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# A QUALITY GRADE CLASSIFICATION METHOD FOR REMANUFACTURING-ORIENTED COMPONENTS

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## ABSTRACT

There have been large quantities of used electromechanical and automobile components for remanufacturing in China. Accurate quality evaluation of used components is significant in determining an appropriate remanufacturing scheme. However, due to the different working status before recycling, the quality conditions of each used component are variable, which brings difficulty for remanufacturing scheme formulation. Therefore, we propose a quality grade classification method for remanufacturing components. In this method, the main quality attributes of used components are determined by using a reduction algorithm according to the rough set theory. Then, by the technique for order preference by similarity to an ideal solution method, the close degree between the actual and the ideal quality attribute values is calculated. Subsequently, the quality grade is defined by determining the close degree. Finally, the remanufacturing scheme of the used components is formulated by the quality grades. The case of used WD615 engine cylinder blocks is chosen as the research object to verify the proposed quality grade classification model. This study can help facilitate and guide the quality grading in remanufacturing practice and benefit remanufacturers in terms of sustainability and improvement.

KEYWORDS: Quality grade, Used components, Remanufacturing, Rough sets, Technique for order preference by similarity to ideal solution.

## 1. INTRODUCTION

Remanufacturing has attracted wide attention due to its advantages in material and energy saving and emission reduction and is often considered a viable approach for the realization of a circular economy [1]. In China, large electromechanical and automobile products are scrapped every year, if the damaged components of these products are remanufactured to be useful components, huge resources would be saved. Remanufacturing takes used components as “blanks”, and adopts special process and

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technology (including surface engineering technology and other processing technology) to restore their size, shape, and performance and form remanufactured products, which are no less than the original product in terms of performance or quality [2]. Many researchers have conducted in-depth studies on the excellent environmental and economic performance of product remanufacturing [3-9].

However, the quality level of “blanks” varies greatly due to the different working conditions, service time, and damage degree [9, 10], which may lead to an uncertain quality state. Moreover, incomplete and redundant quality information often brings quality misjudgment and unreasonable remanufacturing scheme. A general remanufacturing process includes recycling, dismantling, cleaning, inspection, repairing, and assembly, and it can select different remanufacturing technologies in each process (such as in “cleaning” process, it can select the technology of pressure cleaning, electrolytic cleaning, and chemical cleaning). Used components with specific quality conditions can vary in terms of the repairing level and technical efficiency if different remanufacturing technical schemes are selected. Therefore, scientific and reasonable quality grade classification of the “blanks” is a necessary prerequisite for a low cost and high efficient remanufacturing scheme.

Studies related to the quality conditions and remanufacturing scheme planning of used products are available from different perspectives. Xu et al. pointed out that the quality evaluation for “blanks” is the main task to ensure the quality of remanufacturing components [11]. Behret and Korugan argued that production planning and control activities can be difficult for remanufacturing firms due to the uncertainties from stochastic product returns, and the quality difference of waste parts is the direct cause of the high uncertainty of remanufacturing process route and time [12]. Guide identified and discussed seven complicated characteristics that require changes in production planning and control activities [13]. Liao et al. developed a complex quality coefficient measurement method to describe the quality uncertainty in returned items [14]. However, the above studies failed to address the method of the quality grade classification under uncertain conditions of used components. By targeting used components with different quality classification, Jin et al. studied the optimal control strategy of remanufacturing system under the condition of quality uncertainty of recycled products [15]. Wen et al. proposed a quality evaluation method for remanufactured crank by using rough set (RS) and technique for order preference by similarity to an ideal solution (TOPSIS) [16]. Nevertheless, the quality evaluation of conducted investigations related to remanufacturing schemes was not fully developed. Li et al. (2013) established a model of remanufacturing process route for used components on the basis of graphic evaluation technology [17]. Kin et al. proposed a conceptual methodology to aid the selection and planning of the reconditioning processes considering component conditions [18]. Wang et al. presented an optimization method to characterize fault features for remanufacturing process planning [19]. Wen et al. proposed an integrated remanufacturing production planning system by using bi-random variables and a planning model with compensation function approximation [20]. Similarly, the above studies failed to consider the quality factors in remanufacturing scheme planning. Butzer et al. proposed a capability maturity model, which can help to develop measures to improve remanufacturing operation processes [21]. Zhang et al. presented a method to identify product’s design characteristics for remanufacturing by using failure mode feedback and quality function deployment (QFD) [22]. However, the above studies covered limited criteria or failed to address the validation of final results.

Rough Set (RS) theory has the advantages of dealing with uncertainty and eliminating redundant data [23-25], and the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) method can compare and select evaluation objects in accordance with multiple attribute indicators [26]. By combining the two methods, we can extract the main quality attributes of used components from complex quality information and divide the quality grade in accordance with the relative close degree of each attributes to develop an appropriate remanufacturing scheme.

