A nonlinear model between life cycle cost, service time and recycling quality level of waste engine parts under uncertain environment

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Abstract: Engine is the core of auto parts. It has great economic and social benefits for retired engines and their parts by remanufacturing. However, in recycling process, the uncertainty of quality status of retired engines leads to the uncertainty of life cycle cost, which makes it difficult for technicians to evaluate the cost. In order to address the problem mentioned, this study sets up a nonlinear model between the life cycle cost, service time and the quality level of used engine parts by considering damage degree in recycling process of used engine parts as a research index and takes 50 heavy-duty engine connecting rods as an example, which provides a theoretical basis for remanufacturing enterprises to evaluate the cost and determine the remanufacturing process accurately.

1. Introduction
While entering into the new century, the quantity of scrapped motor vehicles is increasing sharply. If the large number of vehicles cannot be properly handled, it will cause a waste of resources and even pollute the environment. In this context, the most effective way for used automobile engines is remanufacturing. However, the uncertainty of the quality of used engines while recycling results in the great uncertainty of the life cycle cost of engine parts, which not only reduces the remanufacturing rate but also increases the difficulty of remanufacturing[1]. Besides, the difficulty of the life cycle cost of used engines is also regarded to be related to the service time. Therefore, it’s necessary to set up a nonlinear model between life cycle cost, service time and quality level of used engine parts, so as to formulate remanufacturing process routes reasonably and improve the efficiency of remanufacturing effectively.

Previously, some scholars have conducted research on the life cycle cost and uncertainty of mechanical parts and made certain achievements[2-4]. But research which concentrates on the uncertainty of the quality level and life cycle cost is relatively rare. The paper studies the quantitative relationship between quality level, service time and life cycle cost by using full time cycle assessment and mathematical statistics as tools. Besides, this paper takes WD615 engine as an example by putting actual data into the model. The results prove the feasibility and effectiveness of the model.

2. Division of system boundaries
The system boundary of the study is shown in Fig 1, which includes six stages: product manufacturing, product usage, product recycling, remanufacturing, product reuse and scrapping.
3. Modeling

3.1. Analysis of the uncertainty of quality level
The differences in the entire life of engine parts lead to uncertainties of multiple stages, which are mainly divided into three stages: the uncertainty of working situations of new products due to differences in service conditions, the uncertainty in remanufacturing stage which is caused by differences in the damage degree of recycled engine parts, and the uncertainty of service time of remanufactured products after putting into use, this study mainly focuses on the second stage.

3.2. Evaluation model of quality level
In the remanufacturing process, a common method is to group the quality levels of waste parts based on different degrees of damage, different groups correspond to different processes[5]. The paper considers the damage degree of an engine part while recycling as the quality level. The evaluation model is expressed as equation 1.

\[ y_i = \sum_{z=1}^{s} k_{iz} \]  

Where \( y_i \) indicates the quality level of the \( i \)-th engine part, \( k_{iz} \) indicates the amount of damage at the \( z \)-th damage situation of the \( i \)-th engine part, \( k_{iz} \) can be obtained from the actual data.

3.3. Life cycle cost model of waste engine parts under uncertain quality levels
According to the system boundary, this paper established the life cycle cost model of engine parts, as shown in equation 2.

\[ C = C_{om} + C_{ou} + C_{ru} + C_{rm} + C_{ra} + C_{rs} \]  

Where \( C_{om} \), \( C_{ou} \), \( C_{ru} \), \( C_{rm} \), \( C_{ra} \), \( C_{rs} \) respectively represent the cost for original manufacturing, product usage after original manufacturing, recycling, remanufacturing, product usage after remanufacturing, and scrapping of an engine part.

3.3.1. The original manufacturing cost \( C_{om} \)
The calculation of original manufacturing cost \( C_{om} \) is shown in equation 3.

\[ C_{om} = \sum_{a=1}^{b} p_{omma} w_{omma} + \sum_{j=1}^{m} p_{omej} w_{omej} + C_{coml} + C_{omw} + C_{omo} \]  

Where \( p_{omma} \) represents the price of the \( a \)-th material; \( w_{omma} \) represents the quantity of the \( a \)-th material; \( p_{omej} \) represents the price of the \( j \)-th energy; \( w_{omej} \) represents the quantity of the \( j \)-th energy;
Coml represents the labor cost; Como represents the management and office cost; Comw represents the equipment depreciation cost.

For the same type of parts, Com, Cre and Crs are assumed to be the same.

3.3.2. The product’s usage cost Cou and Cru

The product’s usage cost Cou and Cru is different due to different service time in respective stages. Based on the service time of waste parts, Cou and Crm can be calculated by equations 4 and 5.

\[ C_{ou} = p_{ou} \int_{0}^{t_o} f_1(t)dt \]  \hspace{1cm} (4)

\[ C_{ru} = p_{ru} \int_{0}^{t_r} f_2(t)dt \]  \hspace{1cm} (5)

Where pou represents the energy price of a new product; f1(t) represents the energy consumption per unit time during the usage of a new product; pru represents the energy price of a product after remanufacturing; f2(t) represents the energy consumption per unit time during the usage of a product after remanufacturing; t₀ represents the service time of a new product; t_r represents the service time of a product after remanufacturing.

