Multi-granularity feasibility evaluation method of the partial destructive disassembly for an end-of-life product

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Abstract
Partial destructive disassembly (PDD) is essential for end-of-life products to improve their automatic disassembly efficiency and reduce disassembly cost. A feasibility evaluation of the PDD is the key step to evaluate whether the PDD can be implemented. However, it has not been studied previously to our knowledge. To deal with this problem, a multi-granularity feasibility evaluation method is proposed. A multi-granularity feasibility evaluation model of the PDD was constructed based on the complex product’s hierarchical structure, which not only described the evaluation indices from the product level to the component level but also presented methods and rules to quantify them. Thus, disassembly entropy was introduced into the target group’s coarse granularity evaluation. The feasibility of the fine-grained index of the PDD for the component layer was constructed based on the product’s failure characteristic. The fine-grained index was calculated by the fuzzy trigonometric function, and its weighting was obtained based on the structure entropy weight method. Thus, the results of the evaluation were used as feedback to guide the PDD process. Finally, a Passat engine case study illustrates the feasibility and effectiveness of the method.

Keywords Partial destructive disassembly · Multi-granularity · Failure characteristics · Disassembly entropy · Structure entropy weight method

1 Introduction

Remanufacturing is an effective method to recover and reuse the residual value of end-of-life (EOL) products [1]. Disassembly is one of the key steps in remanufacturing. According to the depth of the disassembly, dismounting technology, and degree of automation, disassembly can be divided into several categories, such as the serial, parallel, partial destructive, and normal disassembly [2–6]. A reasonable remanufacturing disassembly mode can improve the mass disassembly efficiency and reduce the remanufacturing cost.

Disassembly is mainly divided into normal disassembly, destructive disassembly, and partial destructive disassembly (PDD). Normal disassembly means obtaining the target component without destroying any component. Destructive disassembly means material recovery through violent destruction of dismantling products. PDD is between normal disassembly and destructive disassembly and aims to dismantling components that cannot be disassembled due to serious failure by destroying connectors or low value parts. At present, the study of the PDD is attracting widespread attention. Thus, the separation of components is realized by cutting a certain connector, which is mainly applied to non-detachable connections, such as riveting and welding [7]. Normal disassembly must bypass these connections, whereas partial destructive disassembly combines the advantages of the complete destructive and normal disassembly. Thus, the parallel partial destructive disassembly has important research significance for improving the remanufacturing disassembly efficiency.

PDD is an effective and efficient disassembly mode, which is essential for the automatic disassembly system to perform batch disassembly. It is known that the remanufacturing core
often has un-disassembly connections (e.g., riveting or welding) and a structure with severe failures (e.g., corrosion or fractures). However, owing to the limitations of cost and demolition time, the feasibility of the partial destructive disassembly becomes an important problem to be solved.

2 Literature review

2.1 Evaluation of product disassemblability in normal disassembly mode (NDM)

Much work has been done in the evaluation of disassemblability, which can be divided into two categories: product level evaluation and component level evaluation. In the product level evaluation, Du et al. [8] evaluated the feasibility and effectiveness of machine tool disassembly from the technical, economic, and environmental feasibility perspectives. Suga et al. [9] used the disassembly entropy to evaluate the overall disassemblability of products. Sabaghi et al. [10] used the disassembly accessibility, contact surface, coupling means, and number of connections to evaluate the overall disassemblability of products. In the component level evaluation, Hander et al. [11] extracted the geometric constraint information of the product and interference in the disassembly process, established the interference and correlation matrix, and evaluated the disassembly ability using the interference information. Achillas et al. [12] took the residual life, quantity, quality, disassembly convenience, and environmental impact of parts as the evaluation indexes to obtain the global

| Failure characteristic | Failure types | Failure level | Recycling decision |
|------------------------|--------------|--------------|--------------------|
| Aging ($f_1$)          | Metamorphic type ($c_1$) | Basically no failure ($e_1$) | Reuse ($h_1$) |
| Abrasion ($f_2$)       | Involution forms ($c_2$) | Minor failure ($e_2$) | Remanufacturing ($h_2$) |
| Corrosion ($f_3$)      | Damage type ($c_3$) | General failure ($e_3$) | Material recycling ($h_3$) |
| Deformation ($f_4$)    | Deformation type ($c_4$) | Moderate failure ($e_4$) | Discarding ($h_4$) |
| No failure ($f_5$)     | Loose type ($c_5$) | Major cycle failure ($e_5$) | – |
| Fracture ($f_6$)       | –             | –            | –                 |
| Cavern ($f_7$)         | –             | –            | –                 |
| Burn ($f_8$)           | –             | –            | –                 |
| …                      | –             | –            | –                 |
multi-criteria index by weighted evaluation and to determine the disassembly feasibility of parts. Chen et al. [13] calculated the disassembly efficiency of end-of-life products based on the fuzzy analytic hierarchy process evaluation method. On this basis, Sun et al. [14] introduced the failure rate of parts and established the comprehensive evaluation model of the failure rate and disassembly time.

