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A Fuzzy Decision-Making Method for Green Design for Remanufacturability

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Abstract: Designs for remanufacturing (DfRem) consider the remanufacturability of the product in the early stages of product design, which can greatly increase the reusability of the products. However, product design schemes lack reasonable evaluation indicators for remanufacturability, and the decision-makers of the design scheme have subjective preferences and vague hesitation. These result in inaccurate decision making on DfRem schemes that will affect the successful implementation of product remanufacturing. In order to improve the accuracy of the DfRem scheme decision, a fuzzy decision-making method for green design for remanufacturability is proposed. Firstly, an evaluation indicator system for green design schemes was established that takes into account remanufacturability, reliability, cost, and the environment, and the entropy weighting method is used to quantify and weigh the design scheme evaluation indicators. Then, the hesitation fuzzy set is applied to construct the set of evaluations and the optimal design scheme is selected by applying the comprehensive evaluation method. Finally, the feasibility of the above method is verified by using the green design of an injection mold as an example, and the results show that the above method is able to make accurate and effective design scheme decisions. This method has been implemented in a prototype system using Visual Studio 2022 and Microsoft SQL Server 2022. The results show that the fuzzy decision-making system is accurate and effective for rapidly generating a rational green design scheme for remanufacturability.

Keywords: remanufacturing; green design; decision making; entropy weight; hesitant fuzzy set

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1. Introduction

Remanufacturing is an industrial process that restores used products to a "new" or "better" than "new" functional state, focusing on material, energy, and cost savings [1–3]. The design for remanufacturing (DfRem) is an important part of the remanufacturing system, which can improve product remanufacturability and facilitate the smooth implementation of product remanufacturing [4,5].

However, the DfRem process can generate multiple design solutions, so designers need to make decisions about the best solution. Unlike traditional designs, DfRem is not only focused on product remanufacturability, but also on the reliability. This makes the design scheme decision very complex. To address this problem, it is necessary to make a comprehensive system of DfRem scheme evaluation indicators. Currently, many scholars have conducted studies on DfRem evaluation indicator system construction. Jiang et al. [6] developed a data-driven ecological performance evaluation method for the remanufacturing process which constructed the evaluation indicator containing the energy-saving rate, remanufacturing process cost, and rate of remanufacturing. Ding et al. [7] proposed an integrated multi-criteria decision-making (MCDM) approach which established the remanufacturability evaluation indicator system for the machine tool guideway. Harivardhini et al. [8] proposed an integrated framework for supporting decision making during early design stages of end-of-life, which can help designers compare and select alternative designs of a product that have better disassembly potential. Peng et al. [9] developed an effective and comprehensive multi-criteria decision-making approach which considered the environmental impact, economic cost, and technical property for the remanufacturing process. Wang et al. [10] proposed a demand-matching multi-criteria decision-making method for reverse logistics, which focuses on four types of evaluation indicators including quality condition, sustainability, economy, and risk. There is no doubt that these studies solved the evaluation indicator system for DfRem, including the remanufacturing process design, design for disassembly, and reverse logistics, and these pieces of research promote the smooth implementation for the DfRem scheme's evaluation.

Unfortunately, this literature only considers remanufacturing in terms of the remanufacturing process, disassembly, or reverse logistics, et al., but seldom considers remanufacturing in terms of the product design phase, and has not constructed a design scheme evaluation indicator system with remanufacturability, which makes it impossible to select a beneficial product design scheme for remanufacturability. Gong et al. [11] established the evaluation criteria for the DfRem scheme, which considered the technical, economic, and environmental factors. Although this method contains the remanufacturing cost and environmentality of the remanufacturing process, the research does not provide an accurate quantitative description of the remanufacturability indicator as a technical indicator. Remanufacturability is an individual characteristic of a product, which is an inherent attribute and should be considered as a technical indicator to guide product design. Moreover, DfRem considers the remanufacturability of the product at the design stage, so the remanufacturability of the product should be evaluated in the design scheme. Most importantly, a design scheme evaluation indicator system for remanufacturability needs to be constructed while mainly including the disassemblability, recyclability, detectability, and reliability of product performance, etc.

Furthermore, designers need to develop evaluation indicator weights in order to make accurate design solution decisions. However, experts determine the importance of indicators by scoring the design scheme evaluation indicators. This is mainly an indicator evaluation based on their personal experience and subjective judgment, which cannot objectively reflect the importance of the indicator. The entropy weighting method is a comprehensive evaluation method that can be used for multiple objects and indicators; moreover, the entropy weighting method is based on the information of each indicator for weight calculation, which is easy to calculate and enable objective weighting based on actual information, thus reducing the interference of subjective factors [12], and many fields have already used the entropy weight method to calculate weights, for example, the weights calculation of nanoparticle evaluation indicators [13], the risk assessment of the tunnel [14], the Groundwater quality assessment [15], and so on. Owing to the advantages of the entropy weight, it can be used to calculate the weights of the DfRem scheme evaluation indicators in order to avoid subjective weighting.

Decision making on DfRem schemes requires the quantification of each evaluation indicator, which is generally scored according to designers or experts. However, experts have hesitation in the face of design scheme evaluation indicators and are unable to give a precise evaluation value, but rather an evaluation interval, which makes the evaluation process ambiguous and uncertain. Hesitant fuzzy set, an effective means to cope with the uncertainty and complexity of decision making [16], and many fields have applied this method for uncertainty decision making, for example, the assessment of a sustainable supplier [17], sustainable city logistics [18], risk decision making [19], etc. Obviously, from the research results of hesitant fuzzy sets in various fields, hesitant fuzzy sets can effectively process fuzzy evaluation information and improve the accuracy of evaluation results.