In this study, we use RS theory and TOPSIS method and refer to the fuzzy comprehensive approach [27-29] to propose a quality grade classification method for remanufacturing-oriented used components. In the proposed method, we define the main quality attributes by using attribute reduction according to RS theory. Then, we use TOPSIS to realize the quality grade classification by calculating the close degree. Subsequently, we determine the remanufacturing scheme in accordance with the quality grades of used components. Finally, we take the case of quality grade classification of used WD615 engine cylinder blocks as research object to verify the proposed model.

## 2. THE QUALITY CLASSIFICATION METHOD

### 2.1 Proposed Approach

The general idea of this proposed approach is shown in Fig. 1.

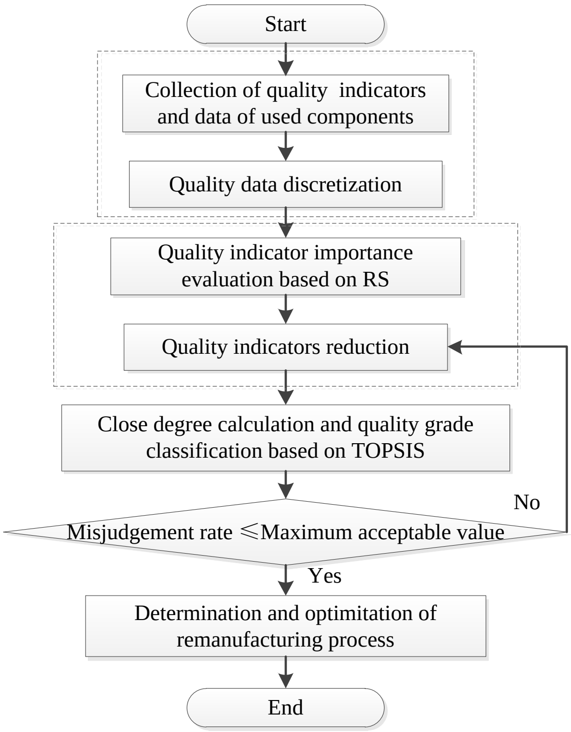

Fig.1. Flowchart of the proposed method.

First, the quality attributes of used components are collected, and the corresponding quality data are discretized according to RS theory. In this study, quality attributes are in fact referred to as the inspection indicators, which are related to the components. For example, the quality attributes of a mechanical product can be defined as: shaft hole grind, surface corrosion, or crack.

Second, the actual quality grades are determined by using the discretized quality data, and through their importance according to RS theory, the main quality attributes are determined and the redundant attributes are eliminated. The redundant attributes are the quality attributes that have little influence on the repaired components and thus can be ignored.

Third, the close degree between the actual and the ideal quality attribute values are calculated by using the TOPSIS method, through which, the model quality grade is determined.

Fourth, the two quality grades (model and actual) are compared, the aim is to analyze the accuracy of the established model. If the misjudgment rate is less than the maximum acceptable value, which indicates that the model is accurate, and the next step goes on. Otherwise, the importance of the quality attribute should be re-determined, and the model should be adjusted. In which, the misjudgment rate is calculated by dividing the number of inconsistencies between the model and the actual results with the total number of samples, and the maximum acceptable value is determined by the industry or company regulations [16].

Finally, the remanufacturing scheme is determined by the quality grade, the determinations can be referred to as the specific component remanufacturing technology and inspection criterion.

## 2.2 RS Theory and Related Definition

For the used components, it needs to identify the key factors that affect the remanufacturing quality by conducting quality attributes reduction [24], and that if the data are continuous values that cannot be classified, it also needs to conduct discretization. Accordingly, we adopt RS algorithm based on information entropy proposed by Xie et al. [25] to accomplish the above tasks. This algorithm exhibits high computational efficiency and does not change the compatibility of the decision system. The RS theory related notations and definitions are given in Table 1.

The RS theory related definitions are introduced as: Definition 1: If $S = (U, A, V, f)$ is a knowledge representation system, $U$ is the nonempty finite set called a domain, attributes $A$ can be divided into two disjoint subsets, namely, conditional attribute set $C$ and decision attribute set $D$, that is, $A = C \cup D$, $C \cap D = \varphi$; $V$ is the attribute value domain, decision table refers to the knowledge representation system with conditional attribute set $C$ and decision attribute set $D$, and $f: U \times A \rightarrow V$ is an information function that specifies the property values of each object in $U$.

