remanufacturing of used products provides products of the same quality as new ones, and effectively reduces economic input, resource consumption and environmental pollution [2-3]. However, the current raw materials for remanufacturing (Cores) are mainly derived from scrapped products, which denotes typical end-of-life cycle remanufacturing [4]. Due to the uncertainty and variation of the degree of damage forms in the service process of products, the quality of these cores varies greatly, resulting in a complex remanufacturing process and low process efficiency which limits the development of the remanufacturing industry [5]. Therefore, it is necessary to proceed from the perspective of the life cycle, through comprehensive decision-making, choosing the best time to implement active remanufacturing during the service period of the product, so as to prevent the "remanufacturing in advance" or "overuse" of the cores, and realize the comprehensive optimization of technology, economy and environment in the product life cycle.

A lot of research have been conducted in the field of the timing for active remanufacturing. Ke et al. [6] identified the active remanufacturing timing domain decision method by analyzing the life cycle service value of electromechanical products. They obtained the optimal active remanufacturing timing considering energy consumption by identifying energy consumption parameter as the core index. Wang et al. [7] obtained the optimal active remanufacturing timing by analyzing the reliability changes of electromechanical products in service life. Liu et al. [8] regarded the cost per unit timing minimize of service as the optimization objective, and obtained the optimal remanufacturing recovery timing. Zhang et al. [9] presented the remanufacturing timing computing method with the optimal carbon emission reduction benefit in engines, and obtained the optimal active remanufacturing timing of carbon emission reduction benefit by analyzing the system boundary of engines. Song et al. [10] considered comprehensively the fatigue and wear of crankshafts, and obtained the optimal active remanufacturing timing of crankshafts. Wang et al. [11] provided an online monitoring signals model to analyze the optimal timing of active remanufacturing of the crankshaft.

Aforementioned studies provide a useful reference for the timing decision of active remanufacturing. However, most of the research has either focussed on a certain damage characteristic of the product, or only taken cost, energy consumption, carbon emissions and other single factors into consideration to determine the timing of active remanufacturing. Few researches on the timing of active remanufacturing consider both economic and environmental aspects, and there is still a lack of valid integration methods. To this end, based on the 3E analysis of product life cycle, a multi-objective optimization model of active remanufacturing timing decision is established, and particle swarm algorithm is used to determine the optimal remanufacturing timing for economic and environmental benefits, which provides a method support for the remanufacturing of used engine.

The rest of this paper is structured as follows: The second part introduces the method of this article, including two stages of product life cycle 3E analysis and multi-objective optimization solution. The third part is the case study. The fourth part summarizes the conclusions and future work.

2. METHODOLOGY

Active remanufacturing is for products in service, according to the failure rule of products over time, the bathtub curve [12] (as shown in Figure 1). According to the different time points of active remanufacturing, it can be divided into "remanufacturing in advance" and "overuse”. There will also be an optimal time for active remanufacturing between these two stages. The implementation of remanufacturing at this moment can effectively prevent the core from being remanufactured in advance or overused.

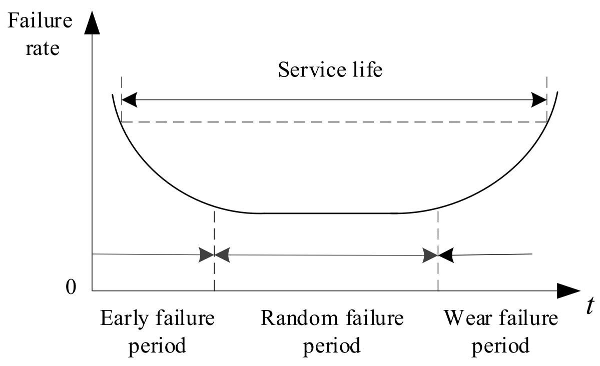

Fig.1 Curve of product failure process

In this paper, the economic, energy and environmental (3E) analysis are used as the performance indicators of active remanufacturing timing research. However, they have different curves over time. Therefore, conflict resolution is needed first, and then the active remanufacturing timing is obtained from a comprehensive perspective, as shown in Figure 2.