### 2.2 Evaluation of product disassemblability in partial destructive mode (PDM)

Compared with feasibility evaluation of product disassemblability in NDM, the feasibility evaluation of product disassemblability in PDM has the advantages of guiding the actual disassembly process and a lower disassembly time.
and energy consumption. It has gradually become an active research topic for scholars. In terms of the feasibility evaluation of product disassemblability in PDM, the main index was constructed from the economy and disassembly efficiency. Song et al. [15] compared the cost of the disassembly sequence scheme between the partial disassembling mode and the normal one. Zhou [16] introduced time, cost, tools, noise, environment, and other indicators to evaluate the partial destructive disassembly sequence planning scheme and screen out the optimal disassembly sequence. Zeng et al. [17] evaluated the balance problem of a partial destructive disassembly line from the aspects of profit and energy consumption. Wang et al. [18] destroyed inexpensive parts and then evaluated the partial destructive disassembly line from the number of stations, smoothness, energy consumption, and disassembly profit.

Studies have conducted the disassembly feasibility evaluation from different perspectives. However, there is no systematic study on the feasibility evaluation of end-of-life products. As Zhang et al. [19], who constructed a multi-granularity of hierarchy disassemblability evaluation model from product level and design units level based on complex products’ hierarchy structure. Zhu et al. [20] constructed a two-level evaluation index system from two levels: product and component. The component level index reflected the features of both current operations, and the product level reflected the previous disassembly process. Finally, the index was quantified by a Look-up Table.

2.3 Research motivation

To sum up, there are two main problems in the partial destructive disassembly evaluation of end-of-life products.

1. Disassembly feasibility evaluation studies focus on the evaluation of individual components and neglect the evaluation of the whole product. However, the number of product components is large, so the overall evaluation is difficult.

2. Most studies focused on the ideal disassembly feasibility analysis rather than considering the influence of the failure characteristics on the disassembly feasibility. In fact, the serious failure characteristics of the components also have an important impact on the disassemblability of the components.
The current weighting methods are mainly based on the analytic hierarchy process (AHP), and thus, there exists subjectivity and randomness in the evaluation results.

To address these problems, we propose a multi-granularity evaluation method for disassembly feasibility of EOL products in partial destructive mode. The remainder of this article is organized as follows. In Section 3, the multi-granularity feasibility evaluation model of a partial destructive disassembly for EOL products is proposed. Section 4 introduces the feasibility evaluation method of a partial destructive disassembly. In Section 5, the proposed model and method are validated with a case study. Concluding remarks are provided in Section 6.

3 Multi-granularity feasibility evaluation model of partial destructive disassembly

PDD aims to improve the disassembly efficiency by partial destructive disassembly operation under the premise of ensuring the integrity of the target component. The PDD encompasses two different disassembly methods: normal disassembly and destructive disassembly. The disassembly’s direction, time, and tools of the EOL products are different with different disassembly methods. However, these factors cannot fully reflect the feasibility of the PDD of the products. Based on the complex products’ hierarchy structure, this study presents a multi-granularity feasibility evaluation model (MGFEM) of the PDD for EOL products. The evaluation objects of the MGFEM are target group and components, and several evaluation indexes are constructed from target group layer and component layer, as shown in Fig. 1.

3.1 Construction of target group

Owing to the large number of complex product components, it is difficult to evaluate them. Therefore, the target group was defined according to the component failure characteristics, which is the parts set composed of those with a high failure probability and high value parts [20] to reduce the complexity of the whole evaluation.

3.1.1 Expression and quantification of the failure characteristics of components

Uncertain changes have taken place in the external characteristics and internal materials of the EOL products, as shown in Table 1. The failure type matrix $M_1$ was established to describe the failure type of complex product part $v_i$, which can be expressed by Eq. (1) as follows:

$$ M_1 = (r_{ij})_{n \times 5} $$

where

$$ r_{ij} = \begin{cases} 1 & \text{Part } v_i \text{ existence of failure type } c_j \\ 0 & \text{Node } v_i \text{ no existence of failure type } c_j \end{cases} $$

In view of the uncertainty and difficulty in accurate quantification of failure characteristics of components, an expert evaluation method was used. The failure state comment set of components is $E = \{e_1, e_2, e_3, e_4, e_5\}$, where $e_1, e_2, e_3, e_4, e_5$
represents basically no failure, minor failure, general failure, moderate failure, and major cycle failure, respectively.