Table 1. RS theory related notations and definitions.

| Notations | Definition | Notations | Definition |
|---|---|---|---|
| $S$ | Knowledge system | $P$ | Reduction set |
| $U$ | Domain | $\gamma_C(D)$ | Dependence between $D$ and $C$ |
| $A$ | Quality attribute sets | $card$ (•) | Cardinality of the set • |
| $V$ | Attribute value domain | $CORE(P)$ | Core of the decision table |
| $f$ | Mapping | $sgf(C_k, D)$ | Importance of attribute $C_k$ |
| $C$ | Conditional attribute set | $\omega$ $(C_k,D)$ | Normalized weight of attribute $C_k$ |
| $D$ | Decision attribute set | IND(D) | Indistinguishable relation |
| $R$ | Equivalence relation set | $POS_C(D)$ | Positive region of $C$ in U/IND(D) |

The discrete process of continuous attributes uses the selected breakpoints to divide the space of conditional attributes, that is, to divide the $m$ dimension space ($m$ is the number of conditional attributes) into finite regions. Attribute reduction finds the minimum attribute set without redundant attributes.

Definition 2: For the knowledge system $S=(U, A, V, f)$, we can define the dependence $\gamma_C(D)$ between decision attribute set $D$ and conditional attribute set $C$ is given by Eq.(1).

$$\gamma_C(D) = \frac{card(POS_C(D))}{card(U)} \tag{1}$$

Where $POS_C(D) = \bigcup_{x \in U/IND(D)} \overline{apr_C(D)}$ is the positive field of attribute set $C$ in U/IND($D$), and card(•) is the cardinality of the set.

If the smallest attribute subset $P \subseteq C \subseteq A$, which satisfies $\gamma P(X)=\gamma C(X)$, then set $P$ is called a reduction set of $C$ and denoted as $red(P)$. The decision table often has more than one reduction, and the intersection $CORE(P)$ of all reductions is called the core of the decision table, which is expressed as given by Eq. (2).

$$CORE(P) = \bigcap_{Ri \in red(\mathrm{P})} R_i, \quad (i = 1, 2, \ldots, n) \tag{2}$$

For $p_k \in C$, ($k$=1, 2, ..., $m$), the importance of the *kth* attribute $p_k$ is given by Eq.(3).

$$sgf(p_k, D) = \gamma_C(D) - \gamma_{C-\{p_k\}}(D) = \frac{card(POS_C(D)) - card(POS_{C-\{p_k\}}(D))}{card(U)} \tag{3}$$

The larger the value of *sgf* ($p_k$, $D$), the more important the feature attributes on the detection results. Using the normalization, we can obtain the normalized weight of quality attributes $p_k$ , by the normalized importance, we can eliminate the redundant attributes which with low importance, the calculation is obtained from Eq.(4).

$$\omega(p_k, D) = \frac{sgf(p_k, D)}{\sum_{p_k \in C} sgf(p_k, D)} \tag{4}$$

Where $0 \le \omega(p_k, D) \le 1$ and $\sum_{k=1}^{m} \omega(p_k, D) = 1$

## 2.3 Principle and Procedure of TOPSIS Method

TOPSIS is an analysis method suitable for comparing and selecting multiple evaluated objects [26]. By this method, we can sort and evaluate the evaluation objects in accordance with their close degrees to idealized targets. The steps of the TOPSIS method are listed as follows:

Step 1: Establish the initial evaluation matrix: Assuming that there are $m$ evaluation objects and $n$ evaluation attributes, the evaluation matrix $A$ can be constructed, as shown in Eq.(5), where $a_{ij}$ represents the *ith* ($i$=1,2, ..., $m$) evaluation object and the *jth* ($j$=1,2, ..., $n$) evaluation attribute.

$$A = (a_{ij})_{m \times n} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \tag{5}$$

The attributes are often with different dimensional units, and thus it need to normalize the value in matrix $A$. Given that we use a cost-type data in this study, then the smaller the value, the better the result. Eq. (6) is adopted for the dimensionless processing.

$$b_{ij}=\frac{a_j^{\max}-a_{ij}}{a_j^{\max}-a_j^{\min}}\quad i=1,2,\cdots,m,\ j=1,2,\cdots,n \tag{6}$$

Where $b_{ij}$ represents the *ith* evaluation object and the *jth* attribute, and the normalized decision matrix is expressed as $B=\left(B_{ij}\right)_{m\times n}$.

Step 2: Establish the weighted decision matrix $X=\left(x_{ij}\right)_{m\times n}$: Assuming that the weight vector of each evaluation object is $\omega=[\omega_1,\omega_2,\cdots,\omega_n]^T$, the weighted attribute can be expressed as follows in Eq.(7).

$$x_{ij}=\omega_j\cdot b_{ij},i=1,2,\cdots,m,\ j=1,2,\cdots,n \tag{7}$$

Step 3: Determine the ideal quality attribute value: Determine the positive ideal value $x_j^*$ and negative ideal value $x_j^0$, as shown in Eq. (8).

$$x_j^*=\{(\max_{1\le i\le m}x_{ij}\,\big|\,j\in J^+),(\min_{1\le i\le m}v_{ij}\,\big|\,j\in J^-)\}=\{x_1^*,x_2^*,...,x_n^*\} \tag{8.1}$$

$$x_j^0=\{(\min_{1\le i\le m}x_{ij}\,\big|\,j\in J^-),(\max_{1\le i\le m}v_{ij}\,\big|\,j\in J^-)\}=\{x_1^-,x_2^-,...,x_n^-\} \tag{8.2}$$

Step 4: Calculate the distance from the actual quality attribute value to the ideal quality attribute value.