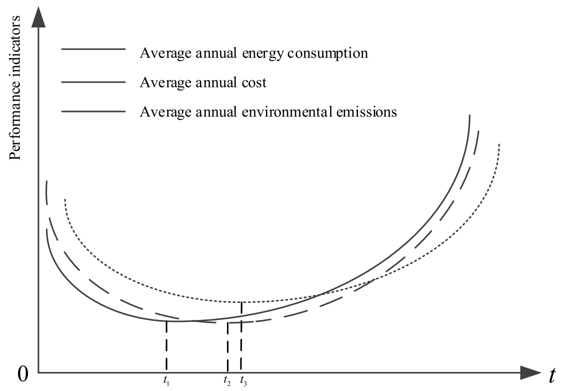

Fig.2 The relationship between different performance indicators

2.1 3E analysis of product life cycle

Product life cycle 3E analysis is a method to quantify the economic, energy, and environmental impact of a product during its life cycle [13]. Its advantages include full-process analysis and extensive coverage. When researching the timing of active remanufacturing, the manufacturing stage, service stage, and remanufacturing stage cost, energy consumption and environmental emissions in the product life cycle are important factors that need to be considered. By analysing the functional relationship between them and time, one can provide effective guidance for the decision of active remanufacturing timing.

(1) LCA and LCC Methods

Life cycle analysis (LCA), is used to evaluate the environmental factors of the product life cycle and its potential impact technology [14]. As the performance of products varies in different stages of the life cycle, LCA needs to be used to analyse the environmental and energy impacts of each stage. Life cycle cost (LCC), is a method of systematically evaluating all related costs of a project, product, or service in the life cycle [15]. Through the combination of LCA and LCC, from the perspective of life cycle impact assessment and economic analysis, the practicability of traditional LCA is improved, and the importance of balancing economic and environmental benefits is reflected.

(2) Energy analysis

The function of product energy consumption with time has strong regularity, which can effectively reflect the quality degradation law of products in service, and is an important index to be considered in the timing decision of active remanufacturing.

- Manufacturing stage

The product manufacturing stage includes: raw material mining, extraction, forging, machining, and assembly, etc. According to the process type, the energy consumption in the manufacturing stage E_M include: energy consumption of raw material processing E_a, energy consumption of core processing E_b.

Assuming the type of raw material is n, the quality of the processed i th raw material is m_i the energy consumption per unit mass is E_{mi}. So, the energy consumption of raw material processing is:

$$E_a=\sum_{i=1}^{n} m_i e_{mi},\ (i=1,2,3...,n) \tag{1}$$

Suppose the core processing procedure is j, the specific energy consumption of the k th process is e_k, the quality of the material removed in each process is m_k. So, the energy consumption of core processing is:

$$E_b=\sum_{k=1}^{j} e_k m_k,\ (k=1,2,3...,j) \tag{2}$$

The energy consumption in the manufacturing stage E_M is:

$$E_M = E_a + E_b \tag{3}$$

- Service stage

The energy consumption during the service stage is mainly related to the energy loss caused by the wear of key engine parts. By recording the consumption of multiple energy types under different usage times, the energy consumption during the service stage can be linearly fitted.

$$E_U(t) = ET_i(t) \times ECF_i \tag{4}$$

Where, $ET_i(t)$ is i th type energy consumption function, which is related to time, ECF_i is i th type energy consumption factor.

- Remanufacturing stage

The remanufacturing process of used products includes: disassembly, cleaning, repair, subsequent processing, inspection, reassembly, etc. The remanufacturing process of products under different service periods is very different. The energy consumption in the remanufacturing stage can be calculated based on the energy consumption list when the product is completely scrapped:

$$E_R(t) = \sum_{i=1}^{n} E_i \lambda_i(t) \tag{5}$$

Where, E_i is the total energy consumption of different processes in the remanufacturing stage, $\lambda_i(t)$ is the energy conversion rate, which is the ratio of the energy consumption of the i th process in the t th year of service to the energy consumption of the i th process when it is scrapped.