To improve the accuracy and reliability of a DfRem scheme decision, this paper proposes a fuzzy decision-making method to select the optimal design scheme. The novelties of this paper are listed in the following: (1) The DfRem scheme evaluation system was constructed to comprehensively consider the remanufacturability indicators at the product design stage, thus ensuring product remanufacturability and improving the remanufacturing efficiency of end-of-life products. (2) A DfRem scheme decision-making method was proposed to fully take into account the hesitancy of decision makers in scoring evaluation indicators, thereby reducing the ambiguity of DfRem scheme decision making. (3) DfRem decision-making software 2024 was developed to visualize the design solution decision-making process and to improve the operability of the DfRem decision-making method, thus improving the decision-making efficiency. The remainder of this paper is structured as follows. Section 2 proposes the framework for decision making on DfRem schemes, which contains DfRem scheme evaluation indicator extraction, evaluation indicator system construction, and the DfRem scheme decision. Section 3 constructs a DfRem scheme evaluation indicator system, including reliability, remanufacturability, cost, and environmental indicators. Section 4 proposes a DfRem scheme decision method based on entropy weight and hesitation fuzzy sets. Section 5 validates the method with a DfRem case for the injection mold, and Section 6 draws conclusions for this study.

2. Decision-Making Framework for DfRem

A green design for remanufacturability contains a large amount of design information and constraint information, so it is necessary to extract key evaluation indicators from the above information, and establish an evaluation indicator system for green design schemes, finally adopt a suitable decision-making method to select the optimal design solution. The specific process is shown in Figure 1.

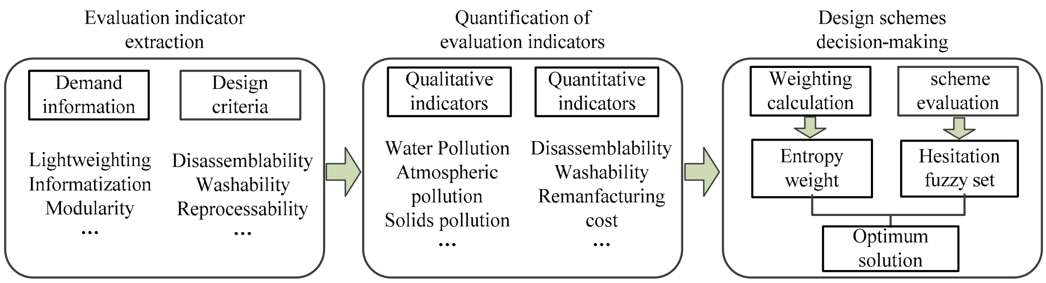

Figure 1. Decision-making framework for DfRem.

The decision-making framework for DfRem includes three main components.

(1) Evaluation Indicator Extraction

The design for remanufacturing needs to take into account remanufacturability requirements, system constraints, and design guidelines. Remanufacturability requirements include connection methods, performance levels, and construction types. System constraints include dimensional constraints, performance constraints, and appearance constraints, etc. System constraints can also be functionally mapped to form functional features of the product. The design guidelines include ease of disassembly, ease of cleaning, and reliability. The green design evaluation indicators need to be extracted from the remanufacturability demand information, and different types of information are described in different ways and quantified in different ways, which can be described by the object element method and transformed into design scheme evaluation indicators. The description is shown in Equation (1).

$$M = (O_r, c_r, v_r, d_r) = \begin{bmatrix} c_{r1} & v_{r1} & d_{r1} \\ \cdots & \cdots & \cdots \\ c_{ri} & v_{ri} & d_{ri} \\ \cdots & \cdots & \cdots \\ c_{rn} & v_{rn} & d_{rn} \end{bmatrix} \tag{1}$$

where M denotes the element information of the product, O_r denotes the r-th target (e.g., product and component), C_{ri} denotes the i-th feature and the corresponding r-th object quantity, respectively, v_{ri} denotes the i-th feature and the corresponding r-th object weight, and d_{ri} denotes the design requirement for the i-th feature of the r-th target.

(2) Quantification of evaluation indicators

Qualitative descriptions are fuzzy evaluations by experts, designers, or clients which are generally described by ambiguous concepts such as degree words and are subjective in nature. Meanwhile, quantitative descriptions are assessed in terms of specific numerical values with objectivity. Since different types of indicators have different levels of measurement, both qualitative and quantitative indicators need to be normalized to ensure the accuracy of the evaluation process.

(3) Design scheme decision making

The evaluation indicator system for green designs containing technical, economic, and environmental factors is constructed from the perspectives of customer demand, enterprise production, and environmental regulations. Meanwhile, the entropy weight method and hesitant fuzzy set (EWM-HFS) are used for the multi-attribute decision making of green design schemes.

3. Evaluation Indicator System Construction

In order to extract and calculate the evaluation indicator values more accurately, the evaluation indicators for green designs for remanufacturability are divided into two levels, the first level indicators include technical, economic, and environmental indicators, the second level indicators are refined based on the first level indicators, for example, technical indicators include easy recyclability, easy disassembly, and reliability, etc. The overall evaluation indicator system is shown in Figure 2.