Calculate the distance $d_i^*$ and $d_i^0$ from attribute $x_{ij}$ to positive and negative ideal values, respectively, as shown in Eq. (9).

$$d_i^*=\sqrt{\sum_{j=1}^{n}(x_{ij}-x_j^*)^2} \tag{9.1}$$

$$d_i^0=\sqrt{\sum_{j=1}^{n}(x_{ij}-x_j^0)^2} \tag{9.2}$$

Step 5: Calculate the relative close degree of evaluation objects in Eq.(10).

$$E_i^*=d_i^0\Big/(d_i^0+d_i^*) \tag{10}$$

Where, $E_i^*\in[0,1]$.

Rank the evaluation objects in accordance with the value of $E_i^*$ where in the higher the value, the better the evaluation object.

## 3. CASE STUDY

We take the used cylinder blocks of WD615 Steyr engine as the research object in this study. WD615 Steyr engine is widely used in long-distance transportation and heavy-duty trucks. Currently, considerable WD615 Steyr engines are remanufactured in China. Approximately 80% of the components can be reused and remanufactured for functional recovery. In the span of three months, we obtain the production data used in this study as the sample data of the proposed quality grade classification model. The used cylinder blocks of WD615 Steyr engine are shown in Fig. 2.

Fig. 2. The WD615 Styer engine cylinder.

### 3.1 Quality Attributes Determination of Cylinder Block

The quality attributes of used cylinder block mainly include the following contents:

1) Geometric accuracy refers to the degree to which the actual geometry of the parts is close to the ideal geometry, including the critical dimension, dimensional tolerance, shape tolerance, and position tolerance.

2) Surface quality, defined as the microscopic irregularities of the surface, including surface roughness, burns, scratches, corrosion, wear, abrasion, cracks, peeling, rust, and other defects, which are often expressed as $R_a$. When $R_a<0.8\mu m$, it is called mirror surface, indicating a very smooth surface.

3) Potential defects, including slag inclusion, porosity, cavity, weld defect, and micro crack.

By conducting an in-depth survey of cylinder blocks in the WD615 Steyr engine remanufacturing company, referring to the general definition about quality attributes in current workshop [20], we use the damage location and degree to define the following quality attributes:

$C_1$: spindle hole out of tolerance, $C_2$: spindle hole grinding, $C_3$: camshaft hole out of tolerance, $C_4$: camshaft hole grinding, $C_5$: tappet hole out of tolerance, $C_6$: cylinder hole out of tolerance, $C_7$: cylinder hole grinding, $C_8$: cylinder hole blister, and $C_9$: upper surface corrosion.

In accordance with the actual inspection and repairing experiences of workers and technicians, as well as the damage degree classification provided by engine remanufacturing company and the existing research on the classification standard of engine crankshaft component [17], the quality grade of cylinder block is divided into four levels. The grades and the classification standards are shown in Table 2.

Table 2. Quality attribute grade classification standard of used cylinder block.

| Grade | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ |
|---|---|---|---|---|---|
| 1 | (0, 0.03) | (0, 0.03） | (0, 0.04） | (0, 0.05） | (0, 0.05） |
| 2 | (0.03,0.05） | (0.03,0.05) | (0.04, 0.06) | (0.05,0.08） | (0.05,0.08) |
| 3 | (0.05,0.10） | (0.05,0.10） | (0.06,0.10） | (0.08,0.20） | (0.08,0.10） |
| 4 | (0.10,0.20） | (0.10,0.20） | (0.10,0.20） | (0.20,0.30） | (0.10,0.20） |
|  | $C_6$ | $C_7$ | $C_8$ | $C_9$ |  |
| 1 | (0, 0.03) | (0, 0.05) | - | - |  |
| 2 | (0.03,0.05） | (0.05,0.10） | Slight | Slight |  |
| 3 | (0.05,0.10） | (0.10,0.20） | Medium | Medium |  |
| 4 | (0.10,0.20） | (0.20,0.300 | Serious | Serious |  |

## 3.2 Actual Quality Grade and Quality Attribute Reduction by RS Theory

For three consecutive months, we collect 300 groups of data each month for cylinder blocks, limited by the space, only 100 groups of quality data in a month are listed as the sample data, as shown in Table 3.