Invite $N$ experts to evaluate the status of failure characteristics, and the evaluation result is $A = [a_i] (i = 1\sim5)$, where $a_i = \frac{n_{ai}}{N}$ and it is the number of experts choosing the $i$-th evaluation value. At this point, the eigenvalue of the failure type $c_j$ of component $v_i$ is shown in Eq. (2).

$$e_{ij} = E \cdot A^T \tag{2}$$

Table 3 Main parts information of Passat engine

| Part number | Component name          | Quantity | Remover | Disassembly direction | Connection type (number) |
|-------------|-------------------------|----------|---------|-----------------------|-------------------------|
| 1           | Train valve cover       | 1        | Wrench  | +X                    | Bolt connection (2)     |
| 2           | Booster pump wheel      | 1        | Wrench  | +Y                    | Bolt connection (2)     |
| 3           | Oil pump                | 1        | Screwdriver | +X                 | Screw (2)               |
| 4           | Oil pump chain          | 1        | Special tool | +Z              | Bolt connection (2)     |
| 5           | Turbocharger flywheel   | 1        | Lama    | +Y                    | Welding                 |
| 6           | Gearbox assembly        | 1        | Wrench  | −Z                    | Bolt connection (2)     |
| 7           | Bearing shell           | 8        | Hand    | +X/−X                 | Welding                 |
| 8           | Connecting rod bearing shell | 8 | Hand   | +X/−X                 | Welding                 |
| 9           | Cylinder                | 1        | Screwdriver | −X               | Screw (2)               |
| 10          | Camshaft                | 2        | Screwdriver | +X             | Screw (2) and geometric constraint |
| 11          | Crankshaft              | 1        | Hand    | +X                    | Geometric constraint    |
| 12          | Pitman                  | 4        | Wrench  | +X                    | Hexagonal nut (1)       |
| 13          | Igniter                 | 4        | Special tool | +X            | Bolt connection (8)     |
| 14          | Cylinder block          | 4        | Hand    | +X                    | Welding                 |
| 15          | Air intake camshaft locking block | 5 | Screwdriver | +X             | Screw (2)               |
| 16          | Exhaust camshaft locking block | 5 | Screwdriver | +X             | Screw (2)               |
| 17          | Oil pan                 | 1        | Wrench  | −X                    | Bolt connection (2)     |
| 18          | Intake manifold         | 1        | Wrench  | +Y                    | Hexagonal nut (1)       |
| 19          | Crankshaft bearing cap  | 4        | Wrench  | +X                    | Bolt connection (2)     |
| 20          | Intake pipe             | 2        | Screwdriver | +Y            | Screw (2)               |
| 21          | Booster belt            | 1        | Special tool | +Y          | Geometric constraint    |
| 22          | Timing belt pulley      | 1        | Lama    | +Z                    | Geometric constraint    |
| 23          | Exhaust manifold        | 1        | Wrench  | −Y                    | Bolt connection (2)     |
| 24          | Timing belt             | 1        | Special tool | +Z       | Elasticity              |
| 25          | Timing belt toothed pulley | 1     | Lama    | +Z                    | Geometric constraint    |
| 26          | Crankshaft wheel        | 1        | Lama    | +Z                    | Geometric constraint    |
| 27          | Camshaft transmission wheel | 1     | Lama    | +Z                    | Geometric constraint    |
| 28          | Valve assembly          | 1        | Wrench  | +X                    | Geometric constraint    |
| 29          | Air filter              | 1        | Screwdriver | +Y             | Screw (2)               |
| 30          | Booster belt tension wheel | 1    | Lama    | +Y                    | Geometric constraint    |
| 31          | Engine support          | 2        | Wrench  | +Y/−Y                 | Hexagonal nut (1)       |
| 32          | Turbocharger            | 1        | Wrench  | +Y                    | Bolt connection (2)     |
| 33          | Connecting rod cap      | 4        | Wrench  | +X                    | Bolt connection (2)     |
| 34          | Clutch flywheel         | 1        | Hand    | −Z                    | Geometric constraint    |
| 35          | Clutch pressure plate   | 1        | Wrench  | −Z                    | Hexagonal nut (1)       |
| 36          | Clutch driven plate     | 1        | Hand    | −Z                    | Geometric constraint    |
| 37          | Clutch cover back plate | 1        | Wrench  | −Z                    | Bolt connection (2)     |
To facilitate the overall feasibility evaluation of a product’s PDD, the products are simply classified according to the failure characteristics of complex products. According to the evaluation of various failure characteristics of parts by many experts, the failure characteristics of the parts are quantified by Eqs. 1 and 2, which can be expressed by Eq. (3).

\[ M_2 = \frac{e_{ij}}{r_{ij}} \text{ (3)} \]

where \( e_{ij} \) represents the characteristic value of the component failure and \( r_{ij} \) represents the failure type of components.