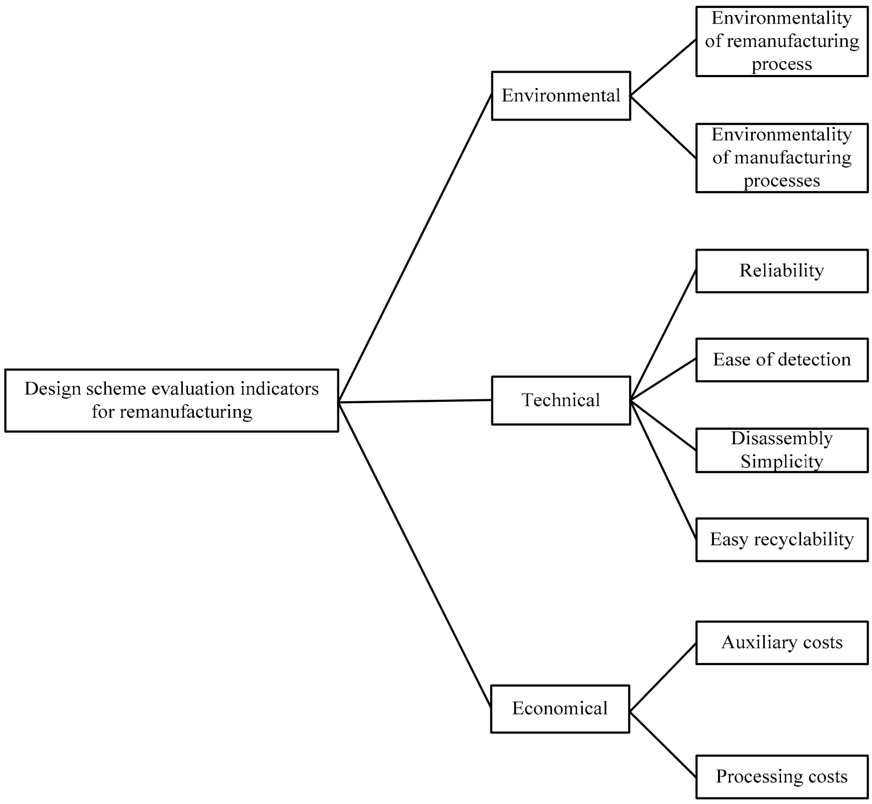

Figure 2. Design scheme evaluation indicator system for remanufacturability.

3.1. Technical Indicators

The technical indicators are evaluated in terms of reliability, disassembly, recyclability, and easy detection, and the process of quantifying each indicator is as follows.

(1) Easy recyclability: Product recycling takes into account factors such as the ease of packaging and transportation and the encapsulation of hazardous materials. The ease

of recycling is mainly measured by the recycling time, and the specific indicators are quantified as follows.

$$T_R = 1 - \frac{T_{R1} - T_{R\min}}{T_{R\max} - T_{R\min}} \tag{2}$$

where T_R denotes the quantified value of the normalized recycling time, T_{R1} denotes the time taken to recycle the product part, $T_{R\min}$ denotes the minimum recycling time, and $T_{R\max}$ denotes the maximum recycling time. All are measured in minutes.

(2) Ease of disassembly: The difficulty of disassembly depends on the number of components, the degree of precision, and the type of connection, etc. The disassembly process minimizes damage to components. The ease of disassembly can be measured by the disassembly time, which is as follows.

$$T_D = 1 - \frac{T_{D1} - T_{D\min}}{T_{D\max} - T_{D\min}} \tag{3}$$

where T_D denotes the quantified value of the normalized product disassembly indicator, T_{D1} denotes the product disassembly time, $T_{D\max}$ denotes the maximum product disassembly time, and $T_{D\min}$ denotes the minimum product disassembly time; the time unit is minutes.

(3) Ease of detection: Since the product is used in different environments and ways, these will affect the quality condition of the product, as well as affecting the difficulty of the parts' quality detection. To simplify the quantification process, the detection time is used to indicate the ease of product detection. Assuming that the product is retired from normal service, the process of quantifying the ease of detection indicator is as follows.

$$T_I = 1 - \frac{T_{I1} - T_{I\min}}{T_{I\max} - T_{I\min}} \tag{4}$$

where T_I is the normalized quantitative value of the product component detectability indicator, T_{I1} is the time required to detect the product component, $T_{I\max}$ is the maximum detection time for the product component, and $T_{I\min}$ is the minimum detection time for the product component; the time unit is minutes.

(4) Reliability: Reliability determines the degree of parts failure during normal service, and also greatly affects the normal operation of products. Generally, the lower the failure degree, the higher the reliability. The reliability of parts can be measured by the normal service time, and then the reliability evaluation indicator is calculated as follows.

$$T_S = \frac{T_{S1} - T_{S\min}}{T_{S\max} - T_{S\min}} \tag{5}$$

where T_{S1} denotes the normal service time of the component, T_S denotes the normalized reliability indicator value, $T_{S\max}$ denotes the maximum service time, and $T_{S\min}$ denotes the minimum service time; the time unit is minutes.

3.2. Economic Indicators

Cost is an important factor to consider in the product design process and determines whether the finished product will be able to circulate in the marketplace, mainly including the processing and auxiliary costs of manufacturing and remanufacturing, and the specific calculation process is as follows.

(1) Processing costs

The green design scheme needs to take into account the manufacturing and remanufacturing costs of the company in order to obtain the maximum economic benefit from the product, which is given by the following formula.

$$C_P = C_M + C_R \tag{6}$$

$$C_Q = 1 - \frac{C_P - C_{P\min}}{C_{P\max} - C_{P\min}} \tag{7}$$

where C_P denotes the total processing cost, C_M denotes the manufacturing cost, C_R denotes the remanufacturing cost, C_Q denotes the normalized processing cost, $C_{P\max}$ denotes the maximum processing cost, and $C_{P\min}$ denotes the minimum processing cost. The unit of cost used is USD.

