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Economic, Environmental and Social Benefits Analysis of Remanufacturing Strategies for Used Products

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Abstract: The operating environment and using conditions of mechanical products are complex and diverse, which has caused a large number of mechanical products to be unable to be remanufactured or have low-remanufacturability. Such products are often ignored by remanufacturing companies and society, which aggravates environmental pollution and waste of resources. Therefore, this article provides a decision-making model for two strategies of complete machine remanufacturing (CMR) and part remanufacturing (PR) for used products with low-remanufacturability. Firstly, from the perspective of the remanufacturing process under the existing technical conditions, the economic, environmental, and social benefits of different remanufacturing solutions are analyzed. Secondly, the entropy method is used to weigh the economic, environmental, and social benefits to reduce the model error, and the linear regression method is used to find the comprehensive benefits of its different remanufacturing strategies. Finally, through the decision-making research on the remanufacturing strategies of the used machine tool CA6180, the results show that the tested machine tool should choose the remanufacturing strategy of PR and put it on the market. Moreover, the decision-making strategy proposed in this paper helps to realize a resource-saving and environment-friendly manufacturing ecology and provides a new perspective for remanufacturing research.

Keywords: decision-making; used products; low-remanufacturability; remanufacturing strategy; comprehensive benefits

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1. Introduction

In recent years, as the process of social industrialization continues to accelerate, the manufacturing industry has undergone rapid development, transformation and upgrading, and it has also been accompanied by a huge use of resources and environmental pollution [1,2]. With the exhaustion of non-renewable energy sources and the further deepening of environmental pollution [3], the sustainable development strategy of energy conservation and emission reduction has attracted more and more attention from governments and scholars [4–6]. Remanufacturing is one of the best methods for the final treatment of used products [7,8], which takes old products as objects and uses existing remanufacturing technology to structure them through reengineering and performance improvement [9,10]. Remanufacturing extends the product's life cycle while tapping its surplus value, and better realizes the maximization of its economic, environmental and social benefits [11,12]. In the research on the remanufacturing of used products, many domestic and foreign scholars have conducted a lot of research. Du et al. [13] analyzed the technical, economic and environmental feasibility of machine tool remanufacturing, and established a comprehensive evaluation model of machine tool remanufacturability. Gong et al. [14] proposed an active remanufacturing timing decision-making method based on economic, energy, and environmental (3E) analysis of product life cycles. From energy, economic and

environmental perspective, Liao et al. [15] comparatively analyze the carbon emissions between whole machine remanufacturing and cannibalization and between component remanufacturing and recycling, the results show that the reductions in carbon emissions increase with rising complex quality coefficient, but its marginal increase rate decreases rapidly. Golinska et al. [16] used grayscale analysis law to analyze the sustainability of remanufacturing enterprises and made reasonable classifications.

At present, the research on remanufacturing is mainly aimed at the remanufacturability evaluation and process strategies selection of waste products or parts with high remanufacturability. Remanufacturability refers to the comprehensive mechanical failure characteristics that enable the remanufacturing of used products to have certain economic and environmental feasibility under certain technical conditions while meeting market demand. Among them, economic and environmental feasibility is a threshold [13], which can be determined through expert experience and business needs. In fact, due to the lack of remanufacturability in the initial stage of product design, the actual working conditions and working environment of the product are complex and diverse, resulting in a large number of used products that cannot fully meet the needs of enterprise remanufacturing. Such products are generally considered by remanufacturers to have low-remanufacturability or even no-remanufacturability. Currently, there is relatively little research on used products with low-remanufacturability, and such products are often ignored by remanufacturing enterprises, which causes lots of waste of resources and environmental pollution. How to promote the recycling and utilization of waste machinery products with low remanufacturability, improve the utilization rate of their resources, and realize the virtuous cycle of resources, economy, and environment is the focus of this paper. However, remanufacturing enterprises are market-oriented for remanufacturing activities. Social benefits of remanufactured products refer to maximizing the use of limited resources to meet the increasing material and cultural needs of people in society and are also important factors that affect whether waste products can be remanufactured. Therefore, it is necessary to conduct qualitative and quantitative analyses of the social benefits of used products with low-remanufacturability. This article uses the social recognition and reliability of remanufactured products to express more intuitively and quantitatively its social benefits.

Through the analysis of the above-mentioned literature, it can be known that remanufacturing costs, benefits, resource consumption, pollutant emissions, social recognition and reliable performance are the key factors that affect the economic, environmental and social benefits of remanufacturing solutions. Therefore, this paper proposes a remanufacturing strategy decision model for remanufacturing used products with low-remanufacturability from the perspective of remanufacturing economy, environment and social benefits through decentralized thinking. The experimental results show that the model proposed in this paper further improves the efficiency of resource utilization, and also greatly promotes the energy-saving and environmental protection achievements of the manufacturing industry.

The main innovations of this article are as follows:

(1) This paper aims to study the waste products with low or even no remanufacturability ignored by manufacturer and analyzes the comprehensive benefits of different reuse methods from the aspects of economy, environment and society by combining quantitative and qualitative methods, and provides a new perspective for the research on the remanufacturing of waste products. The waste products with low remanufacturability also have the potential to continue to be mined, which is of great and far-reaching significance to promote the virtuous cycle of economy, resources and environment.

(2) The design and manufacture of mechanical products are to provide convenience for social production and life, so the social benefit of products is an important factor affecting the decision of remanufacturing plan. However, the social benefits of remanufactured products are rarely mentioned in existing research results through literature review. In order to enhance the stability and feasibility of the decision-making model, this paper adopts the fuzzy expert model to fully analyze the social benefits of remanufactured products with low remanufacturability, and the research results

also verify the necessity of social benefits analysis in the decision-making process of remanufacturing scheme.

(3) The entropy weight method is an effective tool for comprehensive evaluation. It mainly assigns entropy weight to the importance degree of the system according to the influencing factors and evaluates the system comprehensively according to it. This method can effectively reduce the influence of subjective factors in the process of evaluation and decision-making and improve the reliability and generalization ability of the decision-making model. This method is exactly in line with the content and characteristics of this paper, and the case study also verifies its feasibility and high accuracy.

The rest of this article is structured as follows. The second part reviews and analyzes the previous research on remanufacturing strategies for used products. The third part constructs an evaluation model for the remanufacturing strategy of used products with low-remanufacturability and details the evaluation process. The fourth part verifies the feasibility of the model with the remanufacturing of CA6180 using machine tools as an example. The fifth part discusses the research objects and results in depth. The sixth part gives conclusions and future research directions.