### 3.1.2 Quantization of coarse-grained index of target group based on disassembly entropy

Three major factors affecting the PDD feasibility of the target group were selected: failure rate, number of joints, and cost of PDM. In this study, the disassembly entropy introduced by Suga et al. [21] is expanded. The PDD feasibility of the target group is quantitatively assessed using the disassembly entropy. The smaller the disassembly entropy is, the better the PDD feasibility of the target group is.

1. **Failure rate means the proportion of high failure probability components in the target group.** The difficulty of PDD is related to the failure rate of parts. The higher the failure rate is, the more difficult the PDD is, and the greater the feasibility of PDD is. The disassembly entropy of failure rate is

\[ S_1 = \log_2 \left( \frac{N_i}{N_s} \right), \quad (4) \]

where \( N_i \) indicates the total number of sub-assemblies in the target group and \( N_s \) is the total number of sub-assemblies with high failure probability in the target group.

2. **Number of joints**

The destruction of the joints is mainly carried out by means of destruction in PDD due to the low value of the joint in general. The more the number of joints are, the more selectivity to destroy disassembly components are, and the higher the feasibility of PDD. Thus, the disassembly entropy of the number of joints is

\[ S_2 = \log_2 \left( \frac{N_i + N_k}{N_k} \right), \quad (5) \]

where \( N_i \) indicates the total number of sub-assemblies in the target group and \( N_k \) is the total number of connectors methods \( k \) (such as screws, bolted joints, welding, riveting, and non-removable connections) in the target group.

3. **Cost of PDM means the proportion of the sum of normal disassembly cost and destructive disassembly cost in normal disassembly cost.** The smaller the disassembly income is, the lower the cost of PDD is, and the higher the feasibility of PDD is. The disassembly entropy of cost of PDM is

\[ S_3 = \log_2 \left( \frac{C_n + C_m}{C_n} \right), \quad (6) \]

where \( C_n \) indicates the cost of normal disassembly and \( C_m \) is the cost of destructive disassembly.

For complex products, the coarse-grained evaluation of the target group is conducted, and then, the total disassembly entropy of the target group is

\[ S = k_1S_1 + k_2S_2 + k_3S_3, \quad (7) \]

where \( k_i \) (\( i = 1, 2, 3; k_1+k_2+k_3 = 1 \)) is the weight of the disassembly entropy and its value is determined by the degree of influence on the PDD feasibility of the target group. The total disassembly entropy of the target group fairly comprehensively reflects the overall feasibility evaluation of PDD for EOL products and is the foundation of construct MGFEM of an EOL product.

### 3.2 Fine-grained evaluation of component level

#### 3.2.1 Construction of the fine-grained index of the component level

A fine-grained evaluation object is a component. In the actual disassembly process, owing to the serious failure of the
components, they cannot be disassembled, and the disassembly efficiency is improved by destroying some components. Therefore, the PDD feasibility is related to the failure degree and disassembly process of the components. The PDD process of general components is as follows:

1. The position of recognition PDD and normal disassembly components

The position of recognition PDD and normal disassembly components can be evaluated by the index of recognition PDD components, including the recognition of components’ connection types and component’s failure characteristics. The more serious the failure characteristics are, the easier the components’ recognition is, and the stronger the feasibility of PDD is.

2. Different disassembly tool is replaced and alignment with the connector positioning.

The disassembly efficiency of PDD is influenced by transformation between tools with different disassembly methods and the relative positioning accuracy with the connectors. If different disassembly tools are replaced more times and have high positioning accuracy, the cost of PDD will increase, and the energy will be consumed. Therefore, disassembly tools and positioning accuracy were used to evaluate the disassembly feasibility of PDD.

3. Destructive or remove corresponding connectors.

The destruction of connectors involves disassembly direction, disassembly time, pushing force, and accessibility. When the failure degree of the component is serious, the destructive connection will change the previous disassembly direction, and the frequent change of the disassembly direction will reduce the disassembly efficiency and bring inconvenience to the PDD. The serious failure of components will lead to the increase of the required disassembly force and the difficulty of tool accessibility, which seriously affects the disassembly efficiency of PDD. Therefore, the disassembly direction, disassembly time, disassembly force, and accessibility were used to evaluate the disassembly feasibility of PDD. Removing the corresponding connector involves component structure size. The failure degree of components is serious, and the structure is large; the tool is difficult to grasp, and it is difficult to remove the corresponding connectors and the connected components, which affects the disassembly efficiency of local damage.