3.3.3. The remanufacturing cost Crm

The calculation of the remanufacturing cost of used parts is shown in equation 6.

\[ C_{rmi} = \sum_{d=1}^{g} p_{rmmd} w_{rmmd} + \sum_{h=1}^{q} p_{rmeh} w_{rmeh} + C_{rml} + C_{rmw} + C_{rmo} \]  \hspace{1cm} (6)

Where p_{rmmd} represents the price of the d-th material; w_{rmmd} represents the quantity of the d-th material; p_{rmeh} represents the price of the h-th energy; w_{rmeh} represents the quantity of the h-th energy; C_{rml} represents the labor cost; C_{rmw} represents the equipment depreciation cost; C_{rmo} represents the management and office cost.

3.4. Nonlinear model among life cycle cost, quality level and service time

Regarding the life cycle cost of used engine parts as the dependent variable while the quality level \( y \) and the service time \( x \) as independent variables, the nonlinear regression equation was established as shown in equation 7.

\[ C = a_1 x + a_2 y + bxy + c_1 x^2 + c_2 y^2 + d \]  \hspace{1cm} (7)

3.5. Evaluation model of the stability of the fitted curve

The life cycle cost, quality level and service time are all captured directly or calculated according to the data, which are random. In this paper, a test of the goodness of regression equation was used to evaluate the stability of the fitted curve. The goodness of regression equation was expressed by the statistic \( R_c^2 \), as shown in equation 8[6].

\[ R_c^2 = 1 - \frac{\sum_{i=1}^{n} (\hat{C}_i - \bar{C})^2}{\sum_{i=1}^{n} (C_i - \bar{C})^2} \]  \hspace{1cm} (8)

4. Case study

4.1. The failure situation table of 50 connecting rods

Due to the tracking statistics of 50 engines, the main damage type of the connecting rod occurs in the big end, which occurs in 1-2 situations. The amounts of damage of the situations are \( k_{11} \) and \( k_{22} \), the quality level is expressed by the total damage degree according to equation 1. The service time \( x_i \) can
be obtained from actual data, as shown in Table 1.

Table 1. The failure situation table of 50 connecting rods

| Serial number | Service time | Damage degree | Quality level |
|---------------|--------------|---------------|---------------|
|               | $x_i$        | $k_{i1}$      | $k_{i2}$      |
| 1             | 1.167        | 0.018         | 0.026         | 0.044         |
| 2             | 1.25         | 0.018         | 0.026         | 0.044         |
| 3             | 1.25         | 0.017         | 0.026         | 0.043         |
| ...           | ...          | ...           | ...           | ...           |
| 48            | 6.5          | 0.019         | 0.022         | 0.041         |
| 49            | 6.5          | 0.019         | 0.016         | 0.035         |
| 50            | 6.5          | 0.021         | 0.018         | 0.039         |

4.2. Statistical table of life cycle costs of 50 connecting rods

Due to the tracking statistics and calculations by equation 2 to 5, costs of six stages can be obtained, and the life cycle cost can be calculated according to equation 6. Results are shown in Table 2.

Table 2. The cost of each stage of 50 connecting rods

| Serial number | Service time | Quality level | $C_{com}$ | $C_{co}$ | $C_{r}$ | $C_{rm}$ | $C_{ru}$ | Life cycle cost (C) |
|---------------|--------------|---------------|-----------|----------|--------|---------|---------|---------------------|
|               | $x_i$        | $y_i$         |           |          |        |         |         |                     |
| 1             | 1.167        | 0.044         | 931.32    | 854.80   | 304.10 | 58.08   | 3416.92 | 25.00               | 5590.22         |
| 2             | 1.25         | 0.044         | 931.32    | 915.61   | 304.10 | 61.98   | 3416.92 | 25.00               | 5654.93         |
| 3             | 1.25         | 0.043         | 931.32    | 915.61   | 304.10 | 74.41   | 3416.92 | 25.00               | 5667.36         |
| ...           | ...          | ...           | ...       | ...      | ...    | ...     | ...     | ...                 | ...              |
| 48            | 6.5          | 0.041         | 931.32    | 4773.00  | 304.10 | 304.62  | 3416.92 | 25.00               | 9754.96         |
| 49            | 6.5          | 0.035         | 931.32    | 4773.00  | 304.10 | 131.15  | 3416.92 | 25.00               | 9581.49         |
| 50            | 6.5          | 0.039         | 931.32    | 4773.00  | 304.10 | 185.51  | 3416.92 | 25.00               | 9635.85         |

4.3. Nonlinear model among life cycle cost, quality level and service time

According to equation 7, regression simulation was carried out by iterating for 24 times and finally converged by Matlab. In the parameter evaluation table, the regression coefficient of each variable was given and accepted into the regression model, as shown in equation 9.

$$C = 776.528x + 683.787y - 32.826xy + 1.632x^2 - 229.234y^2 + 4274.318$$

Then, the nonlinear regression equation was evaluated according to equation 8, the statistic $R^2$ was 0.996. The result shows that the goodness of nonlinear regression equation is effective. The model can be applied in the actual remanufacturing process.

5. Conclusions

This study sets up a nonlinear model for engine parts in an environment with uncertain quality levels by theoretical methods to study the quantitative relationship of life cycle cost, service time and quality level of engine parts under uncertain environments. The model can be used in the determination of remanufacturing process of mechanical products such as engines, machine tools, compressors, etc. Remanufacturing enterprises can predict the life cycle cost of a mechanical product while retiring through the service time and the quality level of the product by applying the model, which improves
the scientificity of remanufacturing process decision. For the next step, this study will further optimize the quantitative model by reducing the error. Besides, the optimal solution of the model will be obtained based on different constraints caused by actual remanufacturing situation, which improves the practicability of the model.

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