(2) Ancillary costs

To achieve the proper implementation of manufacturing and remanufacturing, it is necessary to add auxiliary equipment and materials, etc., which are calculated as follows.

$$C_E = C_1 + C_2 \tag{8}$$

$$C_D = 1 - \frac{C_E - C_{E\min}}{C_{E\max} - C_{E\min}} \tag{9}$$

where C_E denotes ancillary costs, C_1 denotes ancillary equipment costs, C_2 denotes ancillary material costs, C_D denotes normalized ancillary costs, $C_{E\max}$ denotes maximum ancillary costs, and $C_{E\min}$ denotes minimum ancillary costs. Here, the cost unit is USD.

3.3. Environmental Indicators

To reduce environmental pollution during the product life cycle, the green design scheme needs to consider the environmental pollution of the manufacturing and remanufacturing process. Product development will produce pollutants during production, and remanufacturing can reduce pollutant emissions by reducing component manufacturing, but the remanufacturing process consumes water, electricity, cutting fluid, and metal materials, which also produce pollutants. The main pollutants in the manufacturing and remanufacturing process are noise pollution, water pollution, dust pollution, and solid pollution. Based on historical manufacturing and remanufacturing data, environmental experts score environmental indicators to determine pollution levels, and the environmental indicators are mainly rated as {very good, good, average, poor, very poor} with a corresponding score value of $\{1.0, 0.8, 0.6, 0.4, 0.2\}$.

4. Fuzzy Decision-Making Methods for Design Schemes

The decision making of green design schemes for remanufacturability mainly consists of three parts. Firstly, the entropy weight method is used to quantify and weigh the design scheme indicators, then the hesitation fuzzy set is used to construct the evaluation value set of each indicator, finally the evaluation value of each solution is calculated according to the comprehensive evaluation function and each solution is ranked in order to select the optimal design scheme [20]. The specific evaluation process is described below.

(1) Entropy weighting method: The entropy weighting method is based on the information of each indicator to set the weight, which is easy to calculate and can be objectively assigned based on the actual information to reduce the interference of subjective factors. The entropy weighting method is calculated as follows.

Firstly, the entropy value of each evaluation indicator is calculated using the following.

$$E_i = -\sum_{j=1}^{n} \frac{x_{ij}}{x_i} \ln \frac{x_{ij}}{x_i} \tag{10}$$

where E_i denotes the entropy value of the evaluation indicator of the i-th design scheme, and x_{ij} denotes the value weight of the i-th indicator in the j-th design scheme.

$$x_i = \sum_{j=1}^{m} x_{ij}, \quad i = 1, 2, \cdots, m \tag{11}$$

where x_i denotes the weight of the i-th indicator value for all design schemes and m denotes the m evaluation indicators.

Then the weight of the i-th evaluation indicator can be calculated as follows,

$$w_i = \frac{d_i}{\sum\limits_{i=1}^{m} d_i} \tag{12}$$

$$d_i = 1 - E_i \tag{13}$$

where d_i indicates the degree of information deviation. Then the weight value of each indicator is $w = (w_1, w_2, \ldots, w_m)^T$.

(2) Hesitant fuzzy sets: In the design scheme decision-making process, decision makers usually hesitate to reach a unified opinion on the decision scheme, which will affect the accuracy of the design schemes' evaluation. In order to obtain reasonable decision results, the hesitant fuzzy set can form a collection of fuzzy evaluation opinions of decision makers and obtain the evaluation level of design schemes through fuzzy operations. The specific process is as follows.

(1) Suppose S is a non-empty set, then the hesitant set S is a function whose every element in the set maps to [0, 1], then the functional expression of the hesitant fuzzy set is as follows:

$$A = \{\langle x, h_A(x)\rangle | x \in S\} \tag{14}$$

where $h_A(x)$ denotes the affiliation of element x with respect to the set A and is also the hesitant fuzzy element of the set.

(2) Given that h_i is a hesitant fuzzy element, the evaluation score of h_{ij} is $s(h_{ij}) = \frac{1}{l_h} \sum\limits_{a \in h} a$, where a is a certain evaluation value in h and l_h denotes the number of evaluation indicators in h.

(3) To calculate the evaluation value of each indicator of the design scheme, the evaluation value can be obtained according to the evaluation value of the indicator. Then the set of evaluation values of each design scheme is described as follows.

$$Y = (y_1, y_2, \cdots, y_n) \tag{15}$$

$$y_i = \{s(h_{i1}), s(h_{i2}), \cdots, s(h_{in})\} \tag{16}$$

(4) The evaluation value of each design scheme is calculated as each indicator value has a corresponding weight, which can be obtained through the entropy weighting method. Moreover, the comprehensive evaluation method is used to calculate the evaluation value of each design scheme, mainly by calculating the multiplication of the weights of each design indicator and the scoring value. The process of calculating the comprehensive evaluation value of each design scheme is as follows.

$$S_i = w * y_i = (w_1, w_2, \cdots, w_n) \begin{vmatrix} s(h_{1i}) \\ s(h_{i2}) \\ \cdots \\ s(h_{in}) \end{vmatrix} \tag{17}$$

where w denotes the weight value of each indicator and y_i represents the assessed value of each design indicator for option i. The evaluation value of all design schemes can be calculated and formed into the set $S = (S_1, S_2, \cdots, S_m)$. The best evaluation scheme can be selected by comparing the evaluation value of each design scheme.

