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An entropy - based fuzzy QFD model on used product remanufacturing design

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Abstract
Compared with new products, consumers put forward higher requirements on remanufactured products. Aimed at effectively transforming customer requirements (CRs) to technical characteristics (TCs) of remanufactured product design, an entropy-based fuzzy quality function deployment (QFD) model is proposed. In this model, triangular fuzzy numbers are suggested to express the vagueness information of CRs first, and then the importance of CRs is determined by an entropy-based algorithm, and the relationship between CRs and TCs is well explained by fuzzy QFD; finally, the importance of TCs is determined to clarify the designing emphasis. A remanufacturing engine is conducted to illuminate the practicability of this model. The results show that “Restorability” and “Reliability” will be treated as the key TCs to control, with the importance degree of 0.16 and 0.15. The entropy-based fuzzy QFD model can also be applied to similar product designs.

Keywords: Remanufacturing product, fuzzy quality function deployment, customer requirements, technical characteristics, triangular fuzzy number

INTRODUCTION
Used product remanufacturing can help reduce energy consumption, resource consumption, and environmental pollution[1,2]. Nowadays, the remanufacturing industry processes many types of products, such as automobile engines, construction machinery, and industrial machinery[3-6]. However, because

returned products are used as blanks in remanufacturing, the various failure modes and degrees of failure of such products may lead to dynamic uncertainties and variations in quality levels[7,8]. Unlike traditional manufacturing, a general remanufacturing process comprises the following steps: disassembly, inspection, cleaning, testing, repair, and assembly[9]. Moreover, owing to the distinct remanufacturing processes with new manufacturing, diverse technical characteristics (TCs) may exist[10,11]. Research has indicated that design decisions may greatly influence the efficiency and effectiveness of product remanufacturing, and technical design characteristics need to be considered in remanufacturing used products[12].

Many studies have explored used product remanufacturing design. Ke *et al*. proposed an integrated design method for remanufacturing scheme based on performance demand[13]; Shahbazi *et al*. investigated how circular product design can facilitate automated remanufacturing processes by conducting multiple case studies[14]; Boorsma *et al.* explored how design facilitates the implementation of remanufacturing[15]. Considering the problem that many components of remanufactured products will have been subjected to regular stresses in their first cycle of use, Tant *et al*. pointed out that the integrity of individual components should be assessed before consigning them to storage[16]; Wang *et al*. applied stylized models to a monopoly original equipment manufacturer (OEM) and suggested four legislative scenarios to analyze the fundamental conflicts of interest associated with remanufacturing and product design[17]; Ke *et al*. proposed an integrated design method for remanufacturing by considering carbon emissions[18]. Similarly, Dey *et al*. used analytical approaches to derive closed-loop solutions for complex nonlinear profit functions while accounting for the effects of carbon policies and multi-period delays in payments in the context of product remanufacturing[19]. The research contributions for remanufacturing design are shown in Table 1.

The above studies investigated different aspects of remanufacturing design; however, there remains a research gap: (1) they did not consider customer requirements (CRs) for remanufactured products and the role of TCs of remanufacturing in satisfying these CRs; (2) Remanufacturing design priorities cannot be determined to develop remanufacturing process planning.

With elevated customer expectations regarding the security, reliability, and quality of remanufactured products, some complex relationships must exist between the CRs and TCs[20]. In this regard, accurately defining, decomposing, and converting the CRs to TCs is a new challenge in used product remanufacturing design. However, to date, no study has focused on solving this issue.

Quality function deployment (QFD) is a quality assurance method that involves carefully considering CRs and striving to meet them, and it is widely used in product design and development[21-23]. In recent years, the fuzzy set theory has been applied extensively to multi-criteria decision-making (MCDM)[24-26], and fuzzy QFD has been widely employed as a quality tool to satisfy CRs in product design and development[27-30]. The key step in implementing QFD is converting CRs to product TCs. For remanufactured products, the CRs are often more elevated than those for new products, and customers focus more on product performance, safety, and environmental protection. However, because these requirements are based mostly on artificial judgments and evaluations, they are not expressed exactly, and a fuzzy evaluation is required to incorporate them into the QFD method.