The average annual energy consumption function is:

$$f_1(t) = \frac{E_M + E_U(t) + E_R(t)}{t} \tag{6}$$

(3) Economic Analysis

Controlling the cost of the product's life cycle is of great significance for maximizing economic benefits, and it is also a key factor that cannot be ignored in the study of active remanufacturing timing.

- Manufacturing stage

The cost of the product manufacturing stage includes the purchase cost of raw materials and the cost of electricity consumption. Suppose the unit quality raw material price is a_i Yuan, and the unit power consumption cost is b Yuan. The cost of the product in the manufacturing stage is:

$$C_M = \sum_{i=1}^{n} a_i m_i + E_M b \tag{7}$$

- Service stage

Due to the cost of the product in the service stage mainly includes the cost of using energy such as electric energy or chemical energy. Suppose the price per unit of energy is b_i Yuan. The cost of the product in the service stage is:

$$C_U(t) = E_U(t) b_i \tag{8}$$

- Remanufacturing stage

The cost of the remanufacturing stage mainly includes the cost of using electric energy. Assuming the price of unit electric energy is d Yuan, the cost of the product in the remanufacturing stage is:

$$C_R(t) = E_R(t) d \tag{9}$$

The annual average cost function is:

$$f_2(t) = \frac{C_M + C_U(t) + C_R(t)}{t} \tag{10}$$

(4) Environmental Analysis

In the context of resource depletion and environmental degradation, environmental benefits have received increasing attention from enterprises. Environmental emissions are also one of the important indicators to be considered when making active remanufacturing timing decisions.

- Manufacturing stage

In the product manufacturing stage, the environmental emissions from raw material processing comes from the consumption of crude oil, coal and natural gas, and the environmental emissions from the processing of raw materials is mainly the consumption of electricity. Assuming u_i^k is the mass of the i th pollutant produced by the k th energy per unit mass, the electrical energy during core processing is E_b, w_k is the quality of the k th pollutant produced by the production unit of electricity, l is the type of environmental emissions.

$$W_M = \left[\sum_{i=1}^{n} m_i u_i^1 \ \sum_{i=1}^{n} m_i u_i^2 \ \ldots \ \sum_{i=1}^{n} m_i u_i^k \ \sum_{i=1}^{n} m_i u_i^l\right]^T + E_b\left[w_1 \quad w_2 \quad \cdots \quad w_k \quad w_l\right]^T \tag{11}$$

- Service stage

Assuming that there are n types of environmental emissions produced by the product during service, b_k is the mass of pollutants produced by the combustion of unit mass energy. The environmental emissions during the service stage are:

$$W_U(t) = E_U(t)[b_1 \ b_2 \cdots b_k \ b_n]^T \tag{12}$$

- Remanufacturing stage

The main energy consumption in the remanufacturing process of used products is electrical energy, r_i is the quality of pollutants produced per unit of electrical energy. The environmental emissions at the remanufacturing stage are:

$$W_R(t) = E_R(t)[r_1 \ r_2 \cdots r_k \ r_n]^T \tag{13}$$

The annual average environmental emission function is:

$$f_3(t) = \frac{W_M + W_U(t) + W_R(t)}{t} \tag{14}$$

2.2 Modeling and solving the multi-objective optimization problem

Multi-objective optimization problems are common in various subject areas. They usually use multi-criteria or multi-objective as research objects. In the actual decision-making process, each goal is constrained or affected by other goals. Therefore, most multi-objective optimizations cannot achieve the best results at the same time. The objective function, decision variables, and constraints are the three major elements of a multi-objective optimization problem [16].