2. Literature Review

Remanufacturing engineering refers to engineering activities that carry out a series of technical measures such as high-quality, high-efficiency, energy-saving and environmentally friendly restoration and transformation of used products [17,18]. Traditional remanufacturing engineering is the performance recovery and structural improvement of used products with high remanufacturability. Zhang et al. [19] analyzed the life cycle big data of in-service mechanical and electrical products and proposed a remanufacturing scheme decision model on how to improve the utilization rate of in-service mechanical and electrical products under the background of the big data era. There is a large number of documents for reference on the optimal decision-making problem of the CMR strategy of used products. From the perspective of remanufacturing reliability and cost, Du et al. [20] propose an improved reliability allocation method for remanufactured machine tools integrating neural networks and remanufacturing coefficient. With the fault tree analysis (FTA) model constructed, the fault of remanufactured machine tools can be divided into three levels. From the viewpoints of economy, technology, and environment, Du et al. [21] propose a decision-making method of heavy-duty machine tool remanufacturing based on the AHP-entropy weight and extension theory, established an evaluation index system for the remanufacturing of heavy machine tools. Gao et al. [22] combined the KT method and the entropy weight method from multi-dimensional considerations such as economic, environmental and technical feasibility, and established a product remanufacturing molding program decision model. Considering the perspective of the life cycle, Xiong et al. [23] established a two-level service activity decision model for remanufacturing services based on case-based reasoning technology from the analysis of the five dimensions of remanufacturing value, technology, resources, environment and economy. From the perspective of energy-saving and emission reduction, Shen et al. [24] studied how remanufacturers should make the best remanufacturing decisions under different carbon emission policies. Studies have shown that the number of recycled products is the key to restricting remanufacturers' remanufacturing activities. Ding et al. [25] studied the impact of the carbon tax and recycling legislation on the production and reduction in the carbon dioxide emissions of remanufacturing companies from the perspective of different monopolies and competitive environments.

In addition, the product is composed of many parts. Due to the different manufacturing materials, working conditions, and actual performance of different parts, there are many reasons for product scrap. Therefore, when it is impossible to remanufacture the whole machine of waste product, the parts should be remanufactured and sold to the market with decentralized thinking. Starting from the remanufacturing process, Li et al. [26] analyzed

the difference between the damage condition of used parts and remanufacturing quality requirements and proposed a remanufacturing process strategy decision-making method based on an improved T-S fuzzy neural network. Peng et al. [27] proposed an ecological performance-oriented optimal remanufacturing process strategy decision-making model, which took the ecological performance as the objective, case-based reasoning technology and particle swarm algorithm were used to select the optimal remanufacturing strategy from historical remanufacturing cases. Xiang et al. [28] established a remanufacturing process plan decision-making model through the analysis and research on the process characteristics of used parts and components, using the method of combining the L-M algorithm and BP neural network, which greatly improved the accuracy and efficiency of decision-making. Relying on the ECC intelligent service platform. Liu et al. [29] developed an RA model, which involves four key indicators, namely, the economic remanufacturability index (ERI), quality remanufacturability index (QRI), resource consumption index (RCI), and environmental emission index (EEI). Second, an integrated decision model considering RA is proposed and an improved two-layer structured genetic algorithm is designed to solve the optimal process planning and scheduling results.

Literature analysis shows that the current research on remanufacturing strategies is mainly for used products with high remanufacturability, and the selection of remanufacturing strategies is also simple from CMR or PR. However, there are few mentions of the decision-making problem of remanufacturing strategies for products with low or no remanufacturability. As products lack the design concept of remanufacturing in the initial design stage, and the actual working environment and working conditions of mechanical products are diversified, the failure modes and failure degrees of the products are complex and diverse. Therefore, the remanufacturability of a large number of end-of-life products is relatively low-remanufacturable. How to achieve economic, environmental, and social comprehensive benefits for used products with low-remanufacturability under the existing technical conditions maximization has become the focus of this article. In the research of fully discovering the surplus value of used products, Wang et al. [9] combined the Fault Tree Analysis (FTA) and the matter-element analysis theory to analyze and characterize the failure characteristics of used parts and established a Genetic Algorithm-based (GA) decision model for the remanufacturing and maintenance of used parts. However, the above-mentioned research is mainly from the unilateral remanufacturing of products or parts, and the research objects have high technical, economic, and environmental feasibility. The above research did not consider the market demand-oriented and used products with low-remanufacturability.

Traditional remanufacturing has great subjectivity and randomness, which leads to great differences in the choice of remanufacturing schemes. The above-mentioned articles (as shown in Table 1) mainly study the remanufacturing strategy of used products with high remanufacturability from the dimensions of technology, economy and environment, which neither considers used products with low remanufacturability nor the social benefits of remanufactured products. From the perspective of remanufacturing economy and environment, this paper proposes CMR and PR strategies for used products with low-remanufacturability and establishes a remanufacturing strategy decision-making model based on the entropy weight method. Case verification shows that the model proposed in this paper greatly improves resource utilization and reduces pollution emissions while ensuring economic benefits.

Table 1. Comparison of related literature.

Author	Dimension	Influencing Factors	Research Object	Research Methods	Type
Zhang et al. [19] (2019)	Economy, environment and user experience	User experience, quality, cost, resource consumption and pollution emissions	AR products and original products	quality function deployment, fuzzy quantification and smoothing index	Evaluation
Du et al. [20] (2022)	Reliability allocation	Reliability	Remanufactured machine tools	Fault tree analysis and neural network	Design
Du et al. [21] (2020)	Economy and technology	remanufacturing cost, remanufacturing time, accuracy, reliability, processing efficiency and processing range	Heavy-duty machine tools	AHP entropy weigh and extension theory	Decision-making
Gao and Zhang [22] (2018)	Economy, technology and environment	Expected effect, cost, technical difficulty and resource environment	Used product	KT method and the entropy weight method	Decision-making
Xiong et al. [23] (2017)	remanufacturing value, technology, resources, environment and economy	Remaining service life	Used product	Case-based reasoning technology	Decision-making
Shen and Xiong [24] (2014)	Resources and environment	Number of recycled products	Used product	Analogy	Optimization
Ding et al. [25] (2020)	Environment	Different monopolies and competitive	Used product/part	Inductive summary	Explore
Li et al. [26] (2016)	Technology	Damage condition of used parts and remanufacturing quality requirements	Used part	Improved T-S fuzzy neural network	Decision-making
Peng and Nie [27] (2019)	Economy and environment	Process attributes	Used part	case-based reasoning technology and particle swarm algorithm	Decision-making
Xiang and Qin [28] (2017)	Technology	Process attributes	Used part	L-M algorithm and BP neural network	Decision-making
Liu et al. [29] (2019)	Remanufacturability and economic	Economic remanufacturability, quality remanufacturability, resource and environmental emission	EoL product	Improved genetic algorithm with a two-layer structure	Decision-making
Wang et al. [9] (2020a)	Technology and environment	Failure characteristics	Used product	TOPSIS and cascaded failure network	Decision-making
This study	Economy, environment and social	Costs, benefits, resource consumption, pollutant emissions, social recognition and reliability performance	Used product/part	Activity-based costing method, entropy method and inductive analogy method	Decision-making

3. Model Construction and Decision-Making

3.1. Overall Block Diagram of Decision-Making Model

This research takes used products with low-remanufacturability as the research objects and decides on the optimal remanufacturing strategy from the remanufacturing of CMR and PR. Considering the perspective of remanufacturers, how to choose a remanufacturing strategy to maximize the profits of the enterprise is the core element of the remanufacturing strategy decision-making. From the viewpoint of national sustainable development, how to achieve economic recycling and environmentally friendly industrial development are the goals of remanufacturing development. However, from the perspective of product users, the social recognition and reliability performance of remanufactured products are also important factors that determine whether they can be remanufactured. Therefore, this article proposes a decision-making model for the remanufacturing of used products based on economic, environmental, and social benefits analysis. Starting from the remanufacturing process, the model analyzes the economic, environmental, and social benefits of different remanufacturing strategies, and combines the entropy weight method to match the weight coefficients of the evaluation indicators. Finally, the remanufacturing strategy with the largest comprehensive benefit is selected through the mathematical model. The specific decision-making process is shown in Figure 1.