Entropy is an objective method that finds widespread use in MCDM as a weighting approach to ensure that weights are objective[31-34]. The technique considers the relationship between indicators and evaluates their importance, thereby eliminating the need for subjective judgment or expert experience to determine weights[35,36]. The CRs associated with remanufacturing design are complex, and it is difficult to determine their degrees of importance objectively. In this case, the entropy weighting method is suitable.

Table 1. Contributions for remanufacturing design

No.	Methods or viewpoint	Authors
1	Design decisions may greatly influence the efficiency and effectiveness of product remanufacturing	Zhang *et al.* (2019)[12]
2	Integrated design method for remanufacturing scheme	Ke *et al.* (2022)[13]
3	How circular product design can facilitate automated remanufacturing processes	Shahbazi *et al.* (2022)[14]
4	How design facilitates remanufacturing implementation	Boorsma *et al.* (2020)[15]
5	Integrity of individual components should be assessed	Tant *et al.* (2019)[16]
6	Fundamental conflicts of remanufacturing and product design	Wang *et al.* (2022)[17]
7	Remanufacturing design method considering carbon emissions	Ke *et al.* (2023)[18]
10	Carbon policies and multi-period delays in payments in the context of product remanufacturing	Dey *et al.* (2023)[19]

This study incorporates the concept of entropy into fuzzy QFD to determine the importance of CRs and transform them into TCs of remanufactured products to accurately determine the importance of the TCs. This process is expected to help clarify the design emphasis of product remanufacturing. Although the entropy and fuzzy QFD methods have been widely applied, this study presents an innovation as it is the first exploration of their use in product remanufacturing design to consider CRs and TCs by the methods. The proposed model does not involve complex operations or rely on huge theoretical foundations, but the resulting process is complete and universal, and general technical personnel can quickly understand and apply it, which may be an advantage of the proposed approach.

METHODS

House of quality

House of quality (HoQ), as the important tool of QFD, formally articulates how a company sees the relationship between the CRs and the product design characteristic[37] [Figure 1].

The general principle of HoQ is to identify "whats" and then relate "whats" to "hows". Its details may vary between its variants. As suggested by Hauser and Clausing[38], the HoQ can be built through the following process.

Step 1: Identifying "whats". "whats" are CRs expressed by the customer's own words.
Step 2: Identifying "hows". "hows" are TCs of product and affect one or more "whats", which are listed in the columns of HoQ.
Step 3: Weighting each "what". "what" is listed in a column in the matrix.
Step 4: Determining the relationship matrix of "whats" and "hows". This is the core element of the matrix designated.
Step 5: Determining the importance of the "Hows". The weights of the "hows" are placed at the bottom of HoQ.

Abbreviations and notations

The abbreviations and notations used in this study are listed in Table 2.

Determining the importance of customer requirements

Assuming X customers and M types of requirements exist, expressed as K_m (m = 1, 2, ..., M), the first step in this study is to determine the importance of CRs. Assuming L companies are involved in remanufacturing a product, and one of them is our remanufacturing company identified as C_l, and the L-1 competitors are denoted as C_1, C_2, …, C_{L-1}. Then, the steps for determining the importance of the CRs are as follows:

Table 2. Abbreviations and notations

No.	Notations	Implication	No.	Notations	Implication
1	QFD	Quality function deployment	11	c_{ml}	Ability to achieve the CRs for the *l*th company
2	HoQ	House of quality	12	b_{mx}	Importance of the *m*th CR for the *x*th customer
3	CRs	Customer requirements	13	k_m	Importance of the *m*th CR
4	TCs	Technical characteristics	14	b_m	Average relative importance of the *m*th CR
5	TFN	Triangular fuzzy number	15	c_m	Achievement ability for the *m*th CR
6	AHP	Analytic hierarchy process	16	a_m	Target capability to meet the *m*th CRs
7	X_i	The *i*th customers	17	e_m	Priority level
8	K_m	The *m*th types of CRs	18	u_m	Improvement ability
9	H_i	The *i*th types of TCs	19	r_{mn}	TFN relations between *m*th CR and *n*th TC
10	C_i	The *i*th remanufacturing company	20	h_n	Importance of the *n*th TC

