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An integrated fuzzy approach for evaluating remanufacturing alternatives of a product design

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Abstract

Remanufacturing has emerged as a competitive strategy for manufacturers to tackle environmental and economic challenges. In this paper, an integrated fuzzy approach is developed for the evaluation of remanufacturing alternatives. Then, importance weights of main remanufacturing processes and evaluation criteria are obtained through fuzzy extent analysis. Fuzzy hierarchical TOPSIS is then applied to evaluate the alternatives. A case study is presented to demonstrate the applicability of the proposed approach. The analysis results show that it is a viable approach and can be used as an effective tool for design evaluation from the remanufacturing point of view. Finally, conclusions are discussed and future research directions are suggested.

Keywords: Remanufacturing; Hierarchical model; Life cycle assessment; Fuzzy extent analysis; TOPSIS

Background

In the last two decades, environmental concerns diffuse into almost all aspects of the manufacturing industry and all phases of products' life cycles. This is simply because resources consumed during the course of manufacturing and production are enormously high, and hence, the amount of waste generated from those processes is also notorious [1]. One of such key areas is the end-of-life treatment [2]. Remanufacturing is one of many end-of-life strategies.

Remanufacturing is not a new topic but had not been considered as an important strategic area until the recent decade. In the past, remanufacturing activities focus mainly on recapturing economical values from used products or have been driven by regulatory pressure [3]. Typical activities include recycling of materials and reuse of parts or components, among others, to produce close-to-new refurbished products. Figure 1 shows a flowchart of a typical remanufacturing process. Nevertheless, the processing procedures may vary depending on the nature of the product being remanufactured [4]. Obviously, there are lots of uncertainties in remanufacturing [5]. With the backdrop of increasing environmental awareness, remanufacturing is one of many ways to mitigate environmental impacts by reducing the consumptions of virgin materials, resources in primary production and etc. This has been becoming popular in the last decade [6]. The contemporary school of thought considers that remanufacturing can not only (re-)gain financial benefits, but also reduce the environmental burdens [5]. This is a typical multi-objective problem. Remanufacturing is now referred to as a value-adding process and has emerged

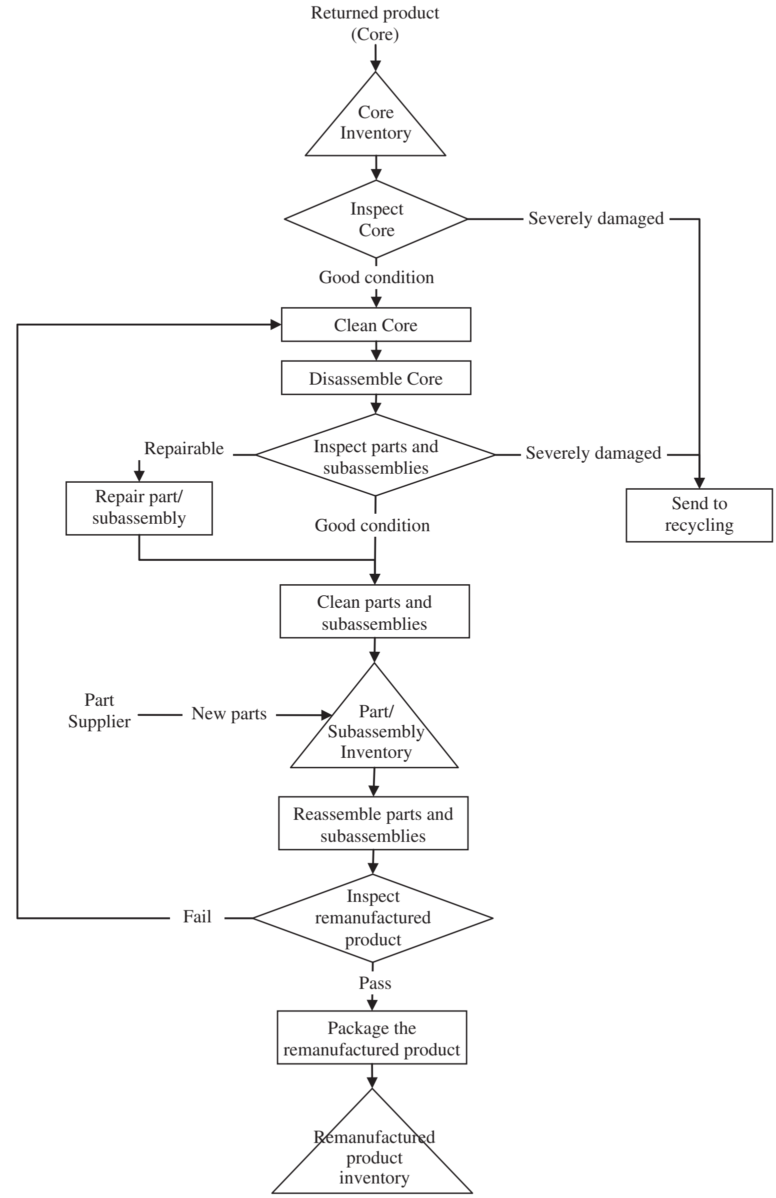


Figure 1 Remanufacturing process [4].

as part of closed-loop supply chains [7]. This trend implies the importance of developing decision-making models when remanufacturing activities are involved.

Life cycle assessment (LCA) provides the basic modelling framework for evaluating the environmental load and impact throughout the entire product life cycle [8]. It is an effective, comprehensive and practical tool in assessing environmental impact of products [9]. For example, Chan et al. [10] adopted the concept of LCA and proposed a comprehensive framework for the selection of green product designs. The life cycle concept is also applicable to remanufacturing process. For instance, Schau et al. [11] conducted an LCA study of remanufactured alternators. Three designs were considered and the associated environmental impacts were evaluated. However, the major obstacle is that remanufacturing activities are not well structured, so applying LCA to evaluate all design options would be time-consuming, if not impractical. Therefore, it is important to provide designers/engineers a more efficient 'screening' approach to assess the environmental and economic performance of alternative designs.

Evaluating the environmental and economic impact of a product or process is essentially a multi-criteria decision-making (MCDM) problem. LCA, for example, considers multiple inputs and multiple outputs, and they are not homogenous in most cases. Saaty [12] developed a groundbreaking tool, called analytic hierarchy process (AHP), to deal with MCDM problems. The merit of AHP is that both qualitative and quantitative factors can be considered in a hierarchical model. Since then, applications of AHP are numerous, with a trend to integrate with other methods [13]. One strand of such integrated approaches is to combine the method with fuzzy theory, which was developed by Zadeh [14] and can handle imprecise information. This characteristic supplements the pairwise comparisons in standard AHP so that a higher degree of uncertainty can be included in the decision-making process. The fuzzy AHP approach provides such practical solution, which is simple and less demanding upon the resources needed to make a decision by converting uncertain variables into linguistic variables. In other words, the process can be simplified in that sense. Nevertheless, it is still very easy to have over a hundred pairwise comparisons in order to make a design selection decision, which relies heavily on subjective decisions and is therefore not effective in terms of computational complexity. This research confronts this challenge through integration of fuzzy extent analysis and fuzzy hierarchical Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) for conducting effective evaluation of design alternatives from the remanufacturing perspective.