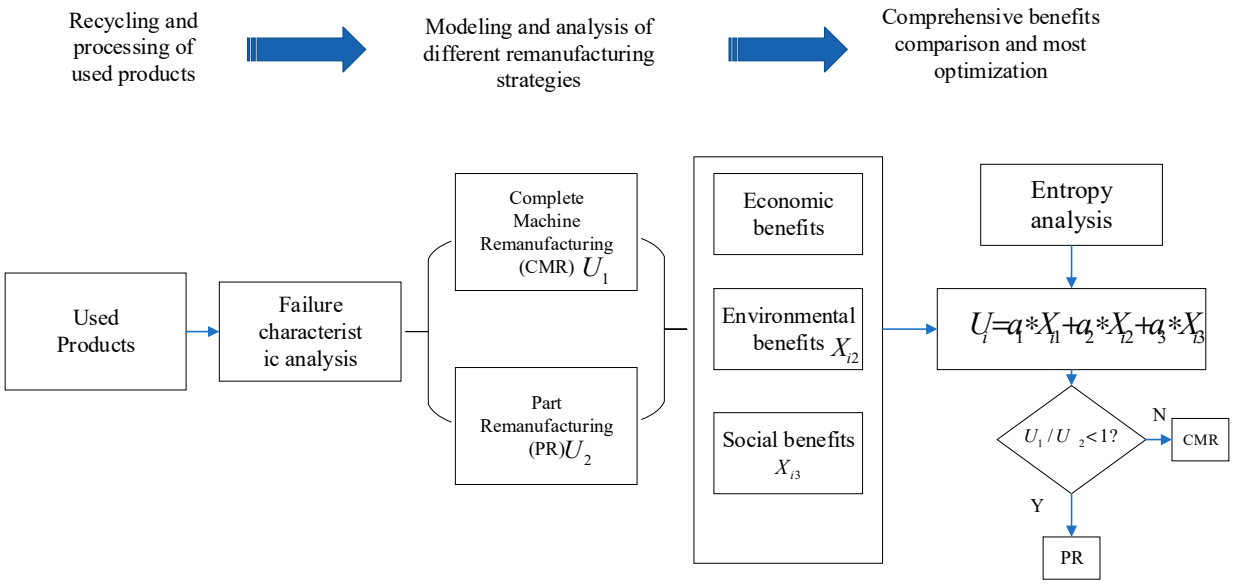

Figure 1. Flow chart of remanufacturing strategies decision-making.

3.2. Model Construction

Electromechanical products have a certain service life. The product is eliminated because of the end of its life or the inability to repair some parts. Due to the complex working environment of the product and the complex and diverse failure modes, a large number of used products are remanufactured (that is, they have low remanufacturability). Favi et al. [30] put forward a series of indicators to evaluate the recyclability of electromechanical products through the analysis of the product remanufacturing process. Zhang et al. [31] analyzed the selection of indicators when designing products' remanufacturing characteristics based on literature analysis, case-based reasoning, and expert evaluation models. Through literature analysis and expert evaluation, this paper analyzes the economic, environmental and social benefits of waste product remanufacturing, and proposes a remanufacturing strategy decision model for CMR and PR. Basing on technical feasibility, the economic benefits of different remanufacturing strategies X_{i1} are analyzed from the viewpoint of the remanufacturing process. Environmental assessment indicators X_{i2} are obtained based on the comparison of resource consumption and pollutant emissions in the remanufacturing and new product manufacturing processes. This paper obtains the social recognition and reliability of remanufactured products through social surveys and uses a combination of fuzzy quantification and weighted average to obtain social benefits X_{i3}. Then, the entropy weight method is used to analyze the importance of the three indicators to the decision-making of the remanufacturing strategies and solve the remanufacturing strategy that maximizes the comprehensive benefits of the model. The detailed evaluation rules are as follows.

Step 1: Economic benefits analysis. Under the existing remanufacturing technologies, the economic benefits analysis of different remanufacturing strategies of recycled products is carried out. First, perform failure detection and simulation repair on recycled products, starting from the benefits and remanufacturing costs after completing the remanufacturing, and analyze the economic benefits of the remanufacturing process; remanufacturing costs include the costs of recycled (C_r) c_1, technical costs (T_C), labor costs (L_c) and other costs (O_c); remanufacturing revenue X_1 represents the difference between the selling price (S_P) of the remanufactured products and the remanufacturing costs.

Step 2: Analysis of environmental benefits. Remanufacturing is an effective way to discover the residual value of used products, but there is also some resource consumption (R_C) and pollutant emissions (P_e) problems in the remanufacturing process. This paper

converts resource depletion into CO_2 emissions after standard carbon combustion and evaluates environmental benefits accordingly.

Step 3: Analysis of social benefits. With the continuous development of science and technology, remanufactured products gradually flow to the market. This paper analyzes the social recognition (R_r) and reliability performance (R_p) of remanufactured products or parts and uses questionnaire surveys to assess their social benefits.

Step 4: Analysis of entropy weight. Due to the lack of historical remanufacturing data and imperfect remanufacturing technology, the accuracy of the decision-making model is not high. In this model, the entropy weight method is used to weigh the evaluation indicators. In the absence of historical data support, the entropy weight analysis method highlights its powerful advantages. The weight coefficient is not affected by subjective factors and is only related to the data itself. To a certain extent, it strengthens the realistic objectivity and generalization ability of the decision-making model.

Step 5: Solving the comprehensive benefits. According to the economic, environmental, and social benefits data in the actual process of CMR and PR, combined with the entropy weight method to analyze the weight coefficients, the comprehensive benefits of CMR and PR will be solved, respectively. The flow chart is shown in Figure 2.