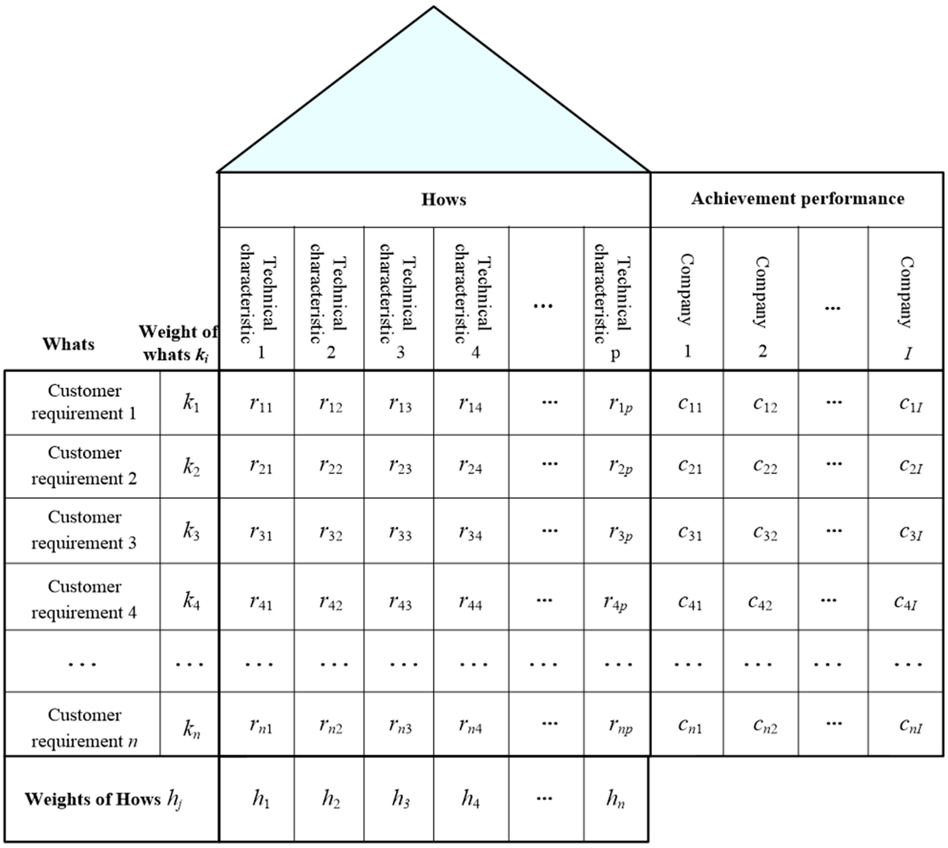

Figure 1. Structure of HoQ. HoQ: House of quality.

(1) Assume that b_{mx} is the importance of the mth CR for the xth customer, expressed as

$$B_{mx}^{T} = \left[b_{11}, b_{12}, \ldots, b_{mx}, \ldots, b_{MX}\right]^{T} \quad (m = 1, 2, \ldots, M; x = 1, 2, \ldots, X) \tag{1}$$

Then, the average relative importance b_m of the mth CR is given as

$$b_m = (b_{m1} + b_{m2} + \ldots + b_{MX}) / X \quad (m = 1, 2, .., M; x = 1, 2, \ldots, X) \tag{2}$$

(2) The degree of satisfaction of the CRs for the L companies can be expressed as follows:

$$C_{ml}^{T} = [c_{11}, c_{12}, \ldots, c_{ML}]^{T} \quad (m = 1, 2, \ldots, M; l = 1, 2, \ldots, L) \tag{3a}$$

$$X_{ml} = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1L} \\ c_{21} & c_{22} & \cdots & c_{2L} \\ \cdots & \cdots & \cdots & \cdots \\ c_{M1} & c_{M2} & \cdots & c_{ML} \end{bmatrix} \tag{3b}$$

(3) Assuming c_{ml} is the ability of the lth company to achieve the CRs, the ability of all the competing companies to achieve the *mth* CR c_m is expressed as

$$c_m = c_{m1} + c_{m2} + \ldots + c_{ml}, m = 1, 2, \ldots, M, \quad l = 1, 2, \ldots, L \tag{4}$$

(4) We introduce the entropy weight theory, where the intermediate variables g_{ml} and $E(K_M)$ are expressed in Equations (5) and (6), respectively, and the priority level of achievement e_m of k_m is expressed in Equation (7).

