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ELV Recycling Service Provider Selection Using the Hybrid MCDM Method: A Case Application in China

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Abstract: With the rapid depletion of natural resources and undesired environmental changes globally, more interest has been shown in the research of green supply chain practices, including end-of-life vehicle (ELV) recycling. The ELV recycling is mandatory for auto-manufacturers by legislation for the purpose of minimizing potential environmental damages. The purpose of the present research is to determine the best choice of ELV recycling service provider by employing an integrating hybrid multi-criteria decision making (MCDM) method. In this research, economic, environmental and social factors are taken into consideration. The linguistic variables and trapezoidal fuzzy numbers (TFNs) are applied into this evaluation to deal with the vague and qualitative information. With the combined weight calculation of criteria based on fuzzy aggregation and Shannon Entropy techniques, the normative multi-criteria optimization technique (FVIKOR method) is applied to explore the best solution. An application was performed based on the proposed hybrid MCDM method, and sensitivity analysis was conducted on different decision making scenarios. The present study provides a decision-making approach on ELV recycling business selection under sustainability and green philosophy with high robustness and easy implementation.

Keywords: end-of-life vehicle (ELV); recycling service provider selection; FVIKOR; combined weight; Shannon Entropy; hybrid MCDM method

1. Introduction

Increasing concerns have been shown for green philosophy and sustainability of manufacturing industries because of the present industrial situation of high emission and energy overconsumption. Vehicle consumption has been one of the staple emissions that influence the environment over its total life cycle [1]. Legislations and policies have been made to enforce the factories and automakers to follow the requirements of environment-friendly economics in the whole supply chain [2].

Electric cars are regarded as an environment-friendly solution to the ecological outcome of people's mobility. Recently, many international automotive organizations show the tendency of using alternative energy, driven by environmentally friendly and sustainable forces [3]. Furthermore, the extended responsible principle (ERP) and polluter pays principle [4] regulated the liability of the industrial factory for their product manufacturing and consumption. Meanwhile, the sustainable practice is policy driven, which means international and domestic governments have initiated to stipulate ISO standards and emission regulations for efficient and eco-friendly performance. All of these stimulate manufacturing organizations to follow "3R" principles (reduce, reuse and recycle) [5]. Sustainable performance with little environment impact has been considered the significant criterion in the green practice of the whole supply chain, such as the green supplier selection [6,7], green material substitution selection [8,9], sustainable design [9] and recycling practice [10,11].

Eco-friendly requirements motivate green practices and sustainable development of automobile industry in recycling of the end-of-life vehicles (ELV) [12]. China has been the world's largest automobile manufacturer and market since 2009 and the automobile industry has become the main contributor of emission [13]. In addition, end-of-life vehicles recycling sector is relatively new compared with metal and paper recycling operations. All cars with maximum lifespan should be dealt with properly without scrapping or irrational breaking-down. As for the destination of ELVs, the majority of ELVs could possibly flow into the black market, and become second-hand vehicles after refurbishing and delivering to underdeveloped areas [13]. Alternatively, some ELVs are delivered to ELV recycling service providers directly. To deal with this dilemma, the related policy making for the regulation of ELV recycling management [13–15] has been studied. Recently, as a huge recycling market, China confronts the problem of potential requirements on recycled material/components. In China, automotive sales keep steadily increasing for its huge potential growth space, and the second-hand car market stimulates the increasing demands of reused parts and materials, which stimulates the development of the recycling industry. ELVs and second-hand cars are in demand, being processed by recycling service providers that operate dismantling, reusing, crushing and recycling companies. Traditional ELVs processing include dismantling, shredding, and landfill disposal.

Normally, an end-of-life vehicle will be taken to an authorized treatment facility (ATF), collected for free in UK [16]. Almost 3500 firms with different sizes in the UK run ATFs [5]. ELV recycling organizations are regarded as the downstream of the vehicle supply chain from the total lifecycle perspective. Large-scale recycling requires specific techniques and expensive plants and equipment, as well as professional authorities. The authorized recycling service provider should meet the following two conditions. The company is required to satisfy the cost efficiency, which is related to economic sustainability. In addition, its recycling operations are required to comply with environmental requirements. Basically, for the purpose of efficiency and cooperative coherence, each car manufacturer negotiates with authorized recycling companies, and each automaker chooses only one recycling service provider to handle ELVs. When a vehicle reaches the state's write-off standard, the last owner can hand in his car to the authorized recycling service provider. Regulations and legislations are explored to motivate final car owners to deliver worn-out vehicles. Bellmann [4] argues that carmakers should pay a fee reserved for future recycling handling. In this particular industry, being authorized by the local government is a prerequisite for organizations with the intention of operating a recycling business. In contrast with other motor towns in China, Chongqing has fewer recycling companies. However, motivated by soaring vehicles manufacturing output and utilization, as well as sustainable government policy, the ELV recycling industry, as an indispensable part of green supply chain management, has become a promising industry and an increasing number of organizations have entered this business. As a green and sustainable operation, the recycling operation itself consists of resources/energy consumption, decomposition work and carbon dioxide emissions. However, little research focuses on the evaluation of the sustainability practices of ELV recycling service providers.