(1) Normalization of multiple objective functions

For linear function models, converting multiple objective functions into a single objective function is an effective solution method. In this paper, the cost, energy consumption and environmental emission functions can all be fitted as linear functions. Before the normalization of multi-objective functions, the functions should be dimensionless so that they are in the same order of magnitude.

$$f_i^{'} = \frac{f_i}{f_{i\max} - f_{i\min}} \tag{15}$$

Where, $f_i^{'}$ is processed function, f_i is the function before processing, $f_{i\max}$ is the maximum value of the i th function, $f_{i\min}$ is the minimum value of the i th function.

The multiply-divide method is used to construct the multi-objective function into a one-objective function, which can optimize the complex models and reduce the calculation amount.

$$f(t) = \left[f_1^{'}(t)\right]^{\alpha_1}\left[f_2^{'}(t)\right]^{\alpha_2}\left[f_3^{'}(t)\right]^{\alpha 3}\cdots\left[f_k^{'}(t)\right]^{\alpha_k} \tag{16}$$

Where, $f_k^{'}(t)$ is the k th function, and a_i is weight value, $\alpha_i \geq 0,\ 1 \leq i \leq k,\ \sum_{i=1}^{k}\alpha_i = 1$.

(2) Objective function of optimization

The goal of optimization is to minimize the normalized function value within the whole service cycle stage of the used products, so the optimized function model can be expressed as:

$$\min f(t),\ t_{\min} < t < t_{\max} \tag{17}$$

Where, $f(t)$ is the normalized function, t is service time of the product, $t_{\min}$ is the minimum service time of the used products, $t_{\max}$ is the maximum service time of the used products.

(3) Model solving with particle swarm optimization

Some global optimization algorithms, such as tabu search, simulated annealing algorithm, they are limited by their respective mechanisms and structures. So, it is difficult for them to optimize complex multi-objective functions efficiently. Particle swarm optimization is inspired by animal foraging behaviour, and its group assistance and random search can effectively solve complex function optimization problems. This method has been widely used in the field of engineering, so the particle swarm optimization algorithm is used to optimize the solution in this paper. The flowchart of particle swarm optimization is shown in Figure 3. In this method, when the optimal solution is found or the maximum number of iterations is reached, the algorithm ends.

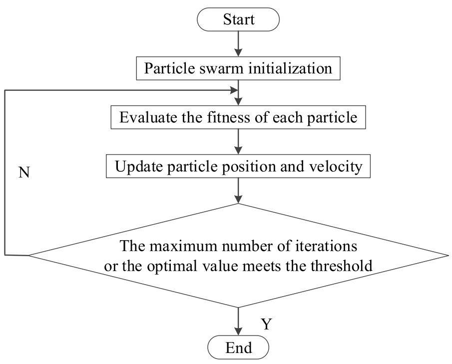

Fig.3 Flowchart of particle swarm algorithm

3. CASE STUDY

As an important part to provide power for automobile, engine has a huge market share, and a large part of it is entering the scrap stage. Therefore, the remanufacturing of used engine has far-reaching significance. In this paper, the engine service life is defined as $5\ a$. If the early implementation of active remanufacturing, the service value of the product cannot be fully utilized, so the engine service time t=2, 3, 4, 5 a is set as the first active remanufacturing timing. And the system boundary is limited to not involving the secondary remanufacturing of the engine.

3.1 Annual average energy consumption

- Manufacturing stage

The list of energy consumption of raw material processing (as shown in Table 1), and parts manufacturing process energy consumption list (as shown in Table 2).