$$g_{ml} = \overline{c}_{ml} / c_m \qquad (m = 1, 2, \ldots, M; l = 1, 2, \ldots, L) \tag{5}$$

$$E(K_M) = -k \sum_{l=1}^{L} g_{ml} \ln(g_{ml}) \qquad (m = 1, 2, \ldots, M) \tag{6}$$

$$e_m = E(K_M) / \sum_{m=1}^{M} E(K_M) \tag{7}$$

(5) Let us assume that a_m is the target capability of company C_l to meet the CRs. Then, the ability of remanufacturing company C_l to improve these CRs is expressed as

$$u_m = a_m / c_{ml} \qquad (m = 1, 2, \ldots, M; l = 1, 2, \ldots, L) \tag{8}$$

(6) Based on the average relative importance b_m, priority level e_m, and improvement ability u_m, the importance of the mth *CR* can be determined using

$$k_m = b_m \times u_m \times e_m \qquad (m = 1, 2, \ldots, M) \tag{9}$$

Relationship between customer requirements and technical characteristics

Assume that the products to be remanufactured have N TCs. Then, the correlation matrix between the CRs and TCs is as

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1N} \\ r_{21} & r_{22} & \cdots & r_{2N} \\ \cdots & \cdots & \cdots & \cdots \\ r_{M1} & r_{M2} & \cdots & r_{MN} \end{bmatrix} \tag{10}$$

The value of r_{mn} can be referenced from Table 1, and the importance of the nth TC is given as

$$h_n = k_1 \times r_{1n} + k_2 \times r_{2n} + \ldots + k_m \times r_{mn} = \sum_{m=1}^{M} k_m \times r_{mn} \qquad (n = 1, 2, \ldots, N) \tag{11}$$

Determining triangular fuzzy number

In this paper, the triangular fuzzy number (TFN) is used to quantify linguistic data for reducing the influence of subjectivity and uncertainty and improving the reliability of decision-making[39]. The relevant linguistic scales are presented in Table 3.

In this study, the non-fuzzy method presented by Xiao and Li is used for TFN defuzzification[40]. The associated calculation is given in

$$\varphi(x) = \frac{1}{2(1+N)} l + \frac{N + 2MN + M}{2(1+M)(1+N)} m + \frac{1}{2(1+M)} u \tag{12}$$

where $\varphi(x)$ is the clear number (CN) of x_i; l, m, and n comprise the TFN; l and u represent the lower and upper bounds of the TFN, respectively; m is the median value of the TFN. M and N are determined using l, m, and u, which indicates that the possibility of m may be M times of u and N times of l.

RESULTS AND DISCUSSION

Case study

The WD615 Steyr engine is extensively employed in long-distance transportation vehicles and heavy-duty trucks in China, and approximately 80% of its components can be reused and remanufactured for functional recovery[41]. However, in the process of remanufacturing design, CRs are often ignored and are not translated into remanufacturing TCs. Therefore, a method that fully considers the CRs and emphasizes the design of the engine remanufacturing process is needed.

Importance of customer requirements

There are four types of WD615 engine customers: X_1 denotes heavy-duty truck customers, X_2 represents engineering machinery customers, X_3 symbolizes mining machinery customers, and X_4 stands for long-distance transportation machinery customers. The CRs are divided into eight categories, as summarized in Table 4.

By conducting a long-term follow-up survey of these WD615 engine customers and using Equations (1) and (2), the TFNs of the relative importance of CRs were determined, as listed in Table 5.

The corresponding clear numbers b_m of CRs importance were obtained using Equation (12), and the results are presented in Table 6.

Table 3. Crisp and fuzzy AHP scales

AHP scale	TFN	Linguistic scales
1	(1,1,1) If diagonal	Equal importance
	(1,1,2) Otherwise	
2	(1,2,3)	Important
3	(2,3,4)	Moderately important
4	(3,4,5)	Intermediate
5	(4,5,6)	Strongly important
6	(5,6,7)	Intermediate
7	(6,7,8)	Very strongly important
8	(7,8,9)	Intermediate
9	(8,9,10)	Extremely important

AHP: Analytic hierarchy process; TFN: triangular fuzzy number.

