Multi-Granularity Feasibility Evaluation Method of the Partial Destructive Disassembly for an End-of-Life Product

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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. 1Thus, 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

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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.

At present, the study of the partial destructive disassembly (PDD) is attracting widespread attention. PDD aims to achieve the unconventional disassembly of some connectors or low-value components by destructive means. 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, demolition time, and environment, 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 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 system of the partial destructive disassembly for EOL products, and the indicator system is incomplete. Some scholars put forward the method of combining the whole and individual in the construction of the normal disassembly feasibility evaluation indicator, such 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.

Figure 1. MGFEM of the PDD for an EOL product

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 parts v_i , which can be expressed by Eq. 1 as follows:

$$M_1 = r_{ij} \quad n \times 4, \quad (1)$$

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

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

$A = (a_{ij} \mid i=1 \sim 5)$, where $a_{ij} = \frac{n_{a_{ij}}}{N}$ and it is the number of experts participating in the evaluation, and $n_{a_{ij}}$ is the number of experts choosing the i evaluation value. At this point, the eigenvalue of the failure type c_j of component v_i is shown in Eq. 2.

$$e_{ij} = E \cdot A^T \quad (2)$$

Table 1. Part failure characteristics and recovery decision information

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)	-	-	-
...	-	-	-

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 Equations (1 and 2), which can be expressed by Eq. 3.

$$M_2 = e_{ij} \cdot r_{ij}, \quad (3)$$

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

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) The disassembly entropy of failure rate is

$$S_1 = \log_2 N_i / N_s, \quad (4)$$

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) The disassembly entropy of the number of joints is

$$S_2 = \log_2 [N_i + N_k / N_k], \quad (5)$$

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) The disassembly entropy of cost of PDM is

$$S_3 = \log_2 [C_n + C_m / C_n], \quad (6)$$

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

$$S = k_1 S_1 + k_2 S_2 + k_3 S_3, \quad (7)$$

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.

It is essential to recognize the PDD components and normal disassembly components during the PDD process. The PDD components should be low value or serious failure. Therefore, the more serious the failure characteristics are, the easier the identification of the failure disassembly components is and the better the PDD feasibility is. However, a serious component failure will lead to the increase of the required disassembly force and the difficulty of tool accessibility, which will seriously affect the efficiency of PDD. Moreover, the change of different disassembly tools and the relative positioning accuracy of the joints also seriously affect the efficiency of PDD. If the replacement of different disassembly tools occurs frequently, or there are the higher positioning accuracy requirements, these will increase the cost and energy consumption. Then, the PDD feasibility is worse. Furthermore, the larger the component structure size is, the more difficult it is for the PDD, because it will take more time to remove the corresponding connections and joints. Thus, eight fine-grained indexes, recognition of PDD components, disassembly tool, disassembly direction, disassembly time, pushing force, accessibility, positioning accuracy and component structure size were determined 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 $[\Delta a_i, \Delta a_j]$ is $[\Lambda_i^a, \Lambda_j^a]$, and the index of recognition of PDD components can be quantified as.

Table 2. The failure characteristics' influence level on fine-grained index

Fine-grained index	Meaning	Description	Mark
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Recognition PDD components	Good to recognize	The failure characteristics of components are obvious and good to recognize	Δa_1
	Easy to recognize	The component failure feature is obvious and easy to recognize	Δa_2
	Difficult to recognize identification	The component failure characteristics are not obvious, so it is difficult to recognize	Δa_3
	No identification	No significant failure of components	Δa_4
Disassembly tool	Does not need to change	Low degree of failure, high recovery value. Hand or common tools required for normal disassembly	Δb_0
	Need to change	Low degree of failure, low recovery value. Replace normal tools with destructive disassembly tools	Δb_1
Disassembly direction	Does not need to change	Low failure and high recovery value. Normal disassembly of connectors without changing its disassembly direction	Δc_0
	Need to change	Low degree of failure, low recovery value. Destroy connectors to change its disassembly direction	Δc_1
Disassembly time ^[22]	Does not need to change	General failure of component, take normal disassembly, according to the original disassembly time	Δt_0
	Need to change	Serious failure of component; takes destructive disassembly to reduce disassembly time	Δt_1
Pushing force	Great	Serious failure of component, difficult to dismantle; needs a greater force to overcome	Δd_1
	Moderation	Medium failure of component, medium disassembly force needed to overcome	Δd_2
	General	Small failure of components requires general disassembly force	Δd_3
	Small	Not obvious failure component, only need to overcome a small force	Δd_4
Accessibility	More difficult	Component with a serious failure, resulting in connector corrosion; challenging to remove connector	Δi_1