Fuzzy extent analysis, developed by Chang [15], stems from the AHP method that is used routinely to estimate comparative weights with a view in solving MCDM problems. Studies that apply fuzzy extent analysis leverage the benefits of fuzzy set theory and make use of linguistic terms (e.g. high, very high) or a fuzzy number in lieu of a precise numerical value when conducting pairwise comparison e.g. [16]. It has been widely applied in different problem environments in the literature: Kahraman et al. [17] developed an analytical selection tool to measure the customer satisfaction in catering firms in Turkey, Celik et al. [18] developed fuzzy AHP methodology based on Chang's extent analysis to model shipping registry selection, and Wang et al. [19] applied fuzzy extent analysis to develop a risk assessment model that enabled a structured analysis of aggregative risk in the food supply chain. The trends in utilizing fuzzy extent analysis in fuzzy AHP evident in the literature have been continued in many of the operational disciplines due to its ease of use and computational simplicity.

Fuzzy TOPSIS [20,21] is derived from the TOPSIS technique proposed by Hwang and Yoon [22] to evaluate the performance of alternatives. TOPSIS ranks the alternatives according to their distances from the ideal and the negative ideal solution. The positive ideal solution maximizes the benefit criteria and minimizes the cost criteria, while the negative ideal solution maximizes the cost criteria and minimizes the benefit criteria. The most preferred alternative is then derived as the shortest distance from the positive ideal solution and the longest distance from the negative ideal solution. Despite its popularity and simplicity in concept, TOPSIS is often criticized for its inability to deal with uncertainty and imprecision inherent in the process of mapping the perceptions of experts [23]. To address the limitation, scholars have made use of fuzzy TOPSIS (combination of fuzzy logic with TOPSIS) for expert systems in areas such as plant location selection [21], supplier selection and evaluation [20], analysis of network uncertainty [24] and assessment of green supply chain initiatives [25]. Fuzzy hierarchical TOPSIS will benefit from both the superiority of the hierarchical structure and easiness of implementation of TOPSIS in a fuzzy environment.

In this article, a decision support model is proposed based on fuzzy synthetic extent analysis method and hierarchical fuzzy TOPSIS method to make quick selection decisions regarding remanufacturing alternatives. This is an effective modelling approach for such evaluation, which is the major contribution of this paper. In addition, this paper also makes practical contributions as shown in the case study which demonstrates the operations of the proposed model. The rest of the paper is organized as follows: The 'Methods' section presents the details of the model. It is then followed with a case study of a real-life example, which is obtained from a published study, in order to demonstrate the applicability of the proposed methodology. Finally, some concluding remarks and directions for future researches are presented in the 'Conclusions' section.

Methods

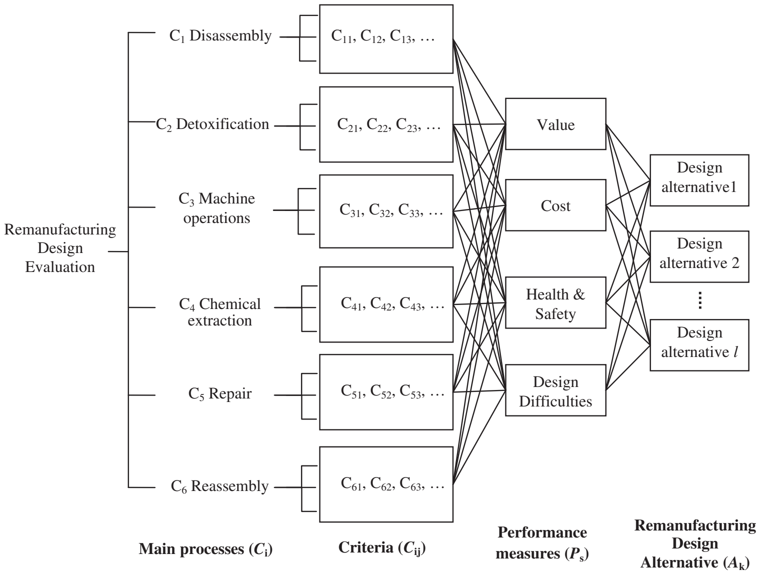
The proposed methodology consists of a hierarchical evaluation model, fuzzy extent analysis and fuzzy hierarchical TOPSIS techniques. In the hierarchical model, the critical aspects for sustainable remanufacturing are first defined and the criteria under each aspect are identified. Fuzzy extent analysis is then used to determine the relative importance weights of evaluation criteria. Finally, the fuzzy hierarchical TOPSIS is applied to assess alternative design options. Details of the proposed method are elaborated in each of the following sections.

The hierarchical model

The proposed model can be broadly divided into four parts as illustrated in Figure 2. The first level is a collection of main remanufacturing processes. Then, the corresponding criteria within each remanufacturing process are identified and presented in the second level. The third level includes the performance measures employed to evaluate the remanufacturing alternatives provided at the final level. In other words, the decision is made based on the relative importance of each process against each performance measure, and then an aggregated score can be computed in order to help make a decision.

The aim of identifying the first level process is to break down the whole remanufacturing operation into a number of processes so that the importance of each process with respect to the remanufacturing operation of different alternatives can be evaluated. This is analogous to the life cycle phases mentioned in the 'Background' section. However, the objective is not the same as life cycle assessment as only remanufacturing is considered in this paper. Due to its unstructured nature, there is no generic process for handling remanufacturing processes either. As a consequence, a number of common processes are observed from the existing literature. With reference to a number of studies [26-29], the following remanufacturing processes are identified:

- C_1. Disassembly
- C_2. Detoxification
- C_3. Machine operations



Where: i is the index of main processes (i= 1,2,…, 6)
j is the index of criteria within each remanufacturing process
k is the index of alternative remanufacturing design (k= 1,2,…, l)
s is the index of performance measures (s= 1,2,…, 4)

Figure 2 A hierarchical model for the evaluation of product designs from the remanufacturing perspective.

- C_4. Chemical extraction
- C_5. Repair
- C_6. Reassembly

Then, associated criteria within each remanufacturing process should be identified and listed at the second level for further evaluation. These criteria could be generic criteria associated with individual remanufacturing processes or be more specific with respect to particular products. This will not undermine the usefulness of the model because this is not a restriction to use pre-defined processes and their associated criteria in the model. Construction of the hierarchical model will be varied dependent on the actual cases, and any new processes can be added accordingly.

At the third level, the performance measures are provided to evaluate the remanufacturing alternatives. Hatcher et al. [30] recently conducted a case study regarding the barriers and challenges for remanufacturing, which can be adopted in this model. They are value (e.g. rare metal content, competition between imitated products, environmental impacts), cost involved, employee health and safety, and design difficulties (e.g. supplier relationship, technological advancement which discourage the use of old components). Finally, all the remanufacturing alternatives are presented at the fourth level for the evaluation.