Table 4. Customer requirements description

K_1	K_2	K_3	K_4	K_5	K_6	K_7	K_8
Reliable use	Perfect function	Energy conservation	Environmental protection	Low failure rate	Cheap price	Long life	Low noise

Table 5. Relative importance of CRs by TFNs

CR	b_{m1}	b_{m2}	b_{m3}	b_{m4}	TFN of b_m
K_1	(6,7,8)	(4,5,6)	(4,5,6)	(5,6,7)	(4.75,5.25,6.75)
K_2	(3,4,5)	(4,5,6)	(5,6,7)	(7,8,9)	(4.75,5.75, 6.75)
K_3	(4,5,6)	(2,3,4)	(1,2,3)	(5,6,7)	(3,4,5)
K_4	(6,7,8)	(1,1,2)	(4,5,6)	(4,5,6)	(3.75,4.5,5.5)
K_5	(4,5,6)	(7,8,9)	(8,9,10)	(6,7,8)	(6.25,7.25,8.25)
K_6	(5,6,7)	(3,4,5)	(6,7,8)	(3,4,5)	(4.25,5.25,6.25)
K_7	(2,3,4)	(6,7,8)	(1,2,3)	(5,6,7)	(3.25,4.5,5.5)
K_8	(1,2,3)	(3,4,5)	(6,7,8)	(4,5,6)	(3.5,4.75,6)

CRs: Customer requirements; TFNs: triangular fuzzy number.

Table 6. Clear number b_m of relative importance for CRs

CR	K_1	K_2	K_3	K_4	K_5	K_6	K_7	K_8
b_m	5.55	5.79	4.06	4.60	7.28	5.30	4.51	4.83

CRs: Customer requirements.

Currently, competition in the engine remanufacturing industry in China is extremely fierce, and it is important to learn about products of competitors during the design and development of engine remanufacturing processes. Let us assume that the competitors of company C_1 are companies C_2 and C_3. Then, using Equation (3), the degrees to which different companies satisfy the relevant CRs were computed, and the results are listed in Table 7.

The corresponding clear numbers of competitive ability for each company were computed using Equation (12), and the results are presented in Table 8. Using Equations (4)-(8), the priority level e_m and the improvement ability u_m of company C_1 were obtained, and the results are listed in Table 8. The e_m and u_m of companies C_2 and C_3 were determined similarly.

Table 7. Satisfied degrees of companies for CRs

CR	X_1			X_2			X_3			X_4		
	C_1	C_2	C_3	C_1	C_2	C_3	C_1	C_2	C_3	C_1	C_2	C_3
K_1	(4,5,6)	(2,3,4)	(4,5,6)	(2,3,4)	(4,5,6)	(4,5,6)	(4,5,6)	(2,3,4)	(6,7,8)	(4,5,6)	(4,5,6)	(6,7,8)
K_2	(8,9,10)	(4,5,6)	(6,7,8)	(4,5,6)	(2,3,4)	(6,7,8)	(6,7,8)	(4,5,6)	(4,5,6)	(6,7,8)	(2,3,4)	(2,3,4)
K_3	(6,7,8)	(8,9,10)	(4,5,6)	(6,7,8)	(6,7,8)	(2,3,4)	(4,5,6)	(6,7,8)	(2,3,4)	(4,5,6)	(8,9,10)	(4,5,6)
K_4	(2,3,4)	(2,3,4)	(4,5,6)	(2,3,4)	(2,3,4)	(1,1,2)	(4,5,6)	(2,3,4)	(2,3,4)	(2,3,4)	(1,1,2)	(4,5,6)
K_5	(6,7,8)	(1,1,1)	(2,3,4)	(2,3,4)	(4,5,6)	(2,3,4)	(1,1,1)	(1,1,1)	(6,7,8)	(4,5,6)	(2,3,4)	(2,3,4)
K_6	(1,1,2)	(1,1,1)	(2,3,4)	(6,7,8)	(2,3,4)	(6,7,8)	(2,3,4)	(2,3,4)	(1,1,2)	(1,1,2)	(4,5,6)	(4,5,6)
K_7	(6,7,8)	(8,9,10)	(2,3,4)	(4,5,6)	(8,9,10)	(4,5,6)	(4,5,6)	(4,5,6)	(2,3,4)	(4,5,6)	(6,7,8)	(4,5,6)
K_8	(4,5,6)	(4,5,6)	(6,7,8)	(4,5,6)	(2,3,4)	(4,5,6)	(6,7,8)	(1,1,1)	(2,3,4)	(6,7,8)	(4,5,6)	(4,5,6)

CRs: Customer requirements.