To sum up, eight fine-grained indexes, including recognition of PDD components, disassembly tool, disassembly direction, disassembly time, pushing force, accessibility, positioning accuracy, and component structure size, were determined based on the failure characteristics and shown in Fig. 1.
3.2.2 Quantization of fine-grained index of the component level based on the failure characteristics

The above indexes are related to the component failure degree, so the component fine-grained indexes were quantified based on the failure characteristics. In addition, the expert evaluation method was used to quantify the failure characteristics of components. Because the influence of the component failure characteristics on the fine-grained evaluation index is fuzzy, the fuzzy trigonometric function was integrated. The assessing scale set was used to grade the effect of the component failure degree on fine-grained indexes. The evaluation grade and value are shown in Table 2.

The different failure grades have different influences on the PDD feasibility. Moreover, the membership function of each index and failure grade was established according to the experts’ experience and the literature [22, 23], as shown in Fig. 2.

Taking the index of recognition of PDD components as an example (Fig. 2), according to the range of the failure characteristic value (Table 2), the membership of the interval \([\Delta a_i, \Delta b_j]\) is \([\Lambda_i^a, \Lambda_j^a]\), and the index of recognition of PDD components can be quantified as.

\[
\begin{array}{c}
\sum_{k=1}^{n} a_{jk} b_{kj} \\
\sum_{k=1}^{n} b_{kj}
\end{array}
\]

3.2.3 Weight calculation based on structure entropy weight method

To avoid the distortion of the evaluation results caused by the mutation value, we used the structural entropy weight method [24] to determine the weighting, and the specific steps are as follows.

Step 1. Certain experts are invited to rank the importance of each fine-grained indicator.

Step 2. The establishment of the fine-grained indicator set, collection of the expert opinions, and construction of the expert opinion matrix are denoted as follows:

\[
A = \begin{bmatrix}
    a_{11} & \cdots & a_{1n} \\
    \vdots & \ddots & \vdots \\
    a_{k1} & \cdots & a_{kn}
\end{bmatrix},
\]

and the membership of the interval \([\Delta a_i, \Delta a_j]\) is \([\Lambda_i^a, \Lambda_j^a]\), where \(a_{jk}(i = 1, 2, \cdots, k; j = 1, 2, \cdots, n)\) indicates the importance ranking of the \(i\)th expert for item \(j\) indicators. The membership of \(a_{ij}\) is \(b_{ij}\), where \(b_{ij}\) is calculated according to the following formula:

\[
b_{ij} = \frac{\ln(m-a_{ij})}{\ln(m-1)},
\]

where \(m\) is the number of transformation parameters [24], in this paper, letting \(m = n + 2\). Determining that the average awareness \(b_j\) of \(k\) experts on index \(u_j\) is

\[
b_j = \frac{b_{1j} + b_{2j} + \cdots + b_{kj}}{k},
\]

then, the blindness \(Q_j[24]\) is

\[
Q_j = \left[ \frac{\max(b_{1j} + b_{2j} + \cdots + b_{kj}) - b_j}{2} \right] + \left[ \frac{\min(b_{1j} + b_{2j} + \cdots + b_{kj}) - b_j}{2} \right].
\]

Then, the overall awareness \(x_j\) of \(k\) experts on index \(u_j\) is

\[
x_j = (1-b_j)(1-Q_j), x_j > 0
\]

The evaluation vector of \(k\) experts for indicators of the whole \(U\) is

\[
X = [x_1, x_2, \cdots, x_j]
\]

Step 3. According to Eq. (12), the weight of index \(u_j\) is

\[
\alpha_j = x_j / \sum_{i=1}^{8} x_j
\]

3.2.4 Comprehensive evaluation of fine-grained indicators

For components, a fine-grained evaluation of the component layer is performed, and then, the fine-grained comprehensive evaluation result \(T\) of the component layer is calculated according to the following equation:

\[
T = \sum_{j=1}^{8} \alpha_j u_j,
\]

Table 5 Evaluation results of the target group disassembly entropy of the Passat engine

| Coarse-grained index                        | Weight | Computation | The coarse-grained index of target group |
|---------------------------------------------|--------|-------------|----------------------------------------|
| Disassembly entropy of failure rate         | 0.33   | 0.34        | 0.112                                  |
| Disassembly entropy of number of connector  | 0.33   | 0.68        | 0.224                                  |
| Disassembly entropy of partial destructive cost | 0.34 | 0.43        | 0.146                                  |
| Total                                       | 1      | –           | 0.482                                  |
where $\alpha_j (j = 1, 2, \cdots, 8)$ is the weight for each fine-grained index calculated by structural entropy weight method and $u_j$ is the fine-grained index.