Fuzzy extent analysis

Here, the fuzzy synthetic extent analysis method is introduced to calculate the synthetic extent value of the pairwise comparison. An extent analysis adaptation to fuzzy AHP was proposed in order to obtain a crisp priority vector from a triangular fuzzy comparison matrix [15]. The triangular fuzzy scale of preferences is given in Table 1, $M_z = (m_{z1}, m_{z2}, m_{z3})$, where $z = 1, 2,\ldots, 9$. Triangular fuzzy numbers (TFNs) M_1, M_3, M_5, M_7 and M_9 are

Table 1 Linguistic classification of triangular fuzzy numbers

Rating level	Linguistic values	TFNs
1	Equal	(1, 1, 1)
3	Moderately more important	(2, 3, 4)
5	Fairly more important	(4, 5, 6)
7	Much more important	(6, 7, 8)
9	Absolute more important	(9, 9, 9)
2, 4, 6, 8	Midpoint preference values lying between above values	(1, 2, 3), (3, 4, 5), (5, 6, 7), (7, 8, 9)

used to represent the pairwise comparison of decision variables in the range from 'Equal' to 'Absolute more important', when these are employed as descriptive terms attached to the level of importance of paired variables. M_2, M_4, M_6 and M_8 represent the midpoint preference values lying between them.

Next, let $P = \{p_1, p_2,\ldots, p_n\}$ be an object set and $Q = \{q_1, q_2,\ldots, q_m\}$ be a goal set. Here, m equals the number of criteria identified in the whole remanufacturing process multiplied by the number of performance measures. According to the method of extent analysis [15], each object is taken and extent analysis is performed for each goal respectively. Therefore, the m extent analysis values for each object are obtained as follows: $M_{g_i}^1, M_{g_i}^2,\ldots, M_{g_i}^m$, $i = 1, 2,\ldots, n$, where all the $M_{g_i}^j$ $(j = 1, 2,\ldots, m)$ are TFNs. The following is a summary of the procedures with reference to the study conducted by Chan and Wang [16].The value of fuzzy synthetic extent with respect to the ith object is defined as

$$S_i = \sum\nolimits_{j=1}^{m} M_{g_i}^j \otimes \left[\sum\nolimits_{i=1}^{n}\sum\nolimits_{j=1}^{m} M_{g_i}^j\right]^{-1}, \tag{1}$$

and $\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^j\right]^{-1}$ can be calculated as

$$\left[\sum\nolimits_{i=1}^{n}\sum\nolimits_{j=1}^{m} M_{g_i}^j\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} m_{3i}}, \frac{1}{\sum_{i=1}^{n} m_{2i}}, \frac{1}{\sum_{i=1}^{n} m_{1i}}\right). \tag{2}$$

The degree of possibility of $M_1 \geq M_2$ is defined as

$$V(M_1 \geq M_2) = \sup_{x \geq y}[\min(u_{M_1}(x), u_{M2}(y))]. \tag{3}$$

When a pair (x, y) exists, such that $x \geq y$ and $u_{M_1}(x) = u_{M2}(y) = 1$, then we have $V(M_1 \geq M_2) = 1$. Since M_1 and M_2 are convex fuzzy numbers, we have that

$V(M_1 \geq M_2) = 1$ if $m_{12} \geq m_{22}$,

$$V(M_1 \geq M_2) = hgt(M_1 \cap M_2) = u_{M_1}(d) \tag{4}$$

where d is the ordinate of the highest intersection point D between u_{M_1} and u_{M_2} (see Figure 3). When $M_1 = (m_{11}, m_{12}, m_{13})$ and $M_2 = (m_{21}, m_{22}, m_{23})$, then the ordinate of D is computed by

$$\begin{aligned} V(M_2 \geq M_1) &= hgt(M_1 \cap M_2) \\ &= \frac{m_{11} - m_{23}}{(m_{22} - m_{23}) - (m_{12} - m_{11})}. \end{aligned} \tag{5}$$

To compare M_1 and M_2, both the values of $V(M_1 \geq M_2)$ and $V(M_2 \geq M_1)$ are required. The degree of possibility for a convex fuzzy number to be greater than k convex fuzzy

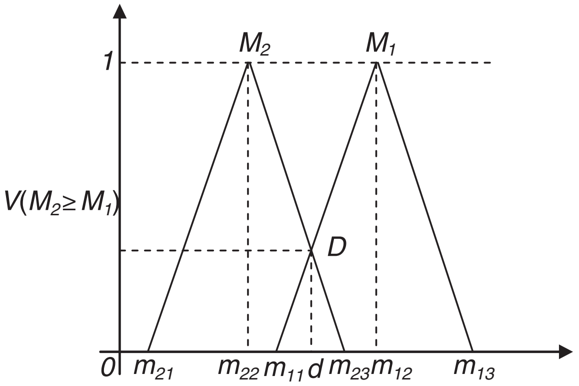


Figure 3 **Membership functions of the set of importance ratings.**

numbers M_i ($i = 1, 2, \ldots, k$) can be defined by

$$\begin{aligned} &V(M \geq M_1, M_2, \ldots, M_k) \\ &= V[(M \geq M_1) \text{ and } (M \geq M_2) \text{ and}, \ldots, \text{and } (M \geq M_2)] \\ &= \min \ V(M \geq M_i), i = 1, 2, \ldots, k \end{aligned} \tag{6}$$

if

$$d(X_i) = \min \ V(S_i \geq S_k). \tag{7}$$

For $k = 1, 2,\ldots, n$; $k \neq i$, then the rating vector is given by

$$W' = (d(X_1), d(X_2), \ldots, d(X_n))^T \tag{8}$$

where X_i ($i = 1, 2,\ldots, n$) are n different criteria. Via normalization, the normalized rating vectors are

$$W = (R(X_1), R(X_2), \ldots, R(X_n))^T \tag{9}$$

where W is a non-fuzzy number that provides priority weights of an evaluation criterion over others.

For the accuracy of the method, the consistency measure is performed to screen out inconsistency between responses. Since M_i is a triangular number, it has to be defuzzified into a crisp number to compute the consistency ratio (CR). The centre of area (COA) approach is used here for defuzzifying M_i. TFN $M_i(m_{i1}, m_{i2}, m_{i3},)$ can be defuzzified into a crisp value by

$$P(Mi) = [(m_{i3} - m_{i1}) + (m_{i2} - m_{i1})]/3 + m_{i1}. \tag{10}$$

Therefore, the CR of each judgement can be calculated and checked to ensure that it is lower than or equal to 0.1.