The ultimate relative importance values k_m of the CRs were obtained using Equation (9), and they are listed in Table 9, along with the corresponding normalized importance values k'_m.

Relationship between CRs and TCs

The key factor in QFD implementation is converting CRs to specific TCs. Based on an investigation conducted by an expert team, the WD615.65 engine has eight TCs, H_1-H_8, listed in Table 10.

The relationship between CRs and TCs are identified by a multidisciplinary team, expressed by r_{mn} (m = 1, 2, ..., 8; n = 1, 2, ..., 8). Using Equation (10), the relationship matrix is listed in Table 11.

Importance of technical characteristics

The relative importance of the TCs and the clear number of r_{ij} can be determined using Equations (11) and (12), respectively, and the results are listed in the HoQ [Figure 2]. According to these results, the importance order of the TCs is as follows: $H_3(0.16) > H_6(0.15) > H_4(0.14) > H_7(0.13) > H_1(0.12) > H_5(0.11) > H_2(0.10) > H_8(0.08)$. In this way, the CRs of the remanufactured engine were transformed into TCs, importance of the TCs was determined, and design emphasis was clarified.

The result illustrated that "Restorability" and "Reliability" will be treated as the key TCs for engine remanufacturing design to control, and "Fuel Applicability" and "Assimilability" are the least important TCs; nevertheless, in the remanufacturing designing, these two TCs should not be neglected. In fact, through the

Table 8. Competitive ability, priority level and improvement ability

CR	Clear number of competitive ability			e_m	b_m	u_m
	C_1	C_2	C_3			
K_1	4.56	4.06	6.04	0.1259	7	1.53
K_2	7.04	4.06	5.55	0.1247	9	1.27
K_3	6.04	8.03	4.06	0.1232	9	1.49
K_4	3.49	2.42	3.62	0.1258	5	1.43
K_5	4.06	2.53	4.06	0.125	7	1.72
K_6	3.17	3.05	4.06	0.1265	5	1.57
K_7	5.55	7.53	4.06	0.1239	9	1.62
K_8	6.04	3.54	4.96	0.1249	7	1.16

CR: Customer requirement.

Table 9. Ultimate relative importance of CRs

TC	K_1	K_2	K_3	K_4	K_5	K_6	K_7	K_8
k_m	1.07	0.92	0.75	0.83	1.57	1.05	0.9	0.7
k'_m	0.14	0.12	0.09	0.11	0.2	0.13	0.12	0.09

CRs: Customer requirements; TC: technical characteristic.

Table 10. Technical characteristic description of remanufacturing engine

H_1	H_2	H_3	H_4	H_5	H_6	H_7	H_8
Fuel economy	Fuel Applicability	Restorability	Cleavability	Dynamic performance	Reliability	Replaceability	Assimilability

Table 11. Relation matrix of CRs and TCs

TC / CR	H_1	H_2	H_3	H_4	H_5	H_6	H_7	H_8
	r_{11}-r_{18}	r_{21}-r_{28}	r_{31}-r_{38}	r_{41}-r_{48}	r_{51}-r_{58}	r_{61}-r_{68}	r_{71}-r_{78}	r_{81}-r_{88}
K_1	(2,3,4)	(2,3,4)	(4,5,6)	(6,7,8)	(4,5,6)	(2,3,4)	(5,6,7)	(4,5,6)
K_2	(3,4,5)	(4,5,6)	(8,9,10)	(5,6,7)	(2,3,4)	(4,5,6)	(6,7,8)	(4,5,6)
K_3	(4,5,6)	(4,5,6)	(8,9,10)	(6,7,8)	(2,3,4)	(6,7,8)	(4,5,6)	(2,3,4)
K_4	(4,5,6)	(2,3,4)	(1,2,3)	(1,1,1)	(2,3,4)	(3,4,5)	(2,3,4)	(3,4,5)
K_5	(2,3,4)	(1,2,3)	(6,7,8)	(2,3,4)	(4,5,6)	(2,3,4)	(6,7,8)	(1,1,1)
K_6	(2,3,4)	(1,1,2)	(1,1,1)	(6,7,8)	(2,3,4)	(6,7,8)	(1,1,2)	(2,3,4)
K_7	(4,5,6)	(5,6,7)	(8,9,10)	(4,5,6)	(4,5,6)	(8,9,10)	(4,5,6)	(2,3,4)
K_8	(6,7,8)	(4,5,6)	(4,5,6)	(3,4,5)	(2,3,4)	(4,5,6)	(2,3,4)	(1,1,1)

CRs: Customer requirements; TCs: technical characteristics.

model process, we can see that, the importance order of TCs highly relies on the relationship expressed by TFNs between CRs and TCs; therefore, accurately determining the TFNs is important. Additionally, the weighs of CRs should be considered.