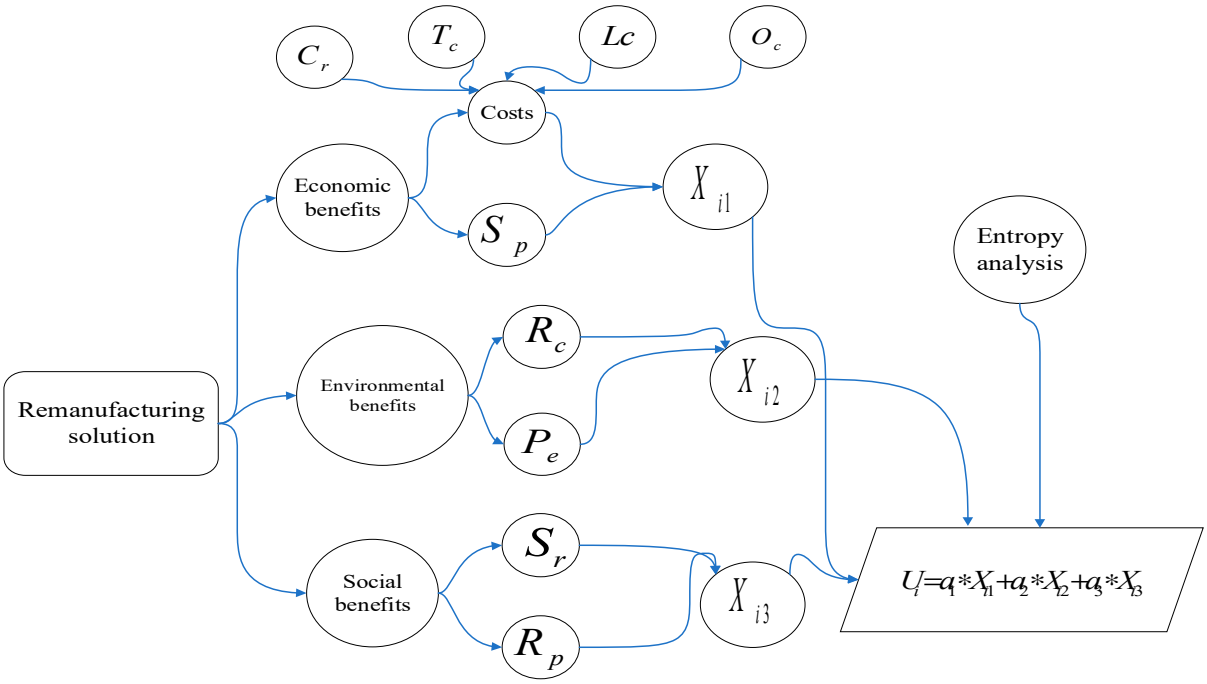

Figure 2. Remanufacturing strategy decision-making system.

3.3. Remanufacturing Economic Benefits

The main purpose of remanufacturing enterprises for remanufacturing activities is to make a profit. Before remanufacturing used products, it is necessary to consider whether it is necessary to remanufacture them from the perspective of economic benefits [32]. Xiang et al. [33] analyzed the remanufacturing costs composition and its influencing factors and established a support vector machine remanufacturing costs prediction model. Yu et al. [34] used a life-cycle model and a process-based cost model to assess the costs associated with greenhouse gas (GHG) emissions, water consumption, and remanufactured LIBs in the context of China, the largest producer of electric vehicles. Remanufacturing revenue X_1 can be expressed as the difference between the remanufactured products' S_p and remanufacturing costs, which can be specified by Formula (1).

$$X_1 = e - c_1 - c_2 - c_3 - c_4 \quad (1)$$

In Formula (1), X_1 represents the income from the remanufacturing of used products; e represents the S_p of remanufactured products or parts; c_1, c_2, c_3 and c_4 represent C_r, T_c, L_c, and O_c of used products or parts, respectively. O_c includes the green treatment costs of non-remanufactured parts, tax rates, and the purchase costs of new parts when choosing the CMR strategy.

(1) C_r

Remanufacturing is a production method in which used products are used as blanks and their performance is restored or structure improved. Due to the diversity of the working environment and the failure states of used products, this largely affects the quality of recycled parts and recycling costs [30]. c_1 can be determined through expert valuation and historical similar used products' C_r.

(2) T_c

The remanufacturing process is the process of structural optimization and performance recovery for used products or parts. The remanufacturing process can be specifically divided into recycling, disassembly, cleaning, inspection and classification, processing, equipment and debugging and packaging [35]. Among them, disassembly, cleaning, inspection and classification, processing, equipment and debugging require remanufacturing technology. T_c (c_2) is expressed by the rated life of the equipment used and its service time, as shown in Formula (2).

$$c_2 = \sum_{i=1}^{6} \frac{t_i}{T_i} \times p_i \tag{2}$$

In Formula (2), t_i and T_i, respectively, represent the actual use time and rated service life of the equipment required for process i in the remanufacturing process. p_i corresponds to the purchase price of the main equipment required for process i.

(3) L_c

Remanufacturing is systematic engineering, including not only the remanufacturing process but also the specific transportation and management process. According to the above analysis, the entire process of remanufacturing requires personnel to operate. L_c in the entire remanufacturing process is represented by c_3, and the specific calculation can be represented by Formula (3).

$$c_3 = \sum_{j=1}^{8} t_j \times \lambda_j \tag{3}$$

In Formula (3), t_j represents the time of manual work in the remanufacturing process j; λ_j represents the remuneration of the staff during the unit's working time. As each process requires different workers, the remuneration is also different. As shown in Table 2.

Table 2. Working hours and remuneration table.

Crafting Process	Actual Working Time/h	Remuneration/ Yuan
Recycle	t_1	λ_1
Disassemble	t_2	λ_2
Cleaning	t_3	λ_3
Detection and classification	t_4	λ_4
Remanufacturing	t_5	λ_5
Remanufacturing equipment and debugging	t_6	λ_6
Package	t_7	λ_7
Other	t_8	λ_8

(4) O_c

The initial design of mechanical products lacked the concept of remanufacturing, resulting in a large number of scrap products being unable to be remanufactured. Environmental protection treatment of parts that cannot be remanufactured, resulting in

environmental protection treatment costs c_{41}, R_c and P_e costs c_{42} during the remanufacturing process, and a new part purchase costs c_{43} when choosing a CMR strategy. Therefore, O_c can be expressed by c_4, specifically as follows Formula (4).

$$c_4 = c_{41} + c_{42} + c_{43} \tag{4}$$

(5) S_p

In recent years, with the continuous improvement of government preferential policies and remanufacturing theories, remanufactured products have gradually entered people's production and life. However, remanufacturing technology is not mature enough and Sris is not comprehensive enough, the sales range of remanufactured products or parts is relatively narrow. Many factors affect the price of remanufactured products or parts, such as S_r, R_p, etc., which makes it difficult to simply measure the S_p of remanufactured products or parts. In this article, S_p (e) of remanufactured products or parts are subject to the actual prices in the market.

3.4. Environmental Benefits

Compared with the new products' manufacturing process, the remanufacturing process has great advantages in saving energy and reducing pollution emissions [36,37]. Starting from the entire remanufacturing process, this article converts the R_c and P_e in different remanufacturing strategies to the standard carbon-burning carbon dioxide emissions. Through investigation and analysis, it is seen that the main R_c for both new products' manufacturing and used products' remanufacturing are coal, water, electricity, gasoline, and diesel. The related R_c and P_e factors are shown in Tables 3 and 4 [32].