Positioning accuracy	Hard	Component's medium failure, resulting in connector surface covered with rust; tool contact with connector difficult	Δi_2
	General	Components generally fail, accessibility general	Δi_3
	Easy	Component shows no failure, no visual obstacles, connectors easily accessible to tools	Δi_4
	High	The lower the degree of failure and the target component, the higher the positioning accuracy requirements	Δg_1
Component structure size ^[18]	Moderation	Component failure degree is general, mainly using normal disassembly, its positioning accuracy requirements are medium	Δg_2
	General	The failure degree of components is generally medium, the damage and non-destructive disassembly are combined, and the positioning accuracy requirements are general	Δg_3
	No precision requirements	Component failure is serious, take destructive disassembly, its positioning accuracy is not required	Δg_4
	More difficult	Component failure is serious and the structure is large, so the tool is difficult to grasp	Δk_1
	General	Components with general failure degree and large structure, medium difficulty in grasping tools	Δk_2
	Easy	Components are basically non-failure and small in structure, and tools are easy to grab	Δk_3

Figure 2. Fine-grained index membership function based on the failure characteristics

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:

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{k1} & \cdots & a_{kn} \end{bmatrix}, \quad (8)$$

and the membership of the interval $[\Delta a_i, \Delta a_j]$ is $[\Lambda_i^a, \Lambda_j^a]$,

where a_{ij} $i=1,2,\dots,k$; $j=1,2,\dots,n$ 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:

$$b_{ij} = -\frac{\ln m - a_{ij}}{\ln m - 1}, \quad (9)$$

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

$$b_j = \frac{b_{1j} + b_{2j} + \dots + b_{kj}}{k}, \quad (10)$$

then, the blindness Q_j [24] is

$$Q_j = \left| \frac{\left[\max b_{1j} + b_{2j} + \dots + b_{kj} - b_j \right]}{2} + \frac{\left[\min b_{1j} + b_{2j} + \dots + b_{kj} - b_j \right]}{2} \right|. \quad (11)$$

Then, the overall awareness x_{ij} of k experts on index u_j is

$$x_j = (1 - b_j)(1 - Q_j), x_j > 0. \quad (12)$$

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

$$X = [x_1, x_2, \dots, x_j]. \quad (13)$$

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

$$\alpha_j = x_j / \sum_{i=1}^8 x_j. \quad (14)$$

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:

$$T = \sum_{j=1}^8 \alpha_j u_j, \quad (15)$$

where α_j $j=1,2,\dots,8$ 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 Figure 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.

Step 3. According to Section 2, the target group is selected according to the failure characteristics.

Step 4. According to Eqs. (4–6), the disassembly entropy of the failure rate and the disassembly entropy of the number of joints can be calculated. 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.

Figure 3. Flowchart of multi-granularity feasibility evaluation method for PDD

5. Case study

To verify the feasibility and effectiveness of this method, we used a Passat engine (Figure 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.

(a) Overall Structure of the Passat engine

(b) After the engine is disassembled

Figure 4. Overall structure and disassembly of a Passat engine

Table 3. Main parts information of Passat engine

Part	Component name	Quanti	Remover	Disassembly	Connection type
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number		ty		direction	(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	1	Lama	+Z	Geometric constraint

	pulley				
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)

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.

$$M_2 = \begin{bmatrix} 1 & 4 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 & 16 & 17 & 18 & 20 & 21 & 24 & 27 & 29 & 34 \\ 0 & 0.27 & 0 & 0.31 & 0 & 0 & 0.48 & 0.65 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.78 & 0.27 \\ 0.92 & 0 & 0 & 0 & 0 & 0.38 & 0 & 0 & 0.28 & 0 & 0.68 & 0 & 0.75 & 0 & 0.8 & 0.9 & 0 & 0.26 & 0 & 0 \\ 0 & 0 & 0.28 & 0 & 0.36 & 0 & 0 & 0 & 0 & 0.27 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.86 & 0 & 0 & 0.84 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.65 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{matrix} c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \end{matrix} \quad (16)$$