Discussion and conclusion

This study presented an entropy-based fuzzy QFD model for the remanufacturing design by fully considering the product CRs and TCs. With this model, the CRs were identified, and their importance values were determined using the entropy weighting method. Then, TFNs were used to express the relationships between the CRs and TCs to help designers fully consider the CRs in product

CRs	Weight k_i	H_1	H_2	H_3	H_4	H_5	H_6	H_7	H_8	Competition analysis C_1	C_2	C_I
K_1	0.14	3.09	3.09	5.05	7.04	5.05	3.09	6.04	5.05	4.06	6.04	4.56
K_2	0.12	4.06	5.05	9.03	6.04	3.09	5.05	7.04	5.05	4.06	5.55	7.04
K_3	0.09	5.05	5.05	9.03	7.04	3.09	7.04	5.05	3.09	8.03	4.06	6.04
K_4	0.11	5.05	3.09	2.13	1.00	3.09	4.06	3.09	4.06	2.42	3.62	3.49
K_5	0.20	3.09	2.13	7.04	3.09	5.05	3.09	7.04	1.00	2.53	4.06	4.06
K_6	0.13	3.09	1.22	1.00	7.04	3.09	7.04	1.33	3.09	3.05	4.06	3.17
K_7	0.12	5.05	6.04	9.03	5.05	5.05	9.03	5.05	3.09	7.53	4.06	5.55
K_8	0.09	7.04	5.05	5.05	4.06	3.09	5.05	3.09	1.00	3.54	4.96	6.04
TC weights h_i		0.12	0.10	0.16	0.14	0.11	0.15	0.13	0.08			

Figure 2. HoQ of engine remanufacturing design. HoQ: House of quality.

remanufacturing. Finally, the importance of the TCs was determined using the fuzzy QFD method. This strategy can connect CRs with remanufacturing design naturally and helps strengthen effective communication and collaboration among remanufacturing implementers.

The WD 615.65 engine was considered as a case study to illustrate the practical applicability of the proposed model. The results showed that the entropy-based fuzzy QFD model was well applicable. The case study considered herein may be simple and seem insufficient to verify the effectiveness and advantages of the method. However, it only demonstrates the process of the proposed model to provide an understanding of how to apply the model. In the future, we will develop a more rigorous case study involving complex products to verify the proposed model. Moreover, the results of the method rely on the data largely; therefore, the credibility of the survey data is important. To ensure the credibility of the survey data of the engine customers, it is recommended that more customers be surveyed and efforts be made to strive for the maximum possible samples.

Compared with similar research, the contribution of this study is summarized as four points: (1) It provided an effective method that can transform CRs to TCs in the remanufactured product design by fully considering the factors of achievement ability of CRs, the average importance of CRs, and the improvement ability of the companies; (2) It offered a good communication tool among the participants of remanufacturing engineering and helps to realize the collaborative management of remanufacturing objectives and design processes; (3) Through the guidelines of the importance of TCs, engineers can clarify the design focus for the used engine remanufacturing, such as developing optimal process routes and procedures for the high "restorability" and "reliability", applying more appropriate repairing materials for the high "Cleavability", and so on; (4) This method can not only be used in designing product remanufacturing processes but also applied to the design of new products. In the latter case, the CRs and TCs should be considered from the perspective of a new product.

While this study clarifies the design emphasis by analyzing the relationships between CRs and TCs, it does not describe remanufacturing process planning, which is reserved for a future study. On the other hand, future work can focus on developing computation software procedures and compiling pseudocode of the algorithm by which users can freely define the CRs and TCs and conveniently determine the designing emphasis.

DECLARATIONS

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Authors' contributions

Made substantial contributions to the conception and design of the study and performed data analysis and interpretation: Shi J, Yu Z, Li M

Performed data acquisition and provided administrative, technical, and material support: Pan Y, Zhu H

Availability of data and materials

Not applicable.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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