5. Case Study

5.1. Design Scheme Analysis and Information Extraction

Taking injection molding as an example, injection molding is a key device for the production of plastic products, and the structure of the mold is shown in Figure 3. The layout and dimensional accuracy of the mold directly determines the reliability and quality of the product. According to the technical requirements of an electronic product company, a set of injection molds was designed to achieve the mass production of hard disk cover shells while satisfying the quality requirements of a hard disk case. Furthermore, the company hoped that the mold would be able achieve one mold with two cavities and improve the injection precision as much as possible. Meanwhile, due to the high development cost of the injection mold, it was hoped that the injection molding would have a high degree of remanufacturability and reliability. Based on the design requirements, the designer can select three feasible designs from the historical design database, with the specific information shown in Table 1.

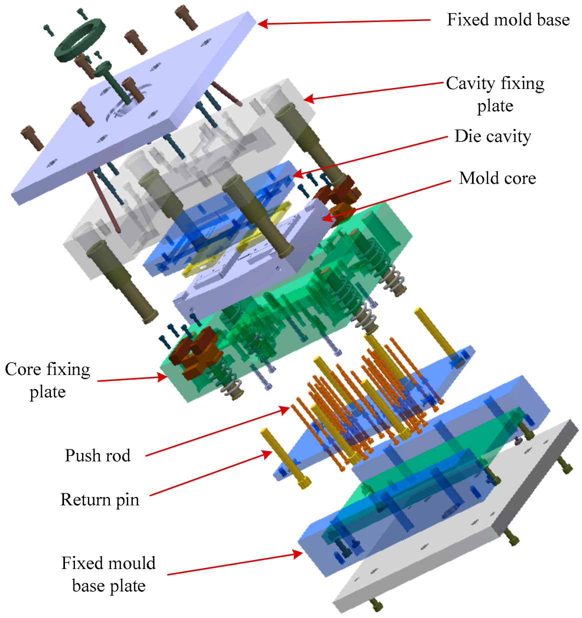

Figure 3. The structure of the injection mold.

Table 1. Design scheme information for injection mold.

Scheme	Material	Total Weight (kg)	Performance	Material Price (USD/kg)	Number of Parts (Pieces)	Number of Modules (Pieces)	Connection Type
A	P20	11	Uniform hardness and good machinability	2.8	98	4	Screws, bolts, pins, welding
	SM45	15	Good machinability, high hardness, good wear resistance	4.9			
	Copper	2	Good toughness and chemical stability	9.8			
B	P20	11	Uniform hardness and good machinability	2.8	90	5	Screws, bolts, pins, welding
	SM45	13.5	Good machinability, high hardness, good wear resistance	4.9			
	Aluminum alloy	1.6	High strength, low toughness, good wear resistance	2.8			
C	P20	12	Uniform hardness and good machinability	2.8	106	3	Screws, bolts, pins
	SM45	15	Good machinability, high hardness, good wear resistance	4.9			
	Copper	2	Good toughness and chemical stability	9.8			

5.2. Design Solution Decisions

Based on the design information in Table 1 and historical manufacturing and remanufacturing data, the design scheme evaluation indicator values for the molds were calculated using Equations (2)–(9), which are shown in Table 2.

Table 2. Quantitative values of evaluation indicators for each design scheme.

Design Scheme	A	B	C
Easy recyclability	$1-\frac{30\ \text{min}-27\ \text{min}}{37\ \text{min}-27\ \text{min}}=0.7$	$1-\frac{29\ \text{min}-27\ \text{min}}{37\ \text{min}-27\ \text{min}}=0.8$	$1-\frac{33\ \text{min}-27\ \text{min}}{37\ \text{min}-27\ \text{min}}=0.6$
Ease of detection	$1-\frac{61\ \text{min}-59\ \text{min}}{69\ \text{min}-59\ \text{min}}=0.8$	$1-\frac{62\ \text{min}-59\ \text{min}}{69\ \text{min}-59\ \text{min}}=0.7$	$1-\frac{61\ \text{min}-59\ \text{min}}{69\ \text{min}-59\ \text{min}}=0.8$
Ease of disassembly	$1-\frac{13\ \text{min}-10\ \text{min}}{20\ \text{min}-10\ \text{min}}=0.7$	$1-\frac{12\ \text{min}-10\ \text{min}}{20\ \text{min}-10\ \text{min}}=0.8$	$1-\frac{14\ \text{min}-10\ \text{min}}{20\ \text{min}-10\ \text{min}}=0.6$
Reliability	$\frac{42367\ \text{min}-41667\ \text{min}}{42667\ \text{min}-41667\ \text{min}}=0.7$	$\frac{42467\ \text{min}-41667\ \text{min}}{42667\ \text{min}-41667\ \text{min}}=0.8$	$\frac{42267\ \text{min}-41667\ \text{min}}{42667\ \text{min}-41667\ \text{min}}=0.6$
Processing costs	$1-\frac{5176\ \text{USD}-4896\ \text{USD}}{6295\ \text{USD}-4896\ \text{USD}}=0.8$	$1-\frac{5036\ \text{USD}-4896\ \text{USD}}{6295\ \text{USD}-4896\ \text{USD}}=0.9$	$1-\frac{5316\ \text{USD}-4896\ \text{USD}}{6295\ \text{USD}-4896\ \text{USD}}=0.7$
Ancillary costs	$1-\frac{1818\ \text{USD}-1399\ \text{USD}}{2798\ \text{USD}-1399\ \text{USD}}=0.7$	$1-\frac{1678\ \text{USD}-1399\ \text{USD}}{2798\ \text{USD}-1399\ \text{USD}}=0.8$	$1-\frac{1958\ \text{USD}-1399\ \text{USD}}{2798\ \text{USD}-1399\ \text{USD}}=0.7$
Environmentality of the manufacturing process	0.8	0.6	0.8
Environmentality of the remanufacturing process	0.8	0.8	0.8

According to the definition of the entropy weight method, MATLAB software 2022 was used to calculate the weight of each evaluation indicator, and the results are as follows.

$$w = [0.0951,\ 0.0835,\ 0.0951,\ 0.0951,\ 0.0951,\ 0.2262,\ 0.0835,\ 0.2262]$$

In order to consider the evaluation indicators comprehensively, industry experts were invited to conduct a subjective evaluation of each indicator. Then, the comprehensive evaluation value of each indicator is shown in Table 3.