According to RS theory, the quality evaluation system of the cylinder blocks can be described as $S= (U, C, D, V, f)$, where the domain $U=(X_1, X_2,\ldots, X_{100})$ is the sample data, the conditional attribute set $C=(C_1, C_2, \ldots, C_9)$ is the quality attribute, and the decision attribute set $D$=(1, 2, 3, 4) is the quality grade. Referred from Table 2, the data of Table 3 can be discretized, and the actual quality grade (column $D$) is obtained, as shown in Table 4.

Table 3. Quality attributes value of cylinder block.

| Sample | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ | $C_8$ | $C_9$ |
|---|---|---|---|---|---|---|---|---|---|
| $X_1$ | 0.060 | 0.066 | 0.049 | 0.087 | 0.090 | 0.082 | 0.053 | - | Medium |
| $X_2$ | 0.034 | 0.047 | 0.038 | 0.058 | 0.040 | 0.045 | 0.078 | Medium | Slight |
| $X_3$ | 0.046 | 0.026 | 0.053 | 0.056 | 0.089 | 0.038 | 0.051 | Slight | Medium |
| $X_4$ | 0.025 | 0.048 | 0.055 | 0.064 | 0.045 | 0.044 | 0.078 | Medium | Slight |
| $X_5$ | 0.125 | 0.055 | 0.018 | 0.280 | 0.098 | 0.015 | 0.218 | - | Medium |
| $X_6$ | 0.037 | 0.044 | 0.038 | 0.059 | 0.045 | 0.048 | 0.066 | Medium | Slight |
| $X_7$ | 0.082 | 0.075 | 0.059 | 0.135 | 0.093 | 0.078 | 0.153 | Serious | Medium |
| $X_8$ | 0.065 | 0.075 | 0.090 | 0.148 | 0.066 | 0.046 | 0.145 | Medium | - |
| $X_9$ | 0.047 | 0.072 | 0.093 | 0.093 | 0.098 | 0.064 | 0.180 | - | Serious |
| $X_{10}$ | 0.029 | 0.025 | 0.033 | 0.047 | 0.045 | 0.028 | 0.046 | - | Slight |
| $X_{11}$ | 0.049 | 0.058 | 0.077 | 0.054 | 0.083 | 0.057 | 0.154 | Medium | Slight |
| $X_{12}$ | 0.034 | 0.086 | 0.055 | 0.088 | 0.090 | 0.068 | 0.065 | - | Medium |
| $X_{13}$ | 0.128 | 0.136 | 0.180 | 0.283 | 0.095 | 0.174 | 0.280 | Serious | Serious |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| $X_{97}$ | 0.125 | 0.179 | 0.135 | 0.296 | 0.158 | 0.155 | 0.132 | Medium | Serious |
| $X_{98}$ | 0.066 | 0.087 | 0.050 | 0.098 | 0.097 | 0.083 | 0.076 | Slight | Medium |
| $X_{99}$ | 0.087 | 0.098 | 0.091 | 0.166 | 0.164 | 0.046 | 0.155 | Medium | - |
| $X_{100}$ | 0.035 | 0.025 | 0.050 | 0.149 | 0.186 | 0.026 | 0.065 | Slight | Medium |

Table 4. Actual quality grade classification after discretization.

| Sample | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ | $C_8$ | $C_9$ | $D$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $X_1$ | 3 | 3 | 2 | 3 | 3 | 3 | 2 | 1 | 3 | 3 |
| $X_2$ | 2 | 2 | 1 | 2 | 1 | 2 | 2 | 3 | 2 | 2 |
| $X_3$ | 2 | 1 | 2 | 2 | 3 | 2 | 2 | 2 | 3 | 2 |
| $X_4$ | 1 | 2 | 2 | 2 | 1 | 2 | 2 | 3 | 2 | 2 |
| $X_5$ | 4 | 3 | 4 | 4 | 3 | 4 | 4 | 1 | 3 | 4 |
| $X_6$ | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 3 | 2 | 2 |
| $X_7$ | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 4 | 3 | 3 |
| $X_8$ | 3 | 3 | 3 | 3 | 2 | 2 | 3 | 3 | 1 | 3 |
| $X_9$ | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 1 | 4 | 3 |
| $X_{10}$ | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 |
| $X_{11}$ | 2 | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 2 | 3 |
| $X_{12}$ | 2 | 3 | 2 | 3 | 3 | 3 | 2 | 1 | 3 | 3 |
| $X_{13}$ | 4 | 4 | 4 | 4 | 3 | 4 | 3 | 4 | 4 | 4 |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| $X_{97}$ | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 4 | 4 |
| $X_{98}$ | 3 | 3 | 2 | 3 | 3 | 3 | 2 | 2 | 3 | 3 |
| $X_{99}$ | 3 | 3 | 3 | 3 | 3 | 2 | 3 | 3 | 1 | 3 |
| $X_{100}$ | 2 | 1 | 2 | 3 | 3 | 1 | 2 | 2 | 3 | 2 |

Using RS theory introduced in Section 2.2 and Eqs. (1-2), the corresponding values can be obtained as follows:

CORE $(C) = \{C_1, C_2, C_6, C_7\}$

U/IND $(D) = \{\{X_{10}, X_{33}, X_{52}, X_{63}, \ldots, X_{96}\}, \{X_2, X_3, X_4, X_{63} \ldots, X_{100}\}, \ldots\}$

U/$(C$-$\{C_1\}) = \{\{X_{10}, X_{74}, \ldots\}, \{X_4, X_6, \ldots\}, \ldots\}$

$\mathrm{POS}_{C\text{-}\{C1\}}(D)=\{X_2, X_3, X_4, \ldots, X_{90}, X_{100}\}$, $\mathrm{POS}_{C\text{-}\{C2\}}(D)=\{X_1, X_2, X_3, \ldots, X_{97}, X_{98}\}$,

Similarly, the expressions for $\mathrm{POS}_{C\text{-}\{C3\}}(D), \ldots, \mathrm{POS}_{C\text{-}\{C9\}}(D)$ can be obtained. Using Eq. (3), the importance of each quality attribute can be obtained as

$$sgf(C_1, D) = \frac{card(POS_C(D)) - card(POS_{C-\{C_1\}}(D))}{card(U)} = 0.285$$

Similarly, it can be seen that:

$sgf\,(C_2, D)=0.256$, $sgf\,(C_3, D)=0.104$, $sgf\,(C_4, D)=0.085$, $sgf\,(C_5, D)=0.067$, $sgf\,(C_6, D)=0.184$, sgf $(C_7, D)=0.195$, $sgf\,(C_8, D)=0.002$, $sgf\,(C_9, D)=0$.

By Eq.(4), the normalized importance of each quality attribute are given as:

$\Omega\ (C_1, D)=0.242$, $\omega(C_2, D)=0.218$, $\omega(C_3, D)=0.088$, $\omega(C_4, D)=0.072$, $\omega(C_5, D)=0.057$, $\omega(C_6, D)=0.156$, $\omega(C_7, D)=0.166$, $\omega(C_8, D)=0.001$, $\omega(C_9, D)=0$.

For example, the normalized importance $C_1$ can be calculated as

$$\omega(C_1, D) = \frac{sgf\,(C_i, D)}{\sum_{i=1}^{9} sgf\,(C_i, D)} = 0.242$$

The importance results show that the indicators of $C_1$, $C_2$, $C_3$, $C_6$, and $C_7$ have a great influence on the quality of remanufacturing cylinder block; $C_4$ and $C_5$ is the posterior; and $C_8$ and $C_9$ belong to the least important indicator, which can be regarded as redundant indicators. Therefore, the reduction set is expressed as *red* $(P) = \{C_1, C_2, C_3, C_4, C_5, C_6, C_7\}$

## 3.3 Model Quality Grade Classification by TOPSIS Method

Following the steps of the TOPSIS method and Eq. (5), combined with Table 1, we construct 4 typical samples of different grades and 100 groups of test samples in the initial evaluation matrix *A* for *red*(*P*), and mark the typical samples with different quality grades with “*”.

$$A=\begin{array}{ccccccccc}
C_1 & C_2 & C_3 & C_4 & C_5 & C_6 & C_7 & & \\
0.030 & 0.030 & 0.040 & 0.050 & 0.050 & 0.030 & 0.050 & X_1^* & 1 \\
0.050 & 0.050 & 0.060 & 0.080 & 0.080 & 0.050 & 0.100 & X_2^* & 2 \\
0.100 & 0.100 & 0.100 & 0.200 & 0.100 & 0.100 & 0.200 & X_3^* & 3 \\
0.200 & 0.200 & 0.200 & 0.300 & 0.200 & 0.200 & 0.300 & X_4^* & 4 \\
0.060 & 0.066 & 0.049 & 0.087 & 0.090 & 0.082 & 0.053 & X_1 & 3 \\
0.034 & 0.047 & 0.038 & 0.058 & 0.040 & 0.045 & 0.078 & X_2 & 2 \\
0.046 & 0.026 & 0.053 & 0.056 & 0.089 & 0.038 & 0.051 & X_3 & 2 \\
0.025 & 0.048 & 0.055 & 0.064 & 0.045 & 0.044 & 0.078 & X_4 & 2 \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & & \vdots \\
0.125 & 0.179 & 0.135 & 0.296 & 0.158 & 0.155 & 0.132 & X_{97} & 4 \\
0.066 & 0.087 & 0.050 & 0.098 & 0.097 & 0.083 & 0.076 & X_{98} & 3 \\
0.087 & 0.098 & 0.091 & 0.166 & 0.164 & 0.046 & 0.155 & X_{99} & 3 \\
0.035 & 0.025 & 0.050 & 0.149 & 0.186 & 0.026 & 0.065 & X_{100} & 2
\end{array}$$