Fuzzy hierarchical TOPSIS

To evaluate remanufacturing alternatives, four fuzzy decision matrixes, $\tilde{D}_s$, are constructed with respect to four performance measures. Assume there are l alternative designs A_k ($k = 1, 2,\ldots, l$) and n main remanufacturing processes. Each remanufacturing process has N_i criteria where the total number of criteria is equal to $\sum_{i=1}^{n} N_i$. $\tilde{x}_{kij}$ represents the value of the jth criterion within *i*th remanufacturing process of the *k*th alternative, which can be crisp data or appropriate linguistic variables which can be further represented by fuzzy numbers (e.g. $\tilde{x}_{kij} = \left(a_{kij}, m_{kij}, b_{kij}\right)$). A hierarchical MCDM problem can be concisely expressed in a fuzzy decision matrix as

$$\tilde{D}_s = \begin{array}{c|ccccccccc|} & & C_1 & & & \cdots & & C_n & & \\ & C_{11} & C_{12} & \cdots & C_{1N_1} & \cdots & C_{n1} & C_{n2} & \cdots & C_{nN_n} \\ A_1 & \tilde{x}_{111} & \tilde{x}_{112} & \cdots & \tilde{x}_{11N_1} & \dots & \tilde{x}_{1n1} & \tilde{x}_{1n2} & \cdots & \tilde{x}_{1nNn} \\ A_2 & \tilde{x}_{211} & \tilde{x}_{212} & \ddots & \tilde{x}_{21N_1} & \dots & \tilde{x}_{2n1} & \tilde{x}_{2n2} & \cdots & \tilde{x}_{2nNn} \\ \vdots & \vdots & \vdots & & \vdots & \dots & \vdots & \vdots & \ddots & \vdots \\ A_K & \tilde{x}_{k11} & \tilde{x}_{K12} & \cdots & \tilde{x}_{K1N_1} & \dots & \tilde{x}_{kn1} & \tilde{x}_{kn2} & \cdots & \tilde{x}_{knNn} \end{array} \tag{11}$$

$$k = 1, 2, \cdots, l; i = 1, 2, \cdots, n; S = 1, 2, 3, 4.$$

where $\tilde{x}_{kij}$ is the fuzzy evaluation score of alternative A_k with respect to criterion C_{ij}. N_i is the number of criteria within the remanufacturing process C_i. s is the number of performance measures.

In general, the evaluation criteria can be classified into two categories: benefit and cost. The benefit criterion means that a higher value is better, while for the cost criterion, the opposite is valid. The data of the decision matrix $\tilde{D}_s$ comes from different sources. Therefore, it is essential to normalize it in order to transform it into a dimensionless matrix, which allows the comparison of the various criteria. Here, the normalized fuzzy decision matrix is denoted by $\tilde{R}$ which is shown as

$$\begin{array}{l} \tilde{R} = \left[\tilde{r}_{kij}\right]_{l \times n}, \\ k = 1, 2, \cdots, l; i = 1, 2, \cdots, n; j = 1, 2, \cdots, N_i. \end{array} \tag{12}$$

The normalization process can then be performed by the following operations:

$$\tilde{r}_{kij} = \begin{cases} \left(\dfrac{a_{kij}}{u_{ij}^{+}}, \dfrac{m_{kij}}{u_{ij}^{+}}, \dfrac{b_{kij}}{u_{ij}^{+}}\right), \forall_{ij}, \tilde{x}_{ij} \text{ is a benefit criterion} \\ \left(\dfrac{u_{ij}^{-}}{a_{kij}}, \dfrac{u_{ij}^{-}}{m_{kij}}, \dfrac{u_{ij}^{-}}{b_{kij}}\right), \forall_{ij}, \tilde{x}_{ij} \text{ is a cost criterion} \end{cases} \tag{13}$$

where u_{ij}^{+} and u_{ij}^{-} present the largest and the lowest value of each criterion, respectively. The weighted fuzzy normalized decision matrix is shown as

$$\tilde{V} = \left[\tilde{v}_{kij}\right]_{k \times n}, k = 1, 2, \cdots, l;\ i = 1, 2, \cdots, n;\ j = 1, 2, \cdots, N_i \tag{14}$$

where $\tilde{v}_{kij} = \tilde{r}_{kij} \otimes W_{ij}$.

Here, W_{ij} is the final weight score for each criterion which is the product of the main remanufacturing process weight score and the criterion weight score with respect to the corresponding process as follows:

$$W_{ij} = w_{C_i} \otimes w_{C_{ij}} = w_i \otimes \begin{bmatrix} w_{i1} \\ w_{i2} \\ \vdots \\ w_{iN_i} \end{bmatrix}, \quad (i = 1, 2, \cdots, n) \tag{15}$$

where w_{C_i} and $w_{C_{ij}}$ denote the weight score of the *i*th main remanufacturing process and the criterion C_{ij}, respectively. Both w_{C_i} and $w_{C_{ij}}$ are obtained through the fuzzy extent analysis method discussed in the 'Fuzzy extent analysis' section. The calculation results of Equation 14 can be summarized as

$$\tilde{V}_s = \begin{array}{c} \\ \\ A_1 \\ A_2 \\ \vdots \\ A_K \end{array} \begin{array}{c} \begin{array}{ccccccccc} & C_1 & & & \cdots & & C_n & & \\ C_{11} & C_{12} & \cdots & C_{1N_1} & \cdots & C_{n1} & C_{n2} & \cdots & C_{nN_n} \end{array} \\ \left[\begin{array}{ccccccccc} \tilde{v}_{111} & \tilde{v}_{112} & & \tilde{v}_{11N_1} & \cdots & \tilde{v}_{1n1} & \tilde{v}_{1n2} & \cdots & \tilde{v}_{1nN_n} \\ \tilde{v}_{211} & \tilde{v}_{212} & \cdots & \tilde{v}_{21N_1} & \cdots & \tilde{v}_{2n1} & \tilde{v}_{2n2} & \cdots & \tilde{v}_{2nN_n} \\ \vdots & \vdots & \ddots & \vdots & \cdots & \vdots & \vdots & \ddots & \vdots \\ \tilde{v}_{k11} & \tilde{v}_{k12} & \ldots & \tilde{v}_{K1N_1} & \cdots & \tilde{v}_{kn1} & \tilde{v}_{kn2} & \cdots & \tilde{v}_{knN_n} \end{array}\right] \end{array} \tag{16}$$

Subsequently, the fuzzy addition principle is used to aggregate the values within each remanufacturing process as follows:

$$\tilde{v}'_{ki} = \sum\nolimits_{j=1}^{C_i} \tilde{v}_{kij}, k = 1, 2, \cdots, l; i = 1, 2, \cdots, n. \tag{17}$$

The matrix $\tilde{V}$ is thus converted into the final weighted normalized fuzzy decision matrix $\tilde{V}'$,

$$\tilde{V}'_s = \begin{array}{c|cccc} & C_1 & C_2 & \ldots & C_n \\ \hline A_1 & \tilde{v}'_{11} & \tilde{v}'_{12} & \ldots & \tilde{v}'_{1n} \\ A_2 & \tilde{v}'_{21} & \tilde{v}'_{22} & \cdots & \tilde{v}'_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_l & \tilde{v}'_{l1} & \tilde{v}'_{l2} & \ldots & \tilde{v}'_{ln} \end{array} . \tag{18}$$

Again, the fuzzy addition principle is used to aggregate the values of performance measures as follows:

$$\tilde{Y} = \Sigma_{s=1}^{4} \tilde{V}'_s, s = 1, 2, 3, 4 \tag{19}$$

and

$$\tilde{Y} = \begin{array}{c|cccc} & C_1 & C_2 & \ldots & C_n \\ \hline A_1 & \tilde{y}_{11} & \tilde{y}_{12} & \ldots & \tilde{y}_{1n} \\ A_2 & \tilde{y}_{21} & \tilde{y}_{22} & \cdots & \tilde{y}_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_l & \tilde{y}_{l1} & \tilde{y}_{l2} & \ldots & \tilde{y}_{ln} \end{array} . \tag{20}$$

The addition operation is important as the hierarchical structure can be reflected only when aggregation of the weighted values within each main remanufacturing process and four performance measures is conducted.