Table 3. Coefficient of main energy conversion standard coal.

Energy	Row Coal	Water	Electric	Gasoline	Diesel Oil
Unit	kg	t	kWh	kg	kg
Coefficient(kgce)	0.7143	0.1229	0.2429	1.4714	1.4571

Table 4. Main energy carbon dioxide emission factors.

Energy	Row Coal	Water	Electric	Gasoline	Diesel Oil
Unit	kg	t	kWh	kg	kg
Coefficient(kgco2/kgce)	1.90	0.194	0.80	2.93	3.01

The environmental benefits (X_2) represents the ratio of the standard CO_2 emissions of R_c in the remanufacturing process to the CO_2 emissions in the new product manufacturing process, as shown in Formula (5).

$$X_2 = \frac{E_{Rp}}{E_{Np}} = \frac{\sum_{i=1}^{5} \mu_i \times e_{Rpi}}{\sum_{i=1}^{5} \mu_i \times e_{Npi}} \tag{5}$$

In Formula (5), E_{Rp} represents P_e during the remanufacturing process of used products; E_{Np} represents P_e during the manufacturing process of new products; μ_i represents the conversion coefficient of energy consumption i converted into standard coal; e_{Rpi} and e_{Npi}, respectively, represent the use of type i energy in the remanufacturing process of used products and the manufacturing process of similar new products. Among them, R_c in the process of new product manufacturing and remanufacturing is converted into the form of standard coal, as shown in Formula (6).

$$e_{N/Rpi} = \sum_{i=1}^{5} \beta_i \times A_i \tag{6}$$

In Formula (6), $e_{N/Rpi}$ represents the total amount of R_c in the process of new products' manufacturing or remanufacturing of used products; β_i represents the conversion factor of type i energy into standard coal; A_i represents the amount of R_c from type i in the process of new products' manufacturing or remanufacturing of used products.

3.5. Social Benefits

Remanufacturing is one of the best final treatment methods for used products [38], which has developed rapidly in the manufacturing industry with its unique advantages in recent years. The country has also invested a lot of manpower, material and financial resources in remanufacturing and environmental pollution control and has achieved gratifying results. With the continuous development of remanufacturing technology and the continuous enhancement of people's awareness of environmental protection, remanufactured products are gradually being favored by remanufacturing enterprises and the public [39,40]. While taking economic feasibility and environmental feasibility into account, more attention should be paid to social benefits. The performance and functions of remanufactured products or parts are complex and diverse, which adds difficulty to the evaluation of their social benefits. The social benefits of remanufactured products not only determine whether they can be remanufactured but are also inseparable from their economic and environmental benefits. However, the social acceptance and reliability of remanufactured products are the main factors affecting their social benefits. Therefore, this article uses a combination of the Delphi method and fuzzy quantification to analyze it quantitatively and qualitatively through the social survey. The Delphi method can effectively solve the errors caused by the difficult-to-define quantities and uncertain factors in the evaluation process.

S_r greatly affects used products' remanufacturing decisions. The social benefits (X_3) includes Srand Rpof remanufactured products. The specific calculation can be expressed by Formula (7).

$$X_3 = S_1 \times \gamma_1 + S_2 \times \gamma_2 \tag{7}$$

In Formula (7), S_1 represents the statistics of the S_r survey table for used remanufactured products or parts in society. S_2 represents the R_p of the remanufactured products or parts. γ_1 and γ_2 represent the weight coefficients, whose magnitude can be determined by the Delphi method or the Analytic hierarchy process (AHP), $\gamma_1 + \gamma_2 = 1$.

(1) S_r

S_r refers to the degree of satisfaction and usage of remanufactured products or parts in society and remanufacturing factories. To reduce the subjective and random influence of the survey data, this survey selected the same number of different contact groups for questionnaire evaluation to be expressed as S_1. The specific formula is shown in Formula (8).

$$S_1 = \frac{\sum_{i=1}^{M} g_i}{M} \tag{8}$$

In Formula (8), M represents the total number of people who received the questionnaire survey g_i represents the satisfaction score of remanufactured products or parts received in the questionnaire survey ($g_i \in [0, 1]$). The closer the score is to 1, the higher the social satisfaction.

(2) R_p

R_p (S_2) is a qualitative evaluation index, expressed by the average value of the evaluation results of the functional integrity S_{21}, operational stability S_{22}, operation convenience S_{23} and safety reliability S_{24} of the remanufactured products or parts, as shown in Formula (9).

$$S_2 = \frac{1}{4}(S_{21} + S_{22} + S_{23} + S_{24}) \tag{9}$$

R_p is difficult to express in simple numerical terms. Based on the Delphi method, this paper compares the performance of the remanufactured product with the performance

of the original product and uses a fuzzy quantitative method to make a qualitative analysis. The comparison results are divided into four grades: poor, fair, good, and equal, corresponding to the values $[0.25, 0.50, 0.75, 1.0]$. The details are shown in Table 5 below.

Table 5. Performance evaluation index.

Performance Level	Poor	Fair	Good	Equal
Performance index S_{2i}	0.25	0.50	0.75	1.0

3.6. Comprehensive Evaluation and Program Decision

From the perspective of the economy, environment and society, this paper proposes a decision-making model for CMR and PR of used products with low-remanufacturability. This paper uses the entropy weight method to analyze and calculate the weight of each decision index. The specific selection steps are as follows.

(1) Remanufacturing strategy decision matrix

This article takes used products with low-remanufacturability as the research objects, exploring the residual value of used products to the greatest extent and maximizing comprehensive benefits. Based on considering economic, environmental, and social benefits, a comprehensive evaluation of CMR and PR strategies is carried out. The decision matrix is shown in Formula (10).

$$U = \begin{bmatrix} L_1 \\ L_2 \end{bmatrix} = \begin{bmatrix} X_{11} X_{12} X_{13} \\ X_{21} X_{22} X_{23} \end{bmatrix} \tag{10}$$

In Formula (10), U represents the result of comprehensive decision-making. L_1 and L_2 represent CMR and PR strategies, respectively. Represents the $j-$th evaluation index value in the $i-$th strategy.