Table 1 List of energy consumption of raw material processing kg

List substances	Steel	Cast iron	Aluminum	Alloy
Coal	5.19	5.86	66.06	5.71
Crude	0.40	0.37	3.99	0.51
Natural gas	0.19	0.02	2.51	1.16

Table 2 List of energy consumption in parts manufacturing process kJ / kg

Manufacturing method of core	Casting	Forging
Energy consumption	400	71.38

According to the data in the table and formulas (12) and (13), the energy consumption in the manufacturing stage is:

$$E_M = 16101\ \mathrm{kW \cdot h} \quad (18)$$

- Service stage

With the increase of service time, the wear of the key parts of the engine is becoming more and more serious, which leads to the deterioration of engine performance. In order to ensure enough torque output, the fuel consumption of the engine will increase. When the engine rated speed is $20000\ \mathrm{r/min}$, annual mileage is $50000\ \mathrm{km}$, the energy consumption during the service stage of the engine is:

$$E_U(t) = 2896.7t^3 - 15510t^2 + 47093t + 3199\ \mathrm{kW \cdot h} \quad (19)$$

- Remanufacturing stage

The energy consumption of the engine remanufacturing stage depends on the processing technology of each key part. The remanufacturing process of the crankshaft is: cleaning, testing, remanufacturing, subsequent processing, inspection, etc.; the remanufacturing process of the cylinder adopts the process of replacement method; the remanufacturing process of the connecting rod is the replacement of the small end bushing, honing, boring cutting, milling, etc. The list of energy consumption during remanufacturing of key engine components is shown in Table 3.

Table 3 Remanufacturing energy consumption list of key engine parts $\mathrm{kW \cdot h}$

Process	Clean	Detection	Subsequent processing
Crankshaft	1.61	0.89	6.62
Connecting rod	0.48	2.8	0.11
Cylinder block	3.61	0.7	17.69
Cylinder head	3.09	13.44	0.21

The energy consumption in the remanufacturing stage of the engine is obtained by fitting:

$$E_R(t) = 103.3t^3 - 690t^2 + 2026.7t + 3380\mathrm{kW \cdot h} \quad (20)$$

So, the average annual energy consumption function is:

$$f_1(t) = \frac{3000t^3 - 16200t^2 + 49119.7t + 22680}{t} \quad (21)$$

3.2 Annual average cost

- Manufacturing stage

The cost of the manufacturing stage includes raw material purchase cost, processing cost and energy consumption cost. According to current market prices, a ton of coal is 499 Yuan, a barrel of crude oil is 290 Yuan, a cubic meter of natural gas is 3 Yuan, the price of industrial electricity is 1 Yuan per kilowatt hour, and a ton of steel is 3800 Yuan. Therefore, the cost of the manufacturing stage is:

$$C_M = 2081.2\ \text{Yuan} \quad (22)$$

- Service stage

The additional fuel consumption caused by performance degradation during the service stage of the engine is the maintenance cost of the engine service stage. The current market price of one ton of diesel is 5300 Yuan. The cost during the service stage of the engine is:

$$C_U(t) = 96.667t^3 - 678t^2 + 1093.3t + 1432\text{Yuan} \quad (23)$$

- Remanufacturing stage

The cost of the engine remanufacturing stage mainly includes the use cost of electric energy, the purchase cost of nickel chromium and nickel. According to the current market price, the price of a ton of nickel is 100,000 Yuan, and the price of a ton of nickel-chromium alloy is 135,000 Yuan. The cost during the remanufacturing stage of the engine is:

$$C_R(t) = 4066.6t - 1448.2 \text{ Yuan} \quad (24)$$

So, the average annual cost function is:

$$f_2(t) = \frac{96.667t^3 - 678t^2 + 5159.9t + 1565}{t} \quad (25)$$

3.3 Annual average environmental emissions

- Manufacturing stage

The raw material processing process consumes coal, crude oil, natural gas, etc., the core processing process consumes electricity, these processes will produce CO, CO_2, SO_2, NO_x, CH_4. Environmental emissions during the manufacturing stage are:

$$W_M = \begin{bmatrix} CO \\ CO_2 \\ SO_2 \\ NO_x \\ CH_4 \end{bmatrix} = \begin{bmatrix} 3.05E-01 \\ 1.08E+03 \\ 2.88 \\ 1.89 \\ 2.72 \end{bmatrix} \text{kg} \quad (26)$$

- Service stage

The environmental emissions generated by each ton of diesel consumed by the engine are shown in Table 4.