Now, let A^+ and A^- denote the fuzzy positive idea solution (FPIS) and fuzzy negative ideal solution (FNIS), respectively. According to the aggregated fuzzy decision matrix, we have

$$\begin{aligned} A^+ &= \left(\tilde{y}_1^+, \cdots, \tilde{y}_i^+, \cdots \tilde{y}_n^+\right) \\ A^- &= \left(\tilde{y}_1^-, \cdots, \tilde{y}_i^-, \cdots \tilde{y}_n^-\right) \end{aligned} \tag{21}$$

where $\tilde{y}_i^+$ and $\tilde{y}_i^-$ are the fuzzy numbers with the largest and the smallest generalized mean, respectively. For each column i, the greatest generalized mean of $\tilde{y}_i^+$ and the lowest generalized mean of $\tilde{y}_i^-$ can be obtained, respectively. Consequently, the FPIS (A^+) and the FNIS (A^-) are derived. Then, the distances (d^+ and d^-) of each alternative from A^+ and A^- can be calculated by the area compensation method as

$$\tilde{d}_k^+ = \sum\nolimits_{i=1}^{n} d\left(\tilde{y}_{ki}, \tilde{y}_i^+\right), \ \ k = 1, 2, \cdots, l; i = 1, 2, \cdots, n \tag{22}$$

$$\tilde{d}_k^- = \sum\nolimits_{i=1}^{n} d\left(\tilde{y}_{ki}, \tilde{y}_i^-\right), \ \ k = 1, 2, \cdots, l; i = 1, 2, \cdots, n \tag{23}$$

$$d\left(\tilde{A},\tilde{B}\right)=\sqrt{\frac{1}{3}\left[(a_1-b_1)^2+(a_2-b_2)^2+(a_3-b_3)^2\right]}. \tag{24}$$

By combining the difference distances d^+ and d^-, the relative closeness index is calculated as follows:

$$\check{\varphi}_{\mathrm{k}}=\frac{\tilde{d}_k^-}{\tilde{d}_k^+ + \tilde{d}_k^-}. \tag{25}$$

According the index value, the remanufacturing alternatives can be ranked from the most preferred to the least preferred feasible options.

Case study

In this section, a case study is presented to illustrate how the proposed approach can be applied to support decision-making for remanufacturing alternative evaluation. The product used in the case study is an automotive alternator. The remanufactured alternators can be used again in the vehicle. According to Kim et al. [31], the alternator has the highest remanufacturing rate. Schau et al. [11] presented a case study of remanufactured alternators, in which they applied life cycle sustainability assessment (LCSA) to three different alternator designs. However, their LCSA approach and derived results are also dependent on the underlying assumptions and data availability. In this study, the authors make reference to the case to demonstrate how the proposed model can facilitate and simplify the evaluation process from a sustainable remanufacturing design perspective. With reference to the case [11], the main remanufacturing processes are defined and the associated evaluation criteria within each process are identified as illustrated in Table 2. The total number of remanufacturing processes for evaluation is not necessary to be restricted to six as shown in Table 2. Since there is no generic guideline for handling remanufacturing processes, it varies between individual products. To be clear, relevant data, e.g. remanufacturing processes and bill of materials, has to be collected to construct a similar hierarchical structure. Here, three different alternative designs are examined through the proposed method. Design 1 is a conventional alternator with belt fitting, fan and steel bearings and cast iron housing. Design 2 is a lightweight alternator with a plastic fan and aluminium housing. Design 3 is an ultra-lightweight alternator where also the belt fitting and bearings are replaced by lightweight parts (aluminium and plastic, respectively).

After constructing the hierarchical model, it is essential to know how important one process (or its associated criterion) is over another for remanufacturing purpose. In other words, decision-makers have to determine the weights between the remanufacturing processes and the associated criteria. The different weights were calculated using the fuzzy extent analysis discussed in the 'Fuzzy extent analysis' section. Using the main remanufacturing processes as an example, the fuzzy comparison matrix of five phases is constructed as described in Table 3.

The importance weights through the pairwise comparison of the five processes with respect to the remanufacturing operation are expressed by TFNs. The different values of fuzzy synthetic extent with respect to the five main processes are denoted by S_1, S_2, S_3, S_4, and S_5, respectively. By applying Equation 2, we have

Table 2 A hierarchical structure for the evaluation of three alternative remanufacturing designs

Remanufacturing processes	Criteria	Performance measures	Alternative designs
C_1. Disassembly	C_{11}. Number of components		
	C_{12}. Joint type of components		
	C_{13}. Disassembly directions		
C_2. Detoxification	C_{21}. Brushing		
	C_{22}. Washing with chemicals		
	C_{23}. Cleaning	P_1. Value	
C_3. Machine operations	C_{31}. Crushing	P_2. Cost	Design 1 (A_1)
	C_{32}. Separation		Design 2 (A_2)
	C_{33}. Polishing	P_3. Health and Safety	Design 3 (A_3)
	C_{34}. Surface grinding	P_4. Design difficulties	
C_4. Repair	C_{41}. Parts repair		
	C_{42}. Parts replacement		
	C_{43}. Testing of parts		
C_5. Reassembly	C_{51}. Hand tools		
	C_{52}. Manual labour		
	C_{53}. Testing of finished products		

$$\begin{aligned} S_1 &= (4.3, 5.5, 7.0) \otimes (1/39.5, 1/29.3, 1/21.3) \\ &= (0.11, 0.19, 0.33) \end{aligned}$$

$$\begin{aligned} S_2 &= (6.0, 10.0, 14.0) \otimes (1/39.5, 1/29.3, 1/21.3) \\ &= (0.15, 0.34, 0.66) \end{aligned}$$

$$\begin{aligned} S_3 &= (4.3, 6.5, 9.0) \otimes (1/39.5, 1/29.3, 1/21.3) \\ &= (0.11, 0.22, 0.42) \end{aligned}$$

$$\begin{aligned} S_4 &= (3.7, 4.0, 5.0) \otimes (1/39.5, 1/29.3, 1/21.3) \\ &= (0.09, 0.14, 0.24) \end{aligned}$$

$$\begin{aligned} S_5 &= (2.9, 3.3, 4.5) \otimes (1/39.5, 1/29.3, 1/21.3) \\ &= (0.07, 0.11, 0.21) \end{aligned}$$

The degree of possibility of S_i over S_j $(i \neq j)$ can be determined by Equations 3, 4, 5.

$$V(S_1 \geq S_2) = 0.54,$$

$$V(S_1 \geq S_3) = 0.87,$$

Table 3 Synthetic pairwise comparison matrix for remanufacturing processes

	C1	C2	C_3	C_4	C_5
C_1	(1, 1, 1)	(1/3, 1/2, 1)	(1, 1, 1)	(1, 1, 1)	(1, 2, 3)
C_2	(1, 2, 3)	(1, 1, 1)	(1, 2, 3)	(1, 2, 3)	(2, 3, 4)
C_3	(1, 1, 1)	(1/3, 1/2, 1)	(1, 1, 1)	(1, 2, 3)	(1, 2, 3)
C_4	(1, 1, 1)	(1/3, 1/2, 1)	(1/3, 1/2, 1)	(1, 1, 1)	(1, 1, 1)
C_5	(1/3, 1/2, 1)	(1/4, 1/3, 1/2)	(1/3, 1/2, 1)	(1, 1, 1)	(1, 1, 1)

Note: CI/RI = 0.073.