Using Eq. (6), the normalized matrix *B* of *A* can be finally obtained, as follows:

$$B=\begin{bmatrix}
0.971 & 0.971 & 0.941 & 0.926 & 0.936 & 0.977 & 0.912 \\
0.857 & 0.857 & 0.824 & 0.815 & 0.750 & 0.862 & 0.730 \\
0.571 & 0.571 & 0.588 & 0.370 & 0.625 & 0.575 & 0.365 \\
0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 \\
0.800 & 0.766 & 0.888 & 0.789 & 0.688 & 0.678 & 0.901 \\
0.949 & 0.874 & 0.953 & 0.896 & 1.000 & 0.891 & 0.810 \\
0.880 & 0.994 & 0.053 & 0.904 & 0.694 & 0.931 & 0.909 \\
1.000 & 0.869 & 0.853 & 0.874 & 0.969 & 0.897 & 0.810 \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
0.423 & 0.120 & 0.382 & 0.015 & 0.263 & 0.259 & 0.613 \\
0.766 & 0.646 & 0.882 & 0.748 & 0.644 & 0.672 & 0.818 \\
0.646 & 0.583 & 0.641 & 0.496 & 0.225 & 0.885 & 0.529 \\
0.943 & 1.000 & 0.882 & 0.559 & 0.088 & 1.000 & 0.858
\end{bmatrix}$$

Take the calculation of $b_{11}$ for example, because $a_1^{\max} = 0.2$ , $a_1^{\min} = 0.025$ , then, $b_{11} = \dfrac{0.2-0.03}{0.2-0.025} = 0.971.$

From Eq. (7), we can obtain the weighted normalized matrix *X* as follows:

$$X = B \times \omega^{T}_{(C_j, D)}$$

$$= \begin{bmatrix} 0.235 & 0.212 & 0.084 & 0.067 & 0.053 & 0.152 & 0.151 \\ 0.207 & 0.187 & 0.073 & 0.059 & 0.043 & 0.134 & 0.121 \\ 0.138 & 0.125 & 0.052 & 0.027 & 0.036 & 0.090 & 0.060 \\ 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 \\ 0.194 & 0.170 & 0.079 & 0.057 & 0.038 & 0.106 & 0.150 \\ 0.230 & 0.191 & 0.085 & 0.064 & 0.057 & 0.139 & 0.134 \\ 0.213 & 0.217 & 0.077 & 0.065 & 0.040 & 0.145 & 0.151 \\ 0.242 & 0.189 & 0.076 & 0.063 & 0.055 & 0.140 & 0.134 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0.104 & 0.026 & 0.034 & 0.001 & 0.015 & 0.040 & 0.101 \\ 0.185 & 0.141 & 0.079 & 0.054 & 0.037 & 0.105 & 0.136 \\ 0.156 & 0.127 & 0.057 & 0.036 & 0.013 & 0.138 & 0.088 \\ 0.228 & 0.218 & 0.079 & 0.040 & 0.005 & 0.156 & 0.142 \end{bmatrix}$$

For example, as the calculation of $x_{11}$, because $\omega$ $(C_1, D) = 0.242$, then, $x_{11} = 0.971 \times 0.242 \approx 0.235$.

Using Eq. (8), the positive and negative ideal values of the matrix is expressed as: $x_j^* =$[0, 0, 0, 0, 0, 0, 0], $x_j^0 =$[0.242, 0.218, 0.085, 0.069, 0.055, 0.156, 0.159]

From Eqs. (9–10), the distance $d_i^*$ and $d_i^0$ from quality attribute $x_{ij}$ to positive and negative ideal values, and the relatively close degrees ($E_i^*$) between each actual and ideal quality attribute value are obtained, as shown in Table 5.

According to the close degrees, the model quality grade of cylinder block can be classified as follows:

Grade 1: $0 \le E_i^* \le 0.05$

Grade 2: $0.05 < E_i^* \le 0.30$

Grade 3: $0.30 < E_i^* \le 0.50$

Grade 4: $0.50 < E_i^* \le 1.00$

Then, the model quality grades of the 100 cylinder block are determined in the last column of Table 5.

Table 5. Model quality grade classification results of cylinder block based on TOPSIS.

| Sample | $d_i^*$ | $d_i^0$ | $E_i^*$ | Model quality grade |
|---|---|---|---|---|
| $X_1$ | 0.401 | 0.013 | 0.031 | 1 |
| $X_2$ | 0.348 | 0.067 | 0.161 | 2 |
| $X_3$ | 0.226 | 0.179 | 0.442 | 3 |
| $X_4$ | 0 | 0.413 | 1 | 4 |
| $X_5$ | 0.332 | 0.089 | 0.212 | 3 |
| $X_6$ | 0.376 | 0.043 | 0.102 | 2 |
| $X_7$ | 0.385 | 0.037 | 0.087 | 2 |
| $X_8$ | 0.381 | 0.042 | 0.100 | 2 |
| ... | … | … | … | … |
| $X_{97}$ | 0.158 | 0.285 | 0.644 | 4 |
| $X_{98}$ | 0.307 | 0.114 | 0.271 | 2 |
| $X_{99}$ | 0.268 | 0.157 | 0.369 | 3 |
| $X_{100}$ | 0.390 | 0.062 | 0.137 | 2 |

### 3.4 Accuracy Analysis of Model Quality Grade Result

The comparison of the model and the actual results of quality grade are shown in Table 6, we use “Yes” or “No” to express the model result of quality grade “consistent or not” with actual quality grade.