### 4 The comprehensive evaluation method

In Section 2, the target group was used as the representative of the whole product level. If the coarse-grained disassembly entropy is less than a given threshold, it indicates that the PDD feasibility of the product is high. Then, the fine-grained evaluation of the component layer is needed to obtain the exact destructible disassembly components. The specific process is shown in Fig. 3. The specific steps are as follows.

**Step 1.** Data (such as product failure information) are obtained according to the literature and practical experience.

**Step 2.** The product failure characteristic matrix is constructed, and the expert evaluation method is used to quantify the failure characteristics and calculate the eigenvalues.

**Table 6** Quantification of the engine’s fine-grained index

| Number | Component name                               | $T_a$ | $T_b$ | $T_c$ | $T_d$ | $T_e$ | $T_f$ | $T_g$ | $T_h$ |
|--------|---------------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| 1      | Train valve cover                           | 0.87  | 1     | 1     | 3.2   | 1.24  | 0.575 | 1.093 | 0.97  |
| 2      | Booster pump wheel                          | 0.027 | 0     | 0     | 1     | 0.12  | 0.12  | 0.1   | 0.192 |
| 3      | Oil pump                                    | 0.036 | 0     | 0     | 1     | 0.16  | 0.16  | 0.1   | 0.256 |
| 4      | Oil pump chain                              | 0.06  | 0     | 0     | 1     | 0.27  | 0.27  | 0.135 | 0.34  |
| 5      | Turbocharger flywheel                       | 0.053 | 0     | 0     | 1     | 0.24  | 0.24  | 0.12  | 0.384 |
| 6      | Gearbox assembly                            | 0.051 | 0     | 0     | 1     | 0.23  | 0.23  | 0.115 | 0.368 |
| 7      | Bearing shell                               | 0.062 | 0     | 0     | 1     | 0.28  | 0.28  | 0.14  | 0.36  |
| 8      | Connecting rod bearing shell                | 0.07  | 0     | 0     | 1     | 0.31  | 0.31  | 0.155 | 0.39  |
| 9      | Cylinder                                    | 0.08  | 0     | 0     | 1     | 0.36  | 0.36  | 0.18  | 0.46  |
| 10     | Camshaft                                    | 0.084 | 0     | 0     | 1     | 0.38  | 0.38  | 0.19  | 0.48  |
| 11     | Crankshaft                                  | 0.15  | 1     | 1     | 1     | 0.6   | 0.36  | 0.96  | 0.61  |
| 12     | Pitman                                      | 0.43  | 1     | 1     | 1.72  | 0.87  | 0.425 | 1.295 | 0.69  |
| 13     | Igniter                                     | 0.062 | 0     | 0     | 1     | 0.28  | 0.28  | 0.14  | 0.36  |
| 14     | Cylinder block                              | 0.06  | 0     | 0     | 1     | 0.27  | 0.27  | 0.135 | 0.34  |
| 15     | Air intake camshaft locking block           | 0.48  | 1     | 1     | 1.92  | 0.91  | 0.44  | 0.83  | 0.72  |
| 16     | Exhaust camshaft locking block              | 0.43  | 1     | 1     | 1.72  | 0.87  | 0.425 | 1.295 | 0.69  |
| 17     | Oil pan                                     | 0.6   | 1     | 1     | 2.4   | 1     | 0.475 | 0.9   | 0.79  |
| 18     | Intake manifold                             | 0.78  | 1     | 1     | 3.2   | 1.18  | 0.538 | 1.021 | 0.91  |
| 19     | Crankshaft bearing cap                      | 0.051 | 0     | 0     | 1     | 0.23  | 0.23  | 0.115 | 0.368 |
| 20     | Intake pipe                                 | 0.68  | 1     | 1     | 3.2   | 1.1   | 0.5   | 0.95  | 0.84  |
| 21     | Booster belt                                | 0.85  | 1     | 1     | 3.2   | 1.23  | 0.562 | 1.069 | 0.95  |
| 22     | Timing belt pulley                          | 0.051 | 0     | 0     | 1     | 0.23  | 0.23  | 0.115 | 0.368 |
| 23     | Exhaust manifold                            | 0.051 | 0     | 0     | 1     | 0.23  | 0.23  | 0.115 | 0.368 |
| 24     | Timing belt                                 | 0.78  | 1     | 1     | 3.2   | 1.15  | 0.525 | 0.998 | 0.88  |
| 25     | Timing belt toothed pulley                  | 0.051 | 0     | 0     | 1     | 0.23  | 0.23  | 0.115 | 0.368 |
| 26     | Crankshaft wheel                            | 0.051 | 0     | 0     | 1     | 0.23  | 0.23  | 0.115 | 0.368 |
| 27     | Camshaft transmission wheel                 | 0.058 | 0     | 0     | 1     | 0.26  | 0.26  | 0.13  | 0.33  |
| 28     | Valve assembly                              | 0.051 | 0     | 0     | 1     | 0.23  | 0.23  | 0.115 | 0.368 |
| 29     | Air filter                                  | 0.65  | 1     | 1     | 3.12  | 1.04  | 0.49  | 0.93  | 0.82  |
| 30     | Booster belt tension wheel                  | 0.051 | 0     | 0     | 1     | 0.23  | 0.23  | 0.115 | 0.368 |
| 31     | Engine support                              | 0.051 | 0     | 0     | 1     | 0.23  | 0.23  | 0.115 | 0.368 |
| 32     | Turbocharger                                | 0.051 | 0     | 0     | 1     | 0.23  | 0.23  | 0.115 | 0.368 |
| 33     | Connecting rod cap                          | 0.051 | 0     | 0     | 1     | 0.23  | 0.23  | 0.115 | 0.368 |
| 34     | Clutch flywheel                             | 0.06  | 0     | 0     | 1     | 0.27  | 0.27  | 0.135 | 0.34  |
| 35     | Clutch pressure plate                       | 0.051 | 0     | 0     | 1     | 0.23  | 0.23  | 0.115 | 0.368 |
| 36     | Clutch driven plate                         | 0.053 | 0     | 0     | 1     | 0.24  | 0.24  | 0.12  | 0.384 |
| 37     | Clutch cover back plate                     | 0.027 | 0     | 0     | 1     | 0.12  | 0.12  | 0.1   | 0.192 |
Step 3. According to Section 2, the target group is selected according to the failure characteristics.