Table 4 Summary of comparative weightings of remanufacturing processes and their associated criteria

Remanufacturing processes	W_l	Criteria	$W_{l\,c}$	Final weights
C_1	0.197	C_{11}. Number of components	0.371	0.073
		C_{12}. Joint type of components	0.415	0.082
		C_{13}. Disassembly directions	0.214	0.042
C_2	0.366	C_{21}. Brushing	0.052	0.019
		C_{22}. Washing with chemicals	0.567	0.208
		C_{23}. Cleaning	0.381	0.140
C_3	0.255	C_{31}. Crushing	0.033	0.008
		C_{32}. Separation	0.231	0.059
		C_{33}. Polishing	0.416	0.106
		C_{34}. Surface grinding	0.320	0.081
C_4	0.106	C_{41}. Parts repair	0.409	0.043
		C_{42}. Parts replacement	0.409	0.043
		C_{43}. Testing of parts	0.182	0.019
C_5	0.076	C_{51}. Hand tools	0.219	0.017
		C_{52}. Manual labour	0.219	0.017
		C_{53}. Testing of finished products	0.561	0.043

$$V(S_1 \geq S_4) = 1,$$

$$V(S_1 \geq S_5) = 1.$$

Similarly,

$$V(S_2 \geq S_1) = 1, \cdot V(S_2 \geq S_3) = 1, \cdot V(S_2 \geq S_4) = 1, \cdot V(S_2 \geq S_5) = 1;$$

$$V(S_3 \geq S_1) = 1, V(S_3 \geq S_2) = 0.69, V(S_3 \geq S_4) = 1, V(S_3 \geq S_5) = 1;$$

$$V(S_4 \geq S_1) = 0.71, V(S_4 \geq S_2) = 0.29, V(S_4 \geq S_3) = 0.60, V(S_4 \geq S_5) = 1;$$

$$V(S_5 \geq S_1) = 0.58, V(S_5 \geq S_2) = 0.21, V(S_5 \geq S_3) = 0.49, V(S_5 \geq S_4) = 84;$$

Based on Equation 7, we obtain

$$\begin{aligned} d(L_1) &= \min\ V(S_1 \geq S_2, S_3, S_4, S_5) \\ &= \min(0.54, 0.87, 1, 1) \\ &= 0.54 \end{aligned} \quad .$$

Table 5 Linguistic classification of performance measures and the corresponding TFNs

Rating level	Linguistic values	TFNs
1	Extremely high	(0, 0, 1/6)
2	Very high	(0, 1/6, 2/6)
3	High	(1/6, 2/6, 3/6)
4	Medium	(2/6, 3/6, 4/6)
5	Low	(3/6, 4/6, 5/6)
6	Very low	(4/6, 5/6, 1)
7	Extremely low	(5/6, 1, 1)

Table 6 The aggregated fuzzy decision matrix with respect to four performance measures

		A_1	A2	A_3
C_1	P_1	(0.07, 0.10, 0.13)	(0.07, 0.10, 0.13)	(0.07, 0.10, 0.13)
	P_2	(0.10, 0.14, 0.17)	(0.07, 0.10, 0.13)	(0.04, 0.07, 0.11)
	P_3	(0.08, 0.11, 0.14)	(0.09, 0.12, 0.15)	(0.09, 0.12, 0.15)
	P_4	(0.09, 0.12, 0.16)	(0.07, 0.11, 0.14)	(0.05, 0.09, 0.12)
C_2	P_1	(0.12, 0.18, 0.24)	(0.12, 0.18, 0.24)	(0.12, 0.18, 0.24)
	P_2	(0.11, 0.17, 0.23)	(0.15, 0.21, 0.27)	(0.18, 0.24, 0.30)
	P_3	(0.11, 0.17, 0.23)	(0.13, 0.19, 0.25)	(0.19, 0.25, 0.31)
	P_4	(0.13, 0.19, 0.25)	(0.12, 0.18, 0.24)	(0.12, 0.18, 0.24)
C_3	P_1	(0.11, 0.15, 0.20)	(0.08, 0.13, 0.17)	(0.06, 0.10, 0.14)
	P_2	(0.06, 0.10, 0.15)	(0.08, 0.13, 0.17)	(0.11, 0.15, 0.19)
	P_3	(0.09, 0.14, 0.18)	(0.08, 0.13, 0.17)	(0.08, 0.12, 0.16)
	P_4	(0.14, 0.18, 0.22)	(0.08, 0.13, 0.17)	(0.03, 0.07, 0.12)
C_4	P_1	(0.04, 0.05, 0.07)	(0.04, 0.06, 0.08)	(0.03, 0.05, 0.06)
	P_2	(0.06, 0.08, 0.10)	(0.04, 0.05, 0.07)	(0.01, 0.02, 0.04)
	P_3	(0.04, 0.05, 0.07)	(0.04, 0.05, 0.07)	(0.04, 0.05, 0.07)
	P_4	(0.06, 0.08, 0.10)	(0.03, 0.05, 0.06)	(0.02, 0.04, 0.05)
C_5	P_1	(0.03, 0.04, 0.05)	(0.03, 0.04, 0.05)	(0.03, 0.04, 0.06)
	P_2	(0.03, 0.05, 0.06)	(0.03, 0.04, 0.05)	(0.02, 0.04, 0.05)
	P_3	(0.03, 0.04, 0.05)	(0.03, 0.04, 0.05)	(0.03, 0.04, 0.05)
	P_4	(0.05, 0.06, 0.07)	(0.03, 0.04, 0.05)	(0.01, 0.02, 0.04)

Similarly,

$$d(L_2) = 1, d(L_3) = 0.69, d(L_4) = 0.29, d(L_5)–0.21 \quad .$$

Therefore, $W' = (0.54,\ 1{,}0.69,\ 0.29,\ 0.21)$ after the normalization process, so the weight vector with respect to the five main remanufacturing processes - C_1, C_2, C_3, C_4 and C_5 - can be expressed as

$$W = (0.197, 0.366, 0.255, 0.106, 0.076).$$

Using the same approach, the weights of identified evaluation criteria with respect to their associated remanufacturing processes can be derived, and the results are summarized in Table 4. The final weight scores for evaluation criteria were obtained by calculating the product of criteria weight scores and the weight scores of its associated

Table 7 The final aggregated fuzzy decision matrix

	A_1	A_2	A_3
C_1	(0.34, 0.47, 0.60)	(0.29, 0.42, 0.55)	(0.25, 0.38, 0.51)
C_2	(0.47, 0.71, 0.96)	(0.51, 0.76, 1.00)	(0.61, 0.85, 1.10)
C_3	(0.40, 0.57, 0.74)	(0.34, 0.51, 0.68)	(0.28, 0.44, 0.61)
C_4	(0.20, 0.27, 0.34)	(0.14, 0.21, 0.28)	(0.09, 0.16, 0.23)
C_5	(0.13, 0.18, 0.23)	(0.11, 0.16, 0.21)	(0.09, 0.14, 0.19)

Table 8 The relative closeness index of alternative remanufacturing designs along with the final ranking

	d^{+}	d^{-}	$\check{\varphi}_{k}$	Rank
A_1	0.138	0.369	0.727	1
A_2	0.285	0.223	0.439	2
A_3	0.369	0.138	0.273	3

remanufacturing process. At the same time, the consistency ratio of each judgement was calculated and checked to ensure that it is lower than or equal to 0.1.