Table 6. Model results accuracy of quality grade classification.

| Sample | Model result | Actual result | Consistent or not |
|---|---|---|---|
| $X_1$ | 1 | 1 | Yes |
| $X_2$ | 2 | 2 | Yes |
| $X_3$ | 3 | 3 | Yes |
| $X_4$ | 4 | 4 | Yes |
| $X_5$ | 3 | 3 | Yes |
| $X_6$ | 2 | 2 | Yes |
| $X_7$ | 2 | 2 | Yes |
| $X_8$ | 2 | 2 | Yes |
| ... | … | … | ... |
| $X_{97}$ | 4 | 4 | Yes |
| $X_{98}$ | 2 | 3 | No |
| $X_{99}$ | 3 | 3 | Yes |
| $X_{100}$ | 2 | 2 | Yes |

The actual judgment of sample No. 98 is grade 3, and in the model, the misjudgment is grade 2. By statistics, the misjudgment ratio in the total sample of 100 cylinder blocks is 2, and the misjudgment rate is 2%. By tracking for 2 more months of remanufacturing cylinder blocks, we find that the misjudgment rate is 2% and 3%, respectively. By consulting with company experts and technicians and referring to the average repairing ratio (the percentage of parts successfully repaired is approximately 90%) of engine components, we set the maximum acceptable value of misjudgment rate in the model to 10%. Therefore, the model evaluation results are in good consistent with the actual judgment result.

### 3.5 Formulation of Remanufacturing Scheme based on Quality Grade

According to the quality grade classification, referred to as the cylinder block WD615 series diesel engine remanufacturing process code and inspection criterion [30], the remanufacturing scheme for four quality grades of used cylinder block is determined as follows:

For the first grade of old cylinder block, the detection indicators are within the normal range. Only the oil passage and cylinder body need to be cleaned, and the main axle hole, cylinder hole, shaft hole, and tappet hole need to be honed until meet the requirements.

For the second grade of old cylinder block, the detection indicators are within the repairing range. Accordingly, we can make the following remanufacturing process route: blast cleaning→ cylinder upper plane grinding→ holes boring→ holes honing→ oil path and cylinder body cleaning→ polishing→ late finishing; where holes refer to spindle hole, shaft hole tappet hole, and cylinder hole.

For the third grade of old cylinder block, considerable out-of-tolerance repairs need to be performed by surface engineering and mechanical machining. Accordingly, remanufacturing process can be adopted as follows: blast cleaning → installing bowl plug→ cylinder upper plane grinding→ crankcase grinding→ plasma spraying→ holes boring→ holes honing→ sleeve setting→ water inspection→ bushing installing→ oil channel and cylinder body cleaning→ late finishing; where holes refer to spindle hole, shaft hole tappet hole, and cylinder hole.

The fourth grade of old cylinder block is seriously out of tolerance, and the repair cost is too high or the repairs are not possible to be remanufactured. This kind of blank can be recycled.

## 4. CONCLUSIONS

In this study, we propose a quality grade classification method of used product components for remanufacturing on the basis of RS theory and the TOPSIS method. In the proposed method, we define the main quality attributes by using attribute reduction according to RS theory. Then, we use the TOPSIS method to determine the quality grade by calculating the relatively close degree between the actual and the ideal quality grade values. Finally, we formulate the corresponding remanufacturing scheme in accordance with the different quality grades of the used components.

We apply the proposed method to the used cylinder blocks of WD615 Steyr engine to prove its validity and practicality. The case results can provide a reference for similar engine component remanufacturing in China. This method can also be applied to other remanufacturing components, such as connecting rod, crankshaft, and flywheel. In addition to cylinder blocks, we have also tested the validity of the proposed method in the application of cylinder head, which provided a quick and effective solution for the remanufacturing scheme arrangement of “blanks”.

This study aims to provide a practical method that enables a quick quality grading of used engine components, and accordingly to provide an effective remanufacturing scheme, which can enhance the conventional quality grade classification method. Although the proposed method is feasible in theory, the calculation process will be more complicated when complex parts and numerous indicators are considered. Therefore, further research can focus on the development of related computer software to improve evaluation efficiency.

## DECLARATION OF CONFLICT OF INTERESTS

The authors have declared no conflict of interests.

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