Table 4 List of environmental emissions from diesel combustion kg

Pollutants	CO_2	CO	CH_4	SO_2	NO_x
Value	3.19E3	11.00	5.91E-2	1.00E-1	9.34

During the service stage of the engine, the main consumption is diesel the environmental emissions generated are CO, CO_2, CH_4, SO_2, NO_x.

$$W_U(t) = \begin{bmatrix} CO \\ CO_2 \\ SO_2 \\ NO_x \\ CH_4 \end{bmatrix} = E_U(t) \begin{bmatrix} 1.22E-4 \\ 3.54E-2 \\ 0.11E-06 \\ 1.37E-04 \\ 6.57E-05 \end{bmatrix} \text{kg} \quad (27)$$

- Remanufacturing stage

The environmental emissions produced during the engine remanufacturing stage are mainly related to the electrical energy consumption.

$$W_R(t) = \begin{bmatrix} CO \\ CO_2 \\ SO_2 \\ NO_x \\ CH_4 \end{bmatrix} = E_R(t) \begin{bmatrix} 2.28E-6 \\ 1.01E-2 \\ 3.52E-05 \\ 2.91E-05 \\ 2.99E-07 \end{bmatrix} \text{kg} \quad (28)$$

So, the average annual environmental emission function is:

$$f_3(t) = \frac{-0.0017t^3 + 78.5t^2 + 704.7667t + 708.4}{t} \quad (29)$$

3.4 Multi-objective optimization solution

First, the three functions are characterized so that they are of the same magnitude. As follows:

$$f_1'(t) = \frac{f_1(t)}{23550},\ f_2'(t) = \frac{f_2(t)}{587},\ f_3'(t) = \frac{f_3(t)}{63} \quad (30)$$

Second, the multi-objective function is converted to a one-objective function by multiply-divide method. In this paper, the weight coefficients of energy consumption, cost, and environmental emissions is chosen as 0.25, 0.50, 0.25 respectively. Therefore, the optimization model is:

$$\min f(t) = f_1'(t)^{0.25} f_2'(t)^{0.5} f_3'(t)^{0.25}$$
$$s.t. \quad (31)$$
$$2 < t < 5$$

In order to implement the particle swarm algorithm, a program is written in MATLAB, the parameters of the particle swarm algorithm are set as follows: population size $N = 100$, particle dimension $D = 1$, the number of evolution $X = 50$, maximum flying speed of particles $V_{\max} = 0.5$ m/s, minimum flying speed of particles $V_{\min} = -0.5$ m/s. The minimum timing for active remanufacturing is $t = 2$ a; The maximum timing for active remanufacturing is $t = 5$ a. The above data and functions are incorporated into the particle swarm algorithm, and an iterative flowchart of optimal timing for active remanufacturing based on the particle swarm algorithm is finally obtained, as shown in Figure 4.

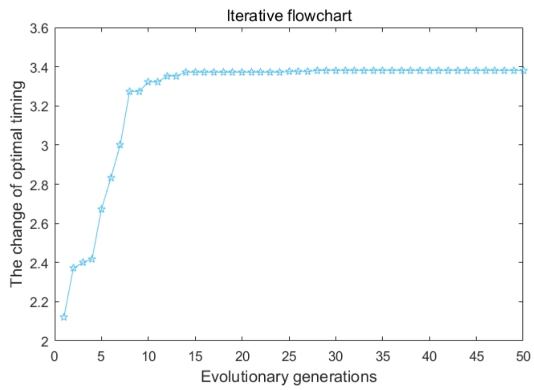

Fig.4 Iterative flowchart of optimal timing for active remanufacturing

The iterative flowchart of the particle swarm algorithm shows that the optimal solution reaches stability at the 30th generation of the population. The optimal timing for active remanufacturing t=3.381 a.