After that, fuzzy hierarchical TOPSIS is employed for the evaluation of three remanufacturing alternatives. Performance was rated to the three alternative designs with respect to the four proposed remanufacturing performance measures against all the evaluation criteria. The qualitative explanation of rating levels and its corresponding TFNs are described in Table 5. The results were then used to constitute a hierarchical decision-making matrix $\tilde{D}$ as shown in the Appendix. The hierarchical decision-making matrix was then normalized using Equation 13. By computing the product of the normalized hierarchical decision matrix $\tilde{D}$ and the final weight scores for each evaluation criterion, the weighted normalized fuzzy decision matrix $\tilde{V}$ is obtained. By aggregating the values belonging to each remanufacturing process by fuzzy addition principle, the weighted normalized fuzzy decision matrix $\tilde{V}'$ is acquired as illustrated in Table 6. By grouping the four performance measure outputs, the final fuzzy decision matrix $\tilde{Y}$ is obtained as shown in Table 7.

The largest generalized mean and the smallest generalized mean of each main criterion could then be selected constituting the FPIS (A^{+}) and the FNIS (A^{-}). Now, the difference distances of each of the alternatives (d_k^{+} and d_k^{-}) can be calculated as in Equations 22, 23, 24. Finally, combining the difference distances, the relative closeness index for each alternative can be obtained. The results are presented in Table 8, together with the corresponding rankings based on the index values. Among the three alternative designs, the conventional alternator design (A_1) has the highest relative closeness index and therefore should be recommended.

Using the relative closeness index, design 1 (A_1) tops the ranking list among the three remanufacturing alternatives. It is followed by design 2 (A_2) and design 3 (A_3). In order to

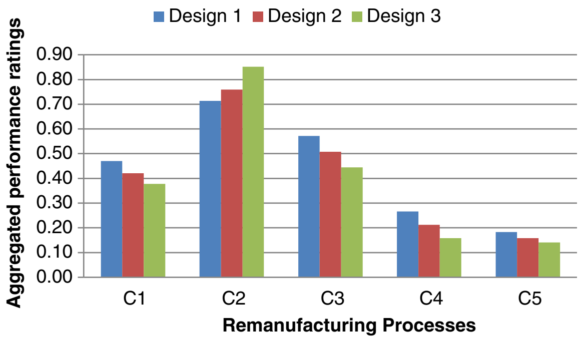


Figure 4 Weighted performance measures of three alternative designs with respect to main remanufacturing processes.

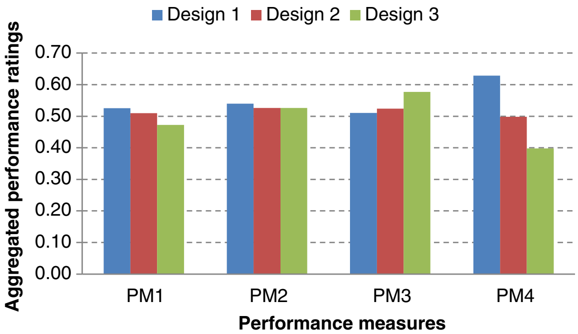


Figure 5 **Performance ratings of three alternative designs with respect to different measures.**

provide insights of this decision, further analysis was conducted. The analysis result displayed in Figure 4, shows the performance ratings of the three alternative designs with respect to the main remanufacturing processes. Overall the detoxification process (C_2) contributes most to the whole remanufacturing operation followed by the machine operations process (C_3). Although design 1 (A_1) has a slightly lower performance than the other designs in the detoxification process, crucially, it performs better in the other remanufacturing processes compared to the other two designs. This is one of the key reasons that design 1 stands out among the alternative remanufacturing designs. This is further proven in the ratings of three alternative designs with respect to different performance measures as illustrated in Figure 5. The conventional alternator design (A_1) tops the list in three out four performance measures including P_1 (value), P_2 (cost) and P_3 (design difficulties). Nevertheless, this does not underline the significance of other remanufacturing processes or performance measures, among which, design 1 (A_1) was scored lower than the other two designs (A_2 and A_3). In fact, it is important for designers to take a balanced approach when evaluating design options for sustainable remanufacturing purpose.

Conclusions

Remanufacturing is increasingly playing an important role in moving towards a more sustainable economy. The concept of remanufacturing can be deemed as a competitive strategy for manufacturers to satisfy diverse requirements from customers as well as policy makers. This paper proposed a hierarchical framework for evaluating alternative designs from the remanufacturing perspective. In addition to the evaluation framework, fuzzy extent analysis is used to calculate the importance weights of remanufacturing processes and associated evaluation criteria, and fuzzy hierarchical TOPSIS is applied to evaluate alternative product designs. A case study of remanufacturing an automotive alternator was presented to validate the proposed methodology and to demonstrate its effectiveness for remanufacturing design evaluation.

This article makes three key contributions. First, from a remanufacturing point of view, this research specifically develops a comprehensive hierarchical model for the evaluation of alternative designs. Key remanufacturing activities, the associated evaluation criteria and performance measures are identified for the purpose of sustainable remanufacturing. Second, the research advances the use of fuzzy MCDM methods as an effective and realistic modelling approach for evaluating design alternatives from the remanufacturing perspective. Compared to other approaches, e.g. LCA, the integrated fuzzy approach proposed in this paper provides a practical design evaluation solution. While the analysis result is in line with the findings from the study of Schau et al. [11], our approach is simple and less demanding upon the computational power and time needed to make a decision. In addition, the proposed approach is less constraining to rigorous data that is required to conduct a conventional LCA. It is still tractable enough to capture the uncertainty of a product remanufacturing life cycle and provides the efficiency and flexibility to tap the subjectivity and preferences of decision-makers. Third, through the case study, it provides some insights into how the application of the proposed integrated fuzzy approach can support a rational product design selection decision in order to achieve sustainable remanufacturing.

Despite the various advantages outlined in the paper, the presented approach also has its own limitations. For example, decision-makers have to make subjective decisions in the pairwise comparisons in evaluating remanufacturing alternatives. Using reliable data sources instead of subjective decision could lead to more accurate decisions. Therefore, one future research direction is to consider a more objective method such as data envelopment analysis (DEA). Furthermore, the dynamic characteristics and interconnection among the evaluation criteria are not considered in the hierarchy model. The interrelationship between these criteria may generate a different result of the importance weights. Future research may need to tackle this shortcoming by using the decision-making trial and evaluation laboratory (DEMATEL) method or analytic network process (ANP).

Appendix

A hierarchical decision-making matrix $\tilde{D}$ is shown in Table 9.