Table 4. Information of target group of the Passat engine

Part number	Component name	Quant ity	Remover	Cost of normal disassembly (¥) [25]	Joint type (number)	Cost of destructive disassembly (¥) [26]
1	Train valve cover	1	Wrench	0.31	Bolt connection (2)	0.2
4	Oil pump	1	Wrench	0.37	Bolt	0.5

chain					connection (2)	
7	Bearing shell	8	Hand	0.76	Welding	0.32
	Connecting rod bearing shell			0.76		
8		8	Hand		Welding	0.31
9	Cylinder	8	Hand	3.76	Screw (2)	0.36
10	Camshaft	2	Screwdriver	0.286	Screw (2) and geometric constraint	0.38
11	Crankshaft	1	Hand	0.84	Geometric constraint	0.24
12	Pitman	4	Wrench	0.006	Hexagonal nut (1)	0.18
13	Igniter	4	Special tool	0.17	Bolt connection (8)	0.4
14	Cylinder block	4	Hand	0.17	Welding	0.18
15	Air intake Camshaft locking block	5	Screwdriver	0.36	Bolt connection (2)	0.3
16	Exhaust camshaft Locking block	5	Screwdriver	0.28	Bolt connection (2)	0.3
17	Oil pan	1	Wrench	0.45	Bolt connection (2)	0.4
18	Intake manifold	1	Wrench	0.17	Hexagonal nut (1)	0.2
20	Intake pipe	2	Screwdriver	0.31	Welding	0.2
21	Booster belt	1	Special tool	3.21	Geometric Constraint	0.18
24	Timing belt	1	Special tool	3.19	Elasticity	0.28
27	Camshaft Transmission Wheel	1	Lama	0.84	Geometric constraint	0.29
29	Air filter	1	Screwdriver	0.286	Screw (2)	0.2

34	Clutch flywheel	1	Hand	0.6	Geometric constraint	0.29
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According to Table 4, letting $N_i = 43$, $N_s = 34$, $N_k = 26$, $C_n = 17.498$, and $C_s = 0.43$, the disassembly entropies of the coarse-grained indexes of the target group are shown in Table 5.

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

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 Equation (15), the fine-grained comprehensive evaluation results of the engine components are shown in Table 8.

Table 6. Quantification of the engine's fine-grained index

Number	Component name	T_a	T_b	T_c	T_t	T_d	T_g	T_i	T_k
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

Table 7. Weight determination step based on the structure entropy weight method

Calculation	T_a	T_b	T_c	T_t	T_d	T_g	T_i	T_k
Group 1	1	2	3	4	5	6	7	8
Group 2	1	2	4	3	7	8	5	6
Group 3	2	1	3	4	6	7	5	8
b_j	0.9821	0.9643	0.8622	0.8389	0.6211	0.4821	0.655	0.4206
b_{ij} (max)	1	1	0.8856	0.8856	0.7325	0.6309	0.7325	0.6309
$1-Q_j$	0.9911	0.9911	0.98835	0.98835	0.8471	0.9911	0.96125	0.9474
x_j	0.0178	0.0354	0.1362	0.1592	0.3210	0.5133	0.3316	0.5490
α_j	0.0086	0.017	0.0660	0.0772	0.1556	0.2488	0.1607	0.2661

Table 8. Fine-grained comprehensive evaluation result of the engine components

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

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.

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 product, 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, in 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. 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.

Ethical Approval

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

Consent to Participate

Not applicable

Consent to Publish

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 patient data. Note this is required where an article reports an individual participant's data in any form (including images, videos, voice recordings etc).

Authors Contributions

Conceptualization, L.G. and X.Z.; methodology, L.G.; validation, L.G. and X.Z.; formal analysis, L.G.; investigation, L.G. and X.Z.; resources, L.G. and X.Z.; data curation, L.G.; writing—original draft preparation, L.G.; writing—review and editing, L.G.; visualization, L.G. and X.Z.; supervision, L.G.; project administration, X.Z.; funding acquisition, X.Z. All authors have read and agreed to the published version of the manuscript.

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Competing Interests

The authors have declared that no competing interests exist

Availability of data and materials

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

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Figures

Figure 1

MGFEM of the PDD for an EOL product

Figure 2

Fine-grained index membership function based on the failure characteristics

Figure 3

Flowchart of multi-granularity feasibility evaluation method for PDD

(a) Overall Structure of the Passat engine

(b) After the engine is disassembled

Figure 4

Overall structure and disassembly of a Passat engine