(2) Standardized decision matrix

In the multi-objective decision-making problem, there are many influencing factors. The meaning and nature of indicator factors are complex and diverse, so it is very necessary to properly preprocess indicators before making a decision [41,42]. The fuzzy vector normalization method is used to process the corresponding indicators and is denoted by Y, as shown in Formula (11).

$$Y = [y_{ij}] = [\frac{X_{ij}}{\sqrt{\sum_{i=1}^{2} {X_{ij}}^2}}] \tag{11}$$

(3) Weight coefficient calculation

To reduce the influence of subjective factors and data randomness on the decision-making results, it is necessary to weigh the various indicators. The traditional weighting methods include the Delphi method (expert consulting method), order relationship analysis method, statistical method and principal component analysis method. In this paper, the entropy weight method with a good ability to deal with disordered and discrete data is used to process the evaluation index. If the number of strategies is a, and the number of evaluation indexes is b, the decision entropy can be expressed as [16].

$$H_j = -\frac{1}{Ina}\left(\sum_{i=1}^{a} f_{ij} In f_{ij}\right) \tag{12}$$

In Formula (12), H_j represents the entropy value of decision-making, where $f_{ij} = \frac{y_{ij}}{\sum_{i=1}^{n} y_{ij}}$, $i = 1, 2, \ldots, a$; $j = 1, 2, \ldots, b$. Each entropy weight α_j of the evaluation is shown in Formula (13).

$$\begin{cases} \alpha_j = \frac{1-H_j}{b-\sum_{j=1}^{n} H_j} \\ \sum_{j=1}^{n} \alpha_j = 1 \end{cases} \tag{13}$$

(4) Remanufacturing strategies decision-making

This article proposes a remanufacturing strategy decision-making model from the perspective of remanufacturing economic, environmental, and social benefits. This model solves the problem of remanufacturing products with low-remanufacturability, maximizing resource utilization efficiency, and reducing environmental pollution. The entropy method has a good comprehensive evaluation effect on the multi-objective discrete system. Therefore, this paper adopts the entropy method to evaluate the remanufacturing plan of used products with low remanufacturability, as shown in Formula (14).

$$U_i = \alpha_1 \times X_{i1} + \alpha_2 \times X_{i2} + \alpha_3 \times X_{i3} \tag{14}$$

In Formula (14), X_{i1}, X_{i2}, and X_{i3}, respectively, represent the evaluation indicators of remanufacturing economic, environmental, and social benefits. α_1, α_2, and α_3 are the entropy weights of the corresponding indicators. If U_1 and U_2, respectively, represent the comprehensive decision-making benefits of CMR and PR of the used product. When the evaluation result is $\frac{U_1}{U_2} < 1$, PR strategy should be selected. When the evaluation result is $\frac{U_1}{U_2} > 1$, CMR strategy should be selected.

4. Case Analysis and Results

With the continuous development of science and technology, people's quality of life has been greatly improved. Remanufacturing has become an important way to save energy and reduce pollution emissions, which has been favored by scholars and research institutions. This paper takes the remanufacturing scheme decision of the used machine tool CA6180 as an example to study the economic, environmental and social benefit assessment of its different remanufacturing schemes. The data in this paper are mainly from Shenyang No.1 Machine Tool Factory, and the social evaluation data are from the product after-sales service data. The research not only provides a strong decision-making basis for remanufacturing companies but also provides theoretical support for the country to formulate relevant laws and regulations on the final disposal of used products.

4.1. Economic Benefits Analysis

The main research objectives of this paper are studying used products with low remanufacturability and proposing a decision-making problem of CMR and PR strategies. In the recycling of used products and the entire remanufacturing process, different remanufacturing strategies have different economic benefits. Through the investigation of the remanufacturing process of the factory's used machine tool CA6180, it can be seen that the costs of the recycled parts in the two remanufacturing strategies remain unchanged. Compared with PR, the costs of disassembly, cleaning and newly purchased parts for CMR will be higher, and its selling price is higher. In PR, cleaning, labor costs and selling prices are lower, while environmental protection costs are higher. Starting from the remanufacturing process, the economic benefits of new products' manufacturing and remanufacturing of the machine tool CA6180 are analyzed. The specific comparison is shown in Table 6 below (The data are mainly from Shenyang No.1 Machine Tool Factory).

Table 6. List of remanufacturing costs and selling price of recycled parts (Unit: Yuan).

Remanufacturing Projects	Process Flow	Remanufacturing Costs	New Product Manufacturing Costs	Parts Remanufacturing Costs
c_1	Raw material prices	1165.70	0	1165.70
c_2	Disassemble	204.96	0	153.72
	Cleaning	789.18	1747.40	931.23
	Detection classification	1178.28	496.88	1355.02
	Remanufacturing	2574.88	7163.31	1712.29
	Remanufacturing equipment and debugging	1289.70	4029.02	876.99
	other	3597.10	4352.49	2553.94
c_3	Recycle	248.00	0	248
	Disassemble	636.00	0	540.60
	Cleaning	340.00	833	302.60
	Detection and classification	572.40	2409.80	752.70
	Remanufacturing	2936.16	10,643.58	3405.94
	Remanufacturing equipment and debugging	529.08	1652.84	355.54
	package	316.90	1024.53	237.04
c_4	Environmental protection	1685.28	2376.24	2039.18
	Used disposal	1068.14	1409.945	699.63
	New purchase costs	3696.14	12,370.98	1596.73
Total costs	$c = \sum_{i=1}^{4} c_i$	22,827.90	50,510.05	18,926.89
Selling price	e	32,940.00	75,000.00	28,830.00

There are no recycling and disassembly costs for the manufacture of new machine tools, but the costs of environmental protection treatment and new purchases of raw materials are much higher than the corresponding costs in the remanufacturing process. In the CMR and PR process, in addition to the recovery cost, other costs are determined by the quality of the recovered parts. It can be seen from the data in the table that CMR's T_c and O_c of the surveyed product are slightly higher than the corresponding costs of PR, while L_c is slightly lower than PR. PR needs to disassemble, clean, and inspect the whole machine, which leads to an increase in L_c.

4.2. Environmental Benefits Analysis

Due to the different working environments and loads of mechanical products, the failure characteristics and failure degree of mechanical products are not the same. The manufacturing and remanufacturing processes are both systematic projects, which also have energy consumption and pollution emissions. This article mainly focuses on the consumption of coal, electricity, gasoline diesel and the discharge of water, and transforming it into CO_2 emissions under the standard form. Then, the P_e of different remanufacturing strategies is compared to obtain the environmental evaluation index. There are two main methods of generation used in the remanufacturing of used products. On the one hand, not all parts in used products can be remanufactured, and severely failed parts need to be treated in an environmentally friendly manner. This process consumes energy and generates waste. On the other hand, the specific remanufacturing process will also produce certain R_c and P_e. According to the historical remanufacturing data of the common machine tool CA6180, the specifically used generation and standardization results in the remanufacturing process can be obtained, as shown in Table 7.

Table 7. Standardization of R_c for different remanufacturing strategies.

Energy	Row Coal	Water	Electric	Gasoline	Diesel Oil	Total
Unit	kg	t	kWh	kg	kg	Standardized
Machine remanufacturing	35.96	19.40	27.80	14.10	11.70	72.62
Component remanufacturing	32.00	21.53	19.02	11.84	9.86	61.92
New manufacturing	58.00	18.00	34.00	12.00	8.00	81.22

The above table lists the R_c and overall carbon dioxide emissions during the new products' manufacturing of machine tool CA6180 and the remanufacturing of its used products. The data in the table shows that remanufacturing can indeed reduce R_c and P_e. Compared with new product manufacturing, the remanufacturing process consumes less energy, but the amount of used water discharge has increased significantly. Compared with CMR, the R_c of PR has decreased. However, the amount of used water discharged due to a large number of cleaning parts has increased.