4. CONCLUSIONS

This work proposes an active remanufacturing timing research method based on 3E analysis of product life cycle, which effectively prevents re-manufactured cores from being remanufactured in advance or overused. The LCA and LCC are integrated in this model to analyse the energy, economic and environmental impacts of the product manufacturing stage, service stage, and remanufacturing stage. A multi-objective optimization model is also established for active remanufacturing timing of average annual energy consumption, cost and environmental emissions, and a particle swarm algorithm is used to solve the model. A certain type of engine is taken as an example, the effectiveness of the proposed method is verified. The work presented here not only introduces a timing decision-making method for active remanufacturing, but it also provides method support for 3E analysis of product life cycle, which may play an important role in cleaner production of enterprises.

In future work, the stages of the life cycle can be analysed in more detail, covering topics such as product transportation process and scrap process. And more efficient algorithms can be developed to improve the accuracy of the results when solving the model.

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REFERENCES

1) Jiang Z, Zhou T, Zhang H, et al: Reliability and cost optimization for remanufacturing process planning. Journal of cleaner production 2016, 135: 1602-1610.
2) Gutowski T G, Sahni S, Boustani A, et al. Remanufacturing and energy savings[J]. Environmental science & technology, 2011, 45(10): 4540-4547.
3) Chen D, Jiang Z, Zhu S, et al: A knowledge-based method for eco-efficiency upgrading of remanufacturing process planning. The International Journal of Advanced Manufacturing Technology 2020, 1-10.
4) Jiang Z, Ding Z, Zhang H, et al: Data-driven ecological performance evaluation for remanufacturing process. Energy Conve rsion and Management 2019, 198: 111844.
5) Qingdi L, Dan S S Z: Time interval decision-making methods for active remanufacturing product based on game theory and neural network. Journal of Mechanical Engineering 2013, 7(006).
6) Ke Q D, Wang H, Song S X, et al: Timing decision-making method with life cycle analysis in predecisional remanufacturing. Journal of Mechanical Engineering 2017, 53(11): 134-143.
7) Chen L, Wang X, Zhang H, et al: Timing decision-making method of engine blades for predecisional remanufacturing based on reliability analysis. Frontiers of Mechanical Engineering 2019, 14(4): 412-421.
8) Liu, Q.T., Chen, X.F., Wang, Q.F: Active remanufacturing timing prediction of engineering machinery based on Weibull distribution. Journal of Guangxi University (Nat Sci Ed) 2018, 43(3): 958-964.
9) Zhang, H., Dong, H.J., Wu, L: Research on the Best Time Point for Remanufacturing of Automotive Engines Based on Carbon Reduction. Environment and Sustainable Development 2019, 44(4): 105-109.
10) Song, S.X., Qiu, Q., Bu, J., et al: Timing of Active Remanufacturing of Crankshaft Based on Fatigue and Wear. Computer Integrated Manufacturing Systems 2019, 26(2): 279-287.
11) Wang Y, Hu J, Ke Q, et al: Decision-making in proactive remanufacturing based on online monitoring. Procedia CIRP 2016, 48: 176-181.
12) Alvarez-Alvarado M S, Jayaweera D. Bathtub curve as a Markovian process to describe the reliability of repairable components[J]. IET Generation, Transmission & Distribution, 2018, 12(21): 5683-5689.
13) Wang T: Research on Engine Reproducing Based on the 3E Life Cycle Assessment of the Theory. Hunan University 2011.
14) Vilches A, Garcia-Martinez A, Sanchez-Montanes B: Life cycle assessment (LCA) of building refurbishment: A literature review. Energy and Buildings 2017, 135: 286-301.
15) Lee H, Shin H, Rasheed U, et al: Establishment of an inventory for the Life Cycle Cost (LCC) analysis of a water supply system. Water 2017, 9(8): 592.
16) Wang D, Tan D, Liu L. Particle swarm optimization algorithm: an overview. Soft Computing 2018, 22(2): 387-408.