Step 4. The disassembly entropy of the failure rate and the disassembly entropy of the number of joints can be calculated according to Eqs. (4)–(6). The total disassembly entropy of the target group can be calculated according to Eq. (7).

Step 5. Determine whether the total disassembly entropy $S$ is greater than the user-defined threshold; if it is greater, go to Step 6. Otherwise, go to Step 7.

Step 6. PDD is not feasible, so take normal disassembly.

Step 7. The fine-grained indexes are determined based on failure characteristics.

Step 8. Fuzzy triangular quantization of fine-grained indexes is performed based on failure characteristics. The structural entropy weight method is used to calculate the weight of each index, and the fine-grained comprehensive evaluation value $T$ of components is calculated using Eq. (15).

Step 9. Sort the PDD components according to the comprehensive evaluation value in descending order. Thus, the disassembly priority of components is determined, and the results of the evaluation used as feedback to guide the PDD process.

5 Case study

To verify the feasibility and effectiveness of this method, we used a Passat engine (Fig. 4) as an example. Assuming that its failure information is known, the failure characteristic matrix of the product can be constructed according to Section 2 through human-computer interaction. Table 3 lists the main components and the related information of the engine.

The eigenvalue of engine parts failure is quantified according to Eq. (3), as shown in Eq. (16), and the target group is constructed according to Eq. (16); the information of the target group of the Passat engine is shown in Table 4.

According to Table 4, letting $N_i = 43$, $N_s = 34$, $N_k = 26$, $C_o = 17.498$, and $C_s = 0.43$, the disassembly entropies of the coarse-grained indexes of the target group are shown in Table 5.

The total disassembly entropy of the target group $S$ is obtained as 0.482 according to Table 5, assuming that the user-defined threshold is 0.6, and $S$ is less than the user-defined threshold. The smaller the disassembly entropy is, the better the PDD feasibility of the EOL products is, and then, the fine-grained evaluation of the component level is needed to identify specific destructive disassembly components.