4.3. Social Benefits Analysis

Remanufacturing companies take profit as their goal. The market has important guiding significance for business operations, and a market leader in the social group. Therefore, it is very necessary to analyze the social benefits of remanufactured products, which is related to whether used products can be remanufactured. In the absence of historical evaluation data, this article evaluates the social benefits of remanufactured products from their S_r and R_p. The social recognition of remanufactured products or parts is obtained by market surveys. To ensure the data is accurate and effective, the participants are divided into four categories: people who do not know remanufactured products B1, have relevant remanufacturing knowledge but have not used remanufactured products crowd B2, remanufactured products' user B3 and related field experts B4. The total number of participants in the assessment is 100, and 25 people from each category are selected to participate. The recognition survey is based on the evaluation of the acceptance of remanufactured used products or parts. The actual situation of the respondent gives a value between $[0,\ 1]$. The higher the score, the easier it is to accept remanufactured products or parts, as shown in Table 8.

Table 8. Survey results of S_r.

Participants	B1			B2			B3			B4		
Evaluation results	Hig-h	low	mid	Hig-h	low	mid	Hig-h	low	mid	Hig-h	low	mid
	0.50	0.00	0.35	0.85	0.40	0.64	0.95	0.56	0.86	1.00	0.75	0.90
Overview	0.6875											

Reliability performance analysis is mainly used to evaluate whether products or components can complete the corresponding function, operational stability, operation convenience, and safety and reliability. This article obtains real-time data based on the actual operation of the remanufactured products or components. The CMR is to evaluate the overall performance of the product, while the PR is to evaluate the performance of the parts individually and takes the average value. The specific data is shown in Table 9. The social benefits of remanufactured products are calculated by the Formula (7), $\gamma_1 = \gamma_2 = 0.5$.

Table 9. P_r of remanufactured products or parts.

Evaluation Analysis	Evaluation Index	Remanufactured Products	Remanufactured Parts
Reliability performance	Functional integrity s_{21}	1.00	1.00
	Operational stability s_{22}	0.75	1.00
	Convenience of operation s_{23}	0.75	1.00
	Safety and reliability s_{24}	0.75	0.75
Overall evaluation result	$s_2 = \frac{(s_{21}+s_{22}+s_{23}+s_{24})}{4}$	0.81	0.93
Social benefit X_3	$X_3 = S_1 \times \gamma_1 + S_2 \times \gamma_2$	0.75	0.81

4.4. Remanufacturing Solution Decision

This article comprehensively analyzes the remanufacturing strategy of the used machine tool CA6180 from the perspective of the economic, environmental, and social benefits of the remanufacturing process. According to the business model of the remanufacturing enterprise, the actual recycling quality of used products, and the social demand, the above three indicators are evaluated for the decision-making of the remanufacturing strategy. To reduce the error caused by the small amount of historical data and the randomness of the data, the entropy weight method is used to weigh the evaluation parameters to increase the accuracy and stability of the system evaluation. The model weighting coefficient can be obtained by Formulas (10)–(14) as $[\alpha_1, \alpha_2, \alpha_3] = [0.51, 0.37, 0.12]$. The detailed calculation results of the parameters in the decision-making are shown in Tables 10 and 11. In addition, it can be seen from Figure 3 that the economic, environmental, and social benefits of CMR and PR are different. The figure shows that the economic and environmental benefits of the PR strategy are significantly higher than the CMR strategy, only the environmental benefits are lower, but the comprehensive benefits are slightly higher than the CMR strategy.

The data in the table shows that the choice of remanufacturing strategy not only affects the economic benefits of remanufacturing enterprises but also affects the contribution of remanufacturing enterprises to energy conservation and environmental protection to a large extent. The data in the figure also shows that waste products with low remanufacturability that are ignored by remanufacturing companies still have economic, environmental and market value to be remanufactured. The comprehensive evaluation of CMR and PR strategies of the used machine tool CA6180 are, respectively, 0.5656 and 0.5806. The results show that the selected PR strategy for the machine tool studied has higher comprehensive benefits.

Table 10. Entropy weight analysis method for weight.

y_{ij}			f_{ij}		
0.6462	0.7554	0.6783	0.46	0.54	0.48
0.7632	0.6553	0.7348	0.54	0.46	0.52
H_j			α_j		
0.9950	0.9964	0.9988	0.51	0.37	0.12

Table 11. Comprehensive evaluation results.

Items	x_1	x_2	x_3	U
CMR	0.4430	0.6750	0.7500	0.5656
PR	0.5232	0.5856	0.8125	0.5806

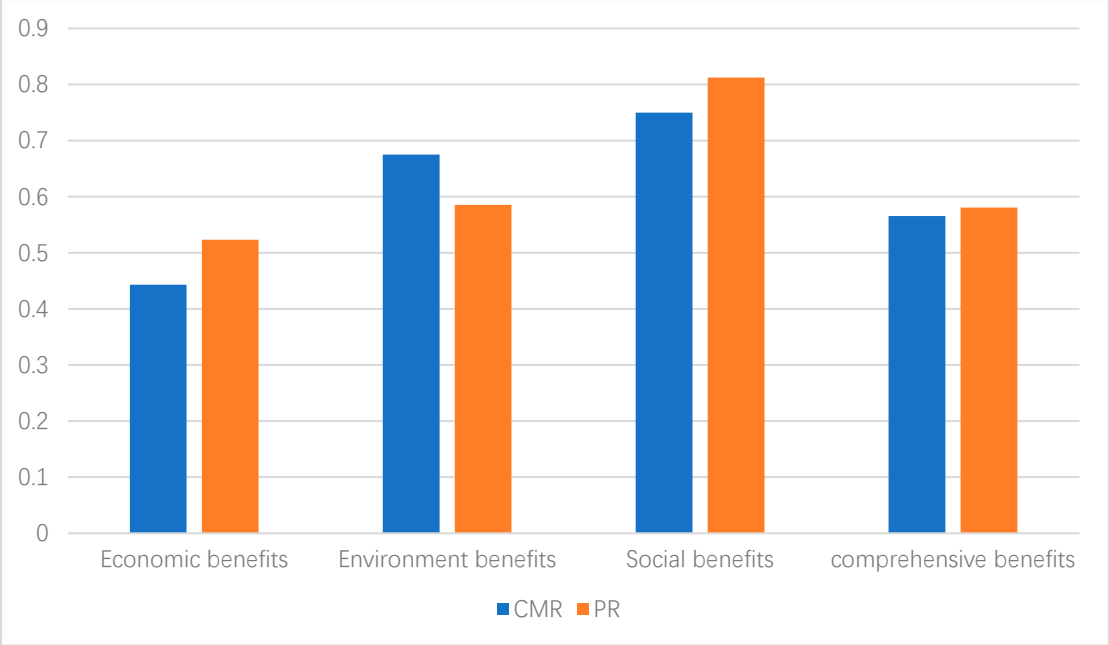

Figure 3. Comprehensive benefits error of CMR and PR strategies.