Table 3. Score values for each evaluation indicator.

Scheme	A	B	C
Easy recyclability	[0.7, 0.85]	[0.8, 0.85]	[0.6, 0.7]
Ease of detection	[0.8, 0.87]	[0.7, 0.76]	[0.8, 0.84]
Ease of disassembly	[0.7, 0.76]	[0.8, 0.84]	[0.6, 0.68]
Reliability	[0.7, 0.75]	[0.8, 0.86]	[0.6, 0.65]
Processing costs	[0.8, 0.83]	[0.9, 0.95]	[0.7, 0.78]
Ancillary costs	[0.7, 0.75]	[0.8, 0.88]	[0.6, 0.72]
Environmentality of the manufacturing process	[0.8, 0.85]	[0.6, 0.73]	[0.7, 0.75]
Environmentality of the remanufacturing process	[0.738, 0.82]	[0.86, 0.92]	[0.79, 0.83]

Based on the definition of the hesitation fuzzy set, each design scheme is defined as a hesitation fuzzy set. Then, the evaluation indicator and evaluation value of each design scheme can be calculated by Equation (16), and the results are as follows.

$$y(h_A) = \{0.775, 0.835, 0.73, 0.725, 0.815, 0.725, 0.825, 0.779\}$$

$$y(h_B) = \{0.825, 0.73, 0.82, 0.83, 0.925, 0.84, 0.665, 0.89\}$$

$$y(h_C) = \{0.65, 0.82, 0.64, 0.625, 0.74, 0.66, 0.725, 0.81\}$$

According to Equation (17), the overall evaluation value of each design scheme can be calculated, and the results are as follows.

$$S_A = 0.7684,\ S_B = 0.8311,\ S_C = 0.7140$$

From the calculation results, it can be seen that design scheme B has the highest evaluation score, which is better than design scheme *A* and *C*. Therefore, design scheme *B* is chosen as the optimal design scheme, which has the lowest manufacturing cost and can take into account the remanufacturability of the injection molding and ensure the strength of the injection molding.

5.3. Sensitivity Analysis

In order to verify the reliability of the decision-making method, the sensitivity of the comprehensive evaluation results was analyzed by adjusting the weight values of each evaluation indicator. The fluctuation of each indicator weight value was set to 0.1 times, 0.2 times, original value, 5 times, and 10 times of the original weight value, and the experimental results are as follows.

(1) From Figures 4 and 6–9, it can be seen that when the indicators weights including ease of recovery, ease of disassembly, reliability, processing costs, and auxiliary costs are increased, the evaluation values of all three design schemes increase, but design scheme B is always the design scheme with the highest overall rating, which indicates that the evaluation model is stable.

(2) As can be seen from Figure 5, when the weight of the ease of detection indicator increases, the evaluation value of all three design schemes increases. Scheme B is the design scheme with the highest overall rating at 0.1, 0.2, and 5 times the original weight, but at 10 times the original weight, the overall evaluation value is slightly lower than that of design scheme A, which is in the second position and has better overall stability.

(3) As can be seen from Figure 10, when the weight of the manufacturing process' environmental indicator increases, the evaluation value of all three design schemes increases. Scheme B is the design scheme with the highest overall rating at 0.1, 0.2, and 5 times the original weight, but at 10 times the original weight, the overall evaluation value is slightly lower than that of design scheme A and is in the second position, which has better overall stability.

(4) From Figure 11, it can be seen that when the weight of the environmental indicators of the remanufacturing process increases, the evaluation value of all three design schemes increases. Scheme A is the second-highest scoring in terms of overall rating at 0.1, 0.2, and 5 times the original weight, but at 10 times the original weight, the overall evaluation value is slightly lower than that of design scheme C, which is in the third position. Although the evaluation ranking of design scheme A decreases at a multiple of 10, design scheme B is always the highest overall rating, and the stability of the evaluation model is better.

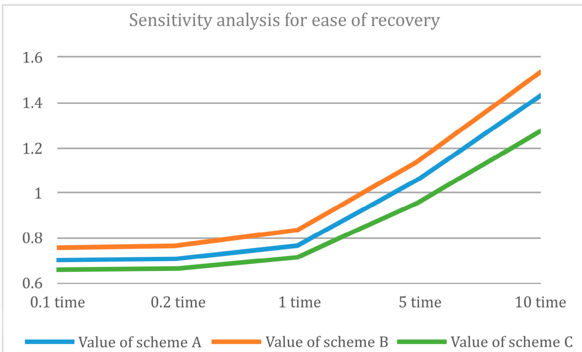

Figure 4. Sensitivity analysis for ease of recovery.