According to Fig. 2, the fine-grained index of PDD was quantified based on the component failure characteristics, which is shown in Table 6. Furthermore, the weight of the fine-grained index is determined by the structural entropy weight method, and the steps are shown in Table 7. According to Eq. (15), the fine-grained comprehensive evaluation results of the engine components are shown in Table 8.
As shown in Table 8, the PDD of the engine is feasible, and the comprehensive score of the train valve cover is the highest, which should be disassembled preferentially. The train valve cover is to cover and seal the cylinder head and isolate pollutants, such as dirt and humidity from the outside. Therefore, it is in a bad environment for a long time, which can result in a serious failure. In engineering practice, destructive disassembly is preferred owing to its low remanufacturing value and possibility of serious failure, which is consistent with the above evaluation result.

| Part number | Component name                                | Comprehensive assessment value |
|-------------|-----------------------------------------------|-------------------------------|
| 1           | Train valve cover                             | 1.1073                        |
| 21          | Booster belt                                  | 1.0931                        |
| 18          | Intake manifold                               | 1.0604                        |
| 24          | Timing belt                                   | 1.0407                        |
| 20          | Intake pipe                                   | 1.0076                        |
| 29          | Air filter                                    | 0.9808                        |
| 17          | Oil pan                                       | 0.9021                        |
| 15          | Air intake camshaft locking block             | 0.8114                        |
| 12          | Pitman                                        | 0.6979                        |
| 16          | Exhaust camshaft locking block                | 0.6979                        |
| 11          | Crankshaft                                    | 0.5448                        |
| 10          | Camshaft                                      | 0.4069                        |
| 9           | Cylinder                                      | 0.3918                        |
| 8           | Connecting rod bearing shell                  | 0.3489                        |
| 7           | Bearing shell                                 | 0.3263                        |
| 13          | Igniter                                       | 0.3263                        |
| 4           | Oil pump chain                                | 0.3161                        |
| 14          | Cylinder block                                | 0.3161                        |
| 34          | Clutch flywheel                               | 0.3161                        |
| 27          | Camshaft transmission wheel                   | 0.3132                        |
| 5           | Turbocharger flywheel                         | 0.3132                        |
| 36          | Clutch driven plate                           | 0.3085                        |
| 6           | Gearbox assembly                              | 0.3041                        |
| 19          | Crankshaft bearing cap                        | 0.3041                        |
| 22          | Timing belt pulley                            | 0.3041                        |
| 23          | Exhaust manifold                              | 0.3041                        |
| 25          | Timing belt toothed pulley                    | 0.3041                        |
| 26          | Crankshaft wheel                              | 0.3041                        |
| 28          | Valve assembly                                | 0.3041                        |
| 30          | Booster belt tension wheel                    | 0.3041                        |
| 31          | Engine support frame                          | 0.3041                        |
| 32          | Turbocharger                                  | 0.3041                        |
| 33          | Connecting rod cap                            | 0.3041                        |
| 35          | Clutch pressure plate                         | 0.3041                        |
| 3           | Oil pump                                      | 0.2434                        |
| 2           | Booster pump wheel                            | 0.2101                        |
| 37          | Clutch cover back plate                       | 0.2101                        |

### 6 Conclusions

This paper proposes a multi-granularity feasibility evaluation method for EOL products to judge the PDD feasibility from the product level to the component level based on the disassembly entropies and the product’s failure characteristic. The highlights of the proposed method are as follows.

1. The multi-granularity feasibility evaluation method proposed in this paper is an effective process. The coarse-grained evaluation of the whole product is performed first. If the total
disassembly entropy of the target group is greater than the user-defined threshold, the following fine-grained evaluation is unnecessary, which reduces the blindness of the evaluation and improves the evaluation efficiency.

(2) The target group is constructed based on the failure characteristics of product components to simplify the overall evaluation difficulty of PDD for EOL, which can provide technical support for the PDD feasibility evaluation of large complex products.

(3) The fine-grained index of PDD was determined and quantified based on the failure characteristics and the fuzzy membership function, which solves the fuzzy effect of product failure on PDD and greatly improves the efficiency in the feasibility evaluation of PDD process.

However, environmental factors have an important impact on the feasibility evaluation of local failure disassembly, but it is difficult to quantify. Environmental factors are not considered in this paper, in the construction of indicators and considerations of environmental factors in subsequent studies. Otherwise, the construction of the target group, only the high failure probability, and key components were considered, and the failure characteristic information of components was difficult to obtain. Thus, software should be developed to perform the extraction of the failure characteristics of an EOL product automatically to increase the evaluation efficiency in the follow-up work.

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Data availability The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval All analyses were based on previous published studies; thus, no ethical approval and patient consent are required.

Consent to participate Not applicable.

Consent for publication A statement under the “Consent to publish” heading confirming that you have obtained consent to publish from the participant (or legal parent or guardian for children) to report individual participant’s data in any form (including images, videos, and voice recordings).

Competing interests The authors declare no competing interests.

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