5. Discussion

Traditional remanufacturing is based on the high remanufacturability of recycled products. Through the performance analysis of used products, the remanufacturing process must meet the requirements of economic, technical, and environmental benefits to performing performance recovery and structural transformation of used products. This is far from enough. In addition, the market leads companies in their production activities. Therefore, the social benefits of remanufactured products are factors that have to be considered before remanufacturing activities. At present, with the continuous development of the intelligent industry, a large number of mechanical products are facing scrap and environmental protection treatment. At the same time, facing a global shortage of resources and increasing environmental pollution, it is urgent to seek a remanufacturing strategy for used products with low-remanufacturability to maximize the residual value of used products and improve the market competitiveness of remanufacturing enterprises. However, the market leads companies in their production activities. Therefore, the social benefits of remanufactured products are factors that have to be considered before remanufacturing activities.

Based on the existing remanufacturing technologies, this paper takes the remanufacturing of the ordinary used machine tool CA6180 as an example and evaluates the comprehensive benefits of CMR and PR from the perspective of the remanufacturing process and social benefits. The data in Figure 3 shows that the economic, social and comprehensive benefits of PR of used machine tool CA6180 are higher than those of CMR. For the remanufacturing of used products with low-remanufacturability, to improve the overall benefits of the remanufacturing strategy, companies can adopt the following measures: (1) Under the conditions of existing remanufacturing technology, the use of integral thinking is adopted for used products with low-remanufacturability to maximize their comprehensive benefits. (2) To increase economic benefits, corresponding remanufacturing thresholds should be set for different parts. When the remanufacturing threshold is exceeded, the parts will be treated as green and renewable. (3) To increase social benefits, companies should vigorously promote the concept of energy conservation and pro-environmental and establish a corresponding reward and punishment mechanism to stimulate employees' enthusiasm and sense of social responsibility. (4) In order to improve the comprehensive benefits of remanufacturing, enterprises should strengthen the follow-up investigation of market products and improve the products' recycling mechanism. With the continuous

advancement of technology, companies need to develop flexible remanufacturing strategy evaluation standard management mechanisms that adapt to market changes.

However, it should be pointed out that this article still has certain limitations. From one point of view, due to the small number of historical remanufacturing strategies, the evaluation results are somewhat one-sided. Enlarging historical remanufacturing cases will improve the accuracy of remanufacturing program decisions. From another point of view, considering the complexity of the social benefits of remanufactured products, this article only uses fuzzy quantitative methods to evaluate them in a small range. Aiming at the problem of recycling and processing products with low-remanufacturability, establishing a more comprehensive treatment strategy will be one of the key tasks of future research.

6. Conclusions

With the continuous development of science and technology, the manufacturing industry has brought great convenience to people's production and life, but also caused the problem of resource shortage and environmental pollution. However, the lack of remanufacturing design concepts in a large number of mechanical products in the initial design, poor working environment and overload operation make them unable to be remanufactured. This kind of rugged mechanical product design, production and use mode caused by the waste of resources and environmental pollution problems are increasing. As a whole, mechanical products are composed of rudder parts. Waste mechanical products can be repaired, degraded, and disassembled as parts and other forms to realize the effective utilization of resources. Therefore, how to maximize the resource utilization of waste products under the existing technological conditions, while taking into account the economic, environmental and social benefits of green sustainability has become the common goal of researchers.

Aiming at the problem of remanufacturing used products with low-remanufacturability, this paper proposes a decision-making model for remanufacturing solutions for used products. This model mainly analyzes and evaluates the economic, environmental, and social benefits of remanufacturing used products and parts under the existing remanufacturing technology conditions. In order to reduce the influence of subjective factors and random data fluctuations in the decision-making process, the entropy weight analysis method greatly reduces the interference of human factors and improves the accuracy of the decision-making model used to weigh the evaluation indicators. Firstly, compared with the traditional remanufacture decision-making model, the model reduces the dependence on historical remanufacturing data in the decision-making process of remanufacturing strategies and greatly improves the generalization ability of the decision-making model. Secondly, compared with the existing research on the decision-making of remanufacturing schemes, the model proposed in this paper not only solves the decision-making problem of remanufacturing strategies for used products with low-remanufacturability but also provides an efficient solution for remanufacturing used products with higher remanufacturability. The structure and form of the algorithm in this paper are relatively simple, which avoids the system instability caused by too many parameters. However, in the process of decision-making and evaluation of remanufacturing methods, this article requires higher data accuracy to increase the difficulty of data acquisition. This is where the model needs to be improved.

There are many methods for decision-making on remanufacturing strategies, such as the grey value analysis method, AHP method, principal component analysis method and neural network model. In future research, combining neural networks and deep learning methods to construct a convenient and efficient remanufacturing strategy decision-making model with strong generalization capabilities is an urgent need to solve.

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Nomenclature

X_1	The income from remanufacturing of used products	β_i	The conversion factor of type i energy into standard coal
e	The selling price of remanufactured products or parts	A_i	The consumption of category i energy during manufacturing or remanufacturing
c_1	The cost of recycling used products	Y	Normalized decision matrix
c_2	The cost of remanufacturing technology	y_{ij}	The normalized coefficient of X_{ij}
c_3	Remanufacturing labor costs	H_j	The entropy value of decision-making
c_4	Other remanufacturing costs	α_i	The i-th index weight coefficient
t_i	The actual use time of the equipment required for process i	X_3	The social benefits of remanufacturing products
T_i	The rated service life of the equipment required for process i	S_1	The social satisfaction with remanufactured products or parts
p_i	The purchase price of the main equipment required for process i	S_2	The expert performance evaluation of remanufactured products or parts
t_j	The time of manual work in the remanufacturing process j	γ_i	Social benefits index weight coefficients
λ_j	The remuneration of the staff during the unit working time	g_i	Remanufacturing products i-th respondent satisfaction rating
c_{41}	Environmental protection cost of remanufacturing process	M	The total number of people who received the questionnaire survey
c_{42}	The costs of remanufacturing energy consumption and waste disposal	S_{21}	The average value of the evaluation results of the functional integrity
c_{43}	Complete machine remanufacturing new parts purchase costs	S_{22}	The average value of the evaluation results of the operational stability
μ_i	Standard coal converted coefficient for energy i	S_{23}	The average value of the evaluation results of the operation convenience
E_{Rp}	CO_2 emissions in remanufacturing process	S_{24}	The average value of the evaluation results of the safety reliability
E_{Np}	New product manufacturing CO_2 emissions	U_i	The i-th remanufacturing strategy comprehensive benefits
X_2	Remanufacturing environmental benefits	L_i	The i-th remanufacturing strategies matrix
e_{Rpi}	The use of type i energy in the remanufacturing process of used products	X_{ij}	The j-th evaluation index value in the i-th strategy.
e_{Npi}	The use of type i energy in the manufacturing process		

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