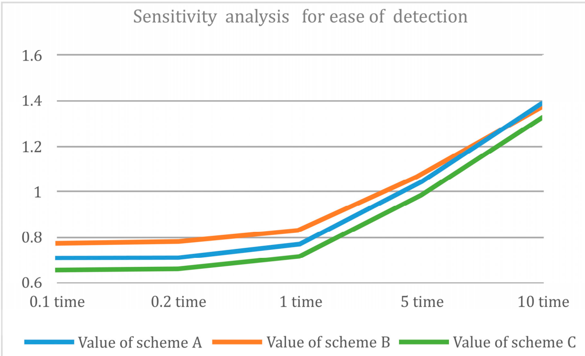

Figure 5. Sensitivity analysis for ease of detection.

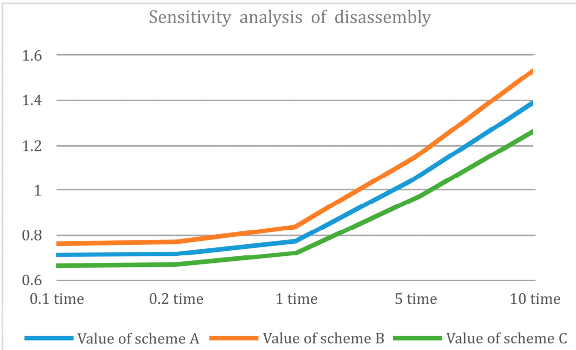

Figure 6. Sensitivity analysis of disassembly.

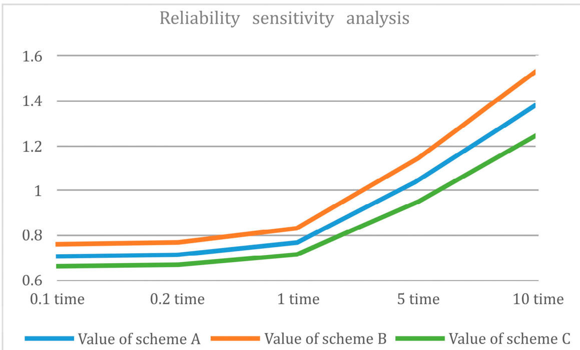

Figure 7. Reliability sensitivity analysis.

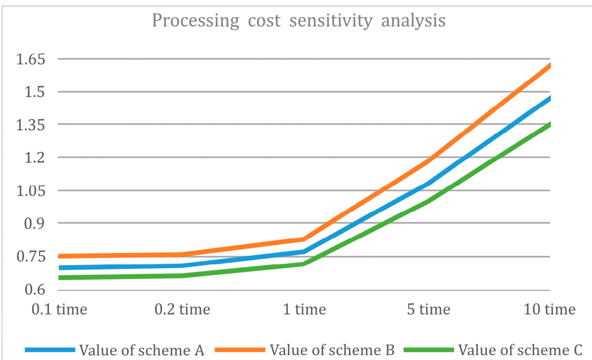

Figure 8. Processing cost sensitivity analysis.

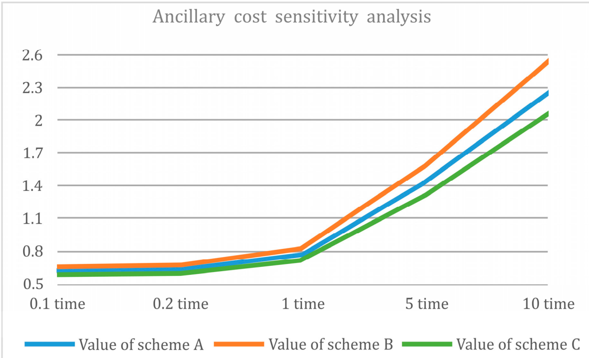

Figure 9. Ancillary cost sensitivity analysis.

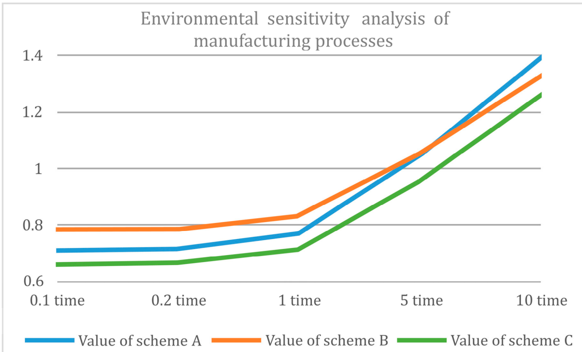

Figure 10. Environmental sensitivity analysis of manufacturing processes.

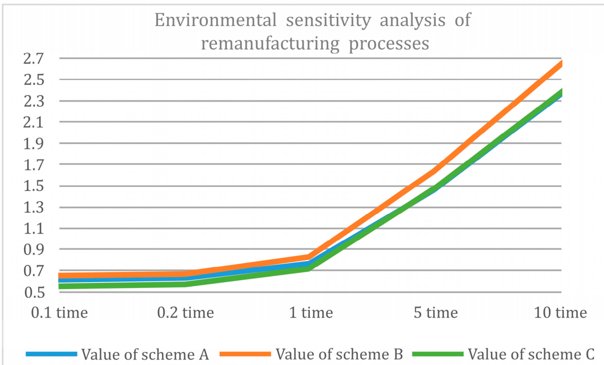

Figure 11. Environmental sensitivity analysis of remanufacturing processes.

From the results of the sensitivity analysis of each indicator, it can be seen that the eight secondary indicators of the design schemes' evaluation system have little influence on the evaluation results when fluctuations occur, and scheme B is always the optimal solution, so the stability of the evaluation model is relatively good.