Table 9 Fuzzy design matrix

		A1			A2			A3		
C_{11}	P_1	2/6	3/6	4/6	2/6	3/6	4/6	2/6	3/6	4/6
	P_2	4/6	5/6	1	2/6	3/6	4/6	0	1/6	2/6
	P_3	2/6	3/6	4/6	2/6	3/6	4/6	2/6	3/6	4/6
	P_4	3/6	4/6	5/6	2/6	3/6	4/6	1/6	2/6	3/6
C_{12}	P_1	2/6	3/6	4/6	2/6	3/6	4/6	2/6	3/6	4/6
	P_2	3/6	4/6	5/6	2/6	3/6	4/6	2/6	3/6	4/6
	P_3	3/6	4/6	5/6	3/6	4/6	5/6	3/6	4/6	5/6
	P_4	3/6	4/6	5/6	2/6	3/6	4/6	1/6	2/6	3/6
C_{13}	P_1	2/6	3/6	4/6	2/6	3/6	4/6	2/6	3/6	4/6
	P_2	2/6	3/6	4/6	2/6	3/6	4/6	2/6	3/6	4/6
	P_3	2/6	3/6	4/6	3/6	4/6	5/6	3/6	4/6	5/6
	P_4	2/6	3/6	4/6	3/6	4/6	5/6	4/6	5/6	1
C_{21}	P_1	2/6	3/6	4/6	2/6	3/6	4/6	2/6	3/6	4/6
	P_2	2/6	3/6	4/6	2/6	3/6	4/6	2/6	3/6	4/6
	P_3	2/6	3/6	4/6	3/6	4/6	5/6	4/6	5/6	1
	P_4	3/6	4/6	5/6	2/6	3/6	4/6	1/6	2/6	3/6
C_{22}	P_1	2/6	3/6	4/6	2/6	3/6	4/6	2/6	3/6	4/6
	P_2	1/6	2/6	3/6	2/6	3/6	4/6	3/6	4/6	5/6
	P_3	1/6	2/6	3/6	2/6	3/6	4/6	3/6	4/6	5/6
	P_4	2/6	3/6	4/6	2/6	3/6	4/6	2/6	3/6	4/6

Table 9 Fuzzy design matrix *(Continued)*

C_{23}	P_1	2/6	3/6	4/6	2/6	3/6	4/6	2/6	3/6	4/6
	P_2	3/6	4/6	5/6	3/6	4/6	5/6	3/6	4/6	5/6
	P_3	3/6	4/6	5/6	2/6	3/6	4/6	3/6	4/6	5/6
	P_4	2/6	3/6	4/6	2/6	3/6	4/6	2/6	3/6	4/6
C_{31}	P_1	1/6	2/6	3/6	2/6	3/6	4/6	3/6	4/6	5/6
	P_2	1/6	2/6	3/6	2/6	3/6	4/6	3/6	4/6	5/6
	P_3	2/6	3/6	4/6	2/6	3/6	4/6	2/6	3/6	4/6
	P_4	3/6	4/6	5/6	1/6	2/6	3/6	0/6	1/6	2/6
C_{32}	P_1	2/6	3/6	4/6	2/6	3/6	4/6	2/6	3/6	4/6
	P_2	3/6	4/6	5/6	2/6	3/6	4/6	1/6	2/6	3/6
	P_3	1/6	2/6	3/6	2/6	3/6	4/6	3/6	4/6	5/6
	P_4	4/6	5/6	1	2/6	3/6	4/6	0/6	1/6	2/6
C_{33}	P_1	2/6	3/6	4/6	2/6	3/6	4/6	2/6	3/6	4/6
	P_2	1/6	2/6	3/6	2/6	3/6	4/6	3/6	4/6	5/6
	P_3	3/6	4/6	5/6	2/6	3/6	4/6	1/6	2/6	3/6
	P_4	3/6	4/6	5/6	2/6	3/6	4/6	1/6	2/6	3/6
C_{34}	P_1	4/6	5/6	1	2/6	3/6	4/6	0/6	1/6	2/6
	P_2	1/6	2/6	3/6	2/6	3/6	4/6	3/6	4/6	5/6
	P_3	2/6	3/6	4/6	2/6	3/6	4/6	2/6	3/6	4/6
	P_4	3/6	4/6	5/6	2/6	3/6	4/6	1/6	2/6	3/6
C_{41}	P_1	1/6	2/6	3/6	3/6	4/6	5/6	2/6	3/6	4/6
	P_2	4/6	5/6	1	2/6	3/6	4/6	0/6	1/6	2/6
	P_3	2/6	3/6	4/6	2/6	3/6	4/6	2/6	3/6	4/6
	P_4	4/6	5/6	1	2/6	3/6	4/6	1/6	2/6	3/6
C_{42}	P_1	3/6	4/6	5/6	2/6	3/6	4/6	1/6	2/6	3/6
	P_2	4/6	5/6	1	2/6	3/6	4/6	0/6	1/6	2/6
	P_3	2/6	3/6	4/6	2/6	3/6	4/6	2/6	3/6	4/6
	P_4	3/6	4/6	5/6	1/6	2/6	3/6	1/6	2/6	3/6
C_{43}	P_1	2/6	3/6	4/6	2/6	3/6	4/6	2/6	3/6	4/6
	P_2	2/6	3/6	4/6	2/6	3/6	4/6	2/6	3/6	4/6
	P_3	2/6	3/6	4/6	2/6	3/6	4/6	2/6	3/6	4/6
	P_4	3/6	4/6	5/6	2/6	3/6	4/6	1/6	2/6	3/6
C_{51}	P_1	2/6	3/6	4/6	2/6	3/6	4/6	2/6	3/6	4/6
	P_2	2/6	3/6	4/6	2/6	3/6	4/6	2/6	3/6	4/6
	P_3	2/6	3/6	4/6	2/6	3/6	4/6	2/6	3/6	4/6
	P_4	3/6	4/6	5/6	2/6	3/6	4/6	1/6	2/6	3/6
C_{52}	P_1	2/6	3/6	4/6	3/6	4/6	5/6	4/6	5/6	1
	P_2	2/6	3/6	4/6	3/6	4/6	5/6	4/6	5/6	1
	P_3	2/6	3/6	4/6	2/6	3/6	4/6	2/6	3/6	4/6
	P_4	4/6	5/6	6/6	2/6	3/6	4/6	0	1/6	2/6
C_{53}	P_1	2/6	3/6	4/6	2/6	3/6	4/6	2/6	3/6	4/6
	P_2	3/6	4/6	5/6	2/6	3/6	4/6	1/6	2/6	3/6
	P_3	2/6	3/6	4/6	2/6	3/6	4/6	2/6	3/6	4/6
	P_4	4/6	5/6	6/6	2/6	3/6	4/6	1/6	2/6	3/6

Abbreviations

AHP: Analytic hierarchy process; ANP: Analytic network process; DEA: Data envelopment analysis; DEMATEL: Decision-making trial and evaluation laboratory; LCA: Life cycle assessment; MCDM: Multi-criteria decision-making; TOPSIS: Technique for Order of Preference by Similarity to Ideal Solution.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

XW contributed to the design of the study, developed the integrated fuzzy methodology and carried out the case study. HKC participated in the design of the study, carried out the literature review and developed the hierarchical model for the product design evaluation from the remanufacturing perspective. Both authors helped draft the manuscript, read and approved the final manuscript.

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