5.4. Model Implementation on Interactive Interface

To improve the operability of the decision-making method, an interactive interface for green design scheme decision making was developed based on Visual Studio 2022 and SQL Server 2022, as shown in Figure 12. This interface consists of a design search layer, an input and quantification layer, a weight calculation layer, and a decision-making layer to facilitate the implementation of the proposed methodology. The interface allows the user to input information regarding the recycling time, disassembly time, testing time, normal service time, processing cost, and ancillary costs. Then the system performs the similarity calculation, and users can receive a recommended case from the existing case database. The design search interface is used to retrieve green design cases that satisfy the design requirements in the case database. The input and quantization interface are used to input the data for each indicator, and the system backend quantifies the value of each indicator. The weight calculation interface provides the weight values of each indicator and users can choose different visualization forms to generate tables, bar charts, or bar graphs. The decision-making interface is used to input the subjective evaluation value of each indicator by industry experts and the system background calculates the evaluation indicator value of each design scheme.

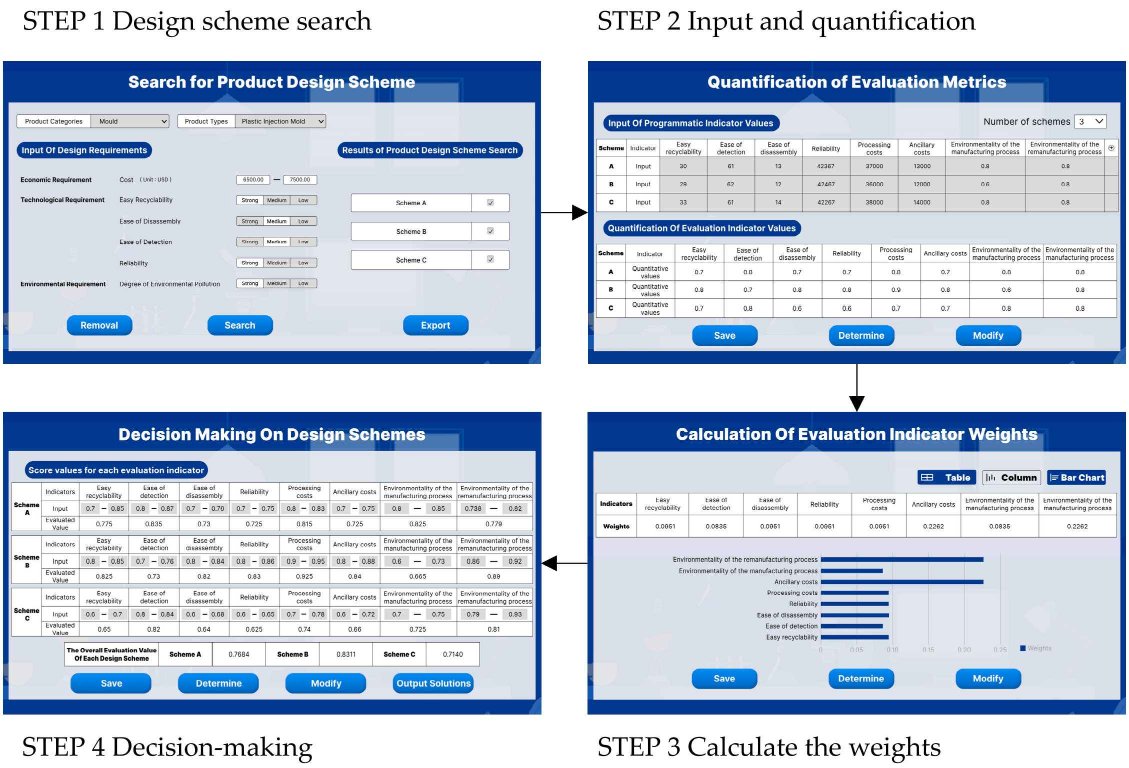

Figure 12. Operational process of green design scheme decision-making system.

6. Conclusions and Future Work

This paper proposes a fuzzy decision-making method for green design for remanufacturability, it has constructed a green design evaluation indicator system that includes economic, technical, and environmental aspects of the products, and it fully considers the characteristics of products such as easy disassembly, easy recycling, and reliability. Moreover, entropy weighting and hesitation fuzzy sets are applied to evaluate and decide on alternative design solutions in order to obtain the optimal design solution. Meanwhile, a design scheme decision-making system was developed to improve the user-friendliness of the methodology. Finally, the feasibility of the above-mentioned method is verified by taking the injection molding design as an example.

The results show that experts normally score the design scheme evaluation indicators by giving a point interval rather than an exact value, resulting in ambiguity in the values of the evaluation indicators, which makes it difficult to ensure the accuracy of the decision. In this method, the entropy weighing method can objectively set the weights of design indicators and the hesitation fuzzy set makes it possible to set the scoring intervals, which solves the hesitation and uncertainty of the expert evaluation results, and these contribute to improving the reliability of the design scheme evaluation results.

Future work requires efforts in the following aspects: (1) The proposed decision-making method only utilizes the existing small amount of data for indicator weight calculation, indicator evaluation, and decision making, and in the future, intelligent technologies such as big data, deep learning, and knowledge reuse can be used to make decisions on design solutions for improving the efficiency of DfRem decision making. (2) The decision-making method proposed in this paper is suitable for decision making with a small number of design schemes. When faced with a large number of design schemes, decision-making efficiency is low and the efficiency analysis technique can be considered for large-scale decision making, such as data envelope analysis. (3) Due to different service environments and usage habits, the remanufacturability of electromechanical products is dynamic and the evaluation of remanufactured electromechanical product design solutions only takes into account the current solid remanufacturability, which needs to be taken into account in future research in order to develop a more accurate and comprehensive design solution evaluation indicator system.

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