The demands of sustainability and green philosophy have resulted in some research focused on the front supply chain of the production, green suppliers and sustainable supplier selection by applying multi-criteria decision making (MCDM) methods [17,18]. However, there is little attention paid to the green practice of ELV recycling service. Therefore, recycling service provider selection is not currently the subject of much economic consideration. Furthermore, the environmental attributes of the implementation of the organization should be taken into account. Specifically, the ELV recycling service provider is a multi-criteria decision making (MCDM) issue that requires considering multiple conflicting criteria. This paper fills this gap by proposing the hybrid MCDM method, which integrates fuzzy aggregation, Shannon Entropy and fuzzy VlseKriterijumska Optimizacija I Kompromisno Resenje (FVIKOR) technique to prioritize all of the alternatives under the sustainable criteria framework. To the best of our knowledge, there are currently few studies published on ELV recycling service provider selection using hybrid MCDM methods.

The remainder of this paper is structured as follows. Section 2 provides an overview of recent studies on green supply chain and recycling industries, as well as the application of hybrid MCDM methods in this field. The solution methodology framework for ELV recycling service provider selection, as well as establishment of implementation procedures is introduced in Section 3. An application in the case company is illustrated in Section 4, including the criteria development and implementation of the proposed hybrid MCDM method. Section 5 presents the results and findings. Finally, we close this paper with conclusions and future research in Section 6.

2. Literature Review

There are three parts in this section. The green ELV recycling practice is presented in the first part. Then we provide a literature review on the hybrid MCDM methods recently used in sustainable practice, especially those integrated with fuzzy techniques. At last, the research gap is addressed, as well as the contributions of this paper.

2.1. Green ELV Recycling Practice

The sustainability and green practices in the automotive industry have been involved in the total life cycle procedures. Cucchiella [19] argued that the top five ELV recycling areas fell into ELV policy, material recycling, ELV environmental issues, the ELV recycling process and ELV strategic and economic issues. Salvado [1] studied sustainability for the automotive industry and the supply chain from the economic, social and environmental perspectives, as well as studying the proposal of the sustainability index. Bellmann [4] illustrated the economic feasibility and environmental impact of the ELV recycling system, as well as its successful implementation of a recycling market. Generally, the recycling costs consist of the recycling operation cost, expenditure on the collection of recyclable components/parts and reverse logistics cost segments. Previous researchers and practitioners have focused on the green ELV recycling procedure issues including the policy-making for ELV recycling, recycling techniques and design for recycling.

To develop the ELV recycling industry and figure out its status quo, the policies and regulations in different unions and organizations have been studied. The laws and regulations on the ELV industry investigated in developed countries provide guidance for the Chinese government [15]. Chen [13] developed a dynamic model on public policy and cost benefit elements for end-of-life (EOL) passenger cars, which provides the public policies on ELV recycling. Che [20] presented a contrast of the ELV recycling management practices in the three Asian countries: Korea, Japan and China. Xia [14] proposed the triple-C (cease-control-combine) remedy strategy and some policies for the auto-makers in the North American market, which would stimulate sustainable development in the economic recession. Martina [2] summarized the sustainability reports of 14 auto-makers in Europe, focusing on their green practices and implementation situations; multiple items including sustainability topics, implementation situations, stakeholder management, product control and management control metrics in these organizations were reported for corporate sustainability recognition.

The related recycling techniques have been addressed for the movement of the ELV recycling industry, including dismantling systems, material recycling and component recycling practices. Unlike the EOL ship recycling industry, ELV recycling has a frequent supply of small units mainly depending on shredding the vehicle hull to obtain ferrous and non-ferrous metal for recycling usage of the separation techniques [21]. Lu [12] made an overview on recent innovations and disbanding technologies during ELV recycling, and argued that the rapid assembly and disassembly technologies are the key drivers in the recycling practice. In order to enforce the green technology, Ahmed Ali [22] studied the composite material selection model based on the expert decision system using the analytic hierarchy process (AHP) method and taking environmental influence into consideration. Poulikidou [8] developed a new decision model on material substitution selection based on life cycle evaluation and environmental influence. Kirwan [5] proposed the three kinds of operations (recycling, reuse and energy recovery) for material recycling. The profit of ELV recycling is the utility of its output, which corresponds to the recycling forms. The most profitable with high value is definitely undamaged and reusable components, which can be reused for spare parts. The second value origin comes from the recycling of uncontaminated scrap materials; profit depends on the contamination degree and recyclability. Generally speaking, energy recovery is another recycling pattern with the least profit. The ELV recycling industry has potential value from the economic perspective [23]. After studying component recycling and environmental impacts through the material flow analysis (MFA) and lifecycle assessment (LCA) techniques, Diener [11] argued that it was far from sufficient to do the case study of remanufacturing and more efforts should be made for recycling. Mathieux [10] presented the case study with ELV aluminum recycling and used material flow analysis (MFA).

As for the phenomenon that certain vehicle components are practically difficult to disassemble, Tian [9] illustrated the difficulty of handling polymers in dashboards and argued that the designers of vehicles should explore the material for more convenient end-of-life processing without sacrificing the original function requirements and performances. Kirwan [5] suggested that more complicated materials from a wide range of metals and composites could be used, and the multifunctional components would be designed to reduce the end-of-life materials from the green perspective. Keivanpour [24] proposed a new method based on fuzzy rule and game theory to analyze the strategic behavior of auto-makers in the eco-ELV practice, which would provide managerial insights for decision-makers with the discussion of several scenarios. From the illustrated literature above, the automobile manufacturers have started to focus on their responsibility in ELV recycling under the sustainability and ERP principle, as well as on the public regulations. Vehicle suppliers are pressed to take recyclability into their design modules. Considering the approximate 12-year lifespan of vehicle products, the design for recycling mainly would be focused on theoretical study and initial practical application. The design for recycling would absolutely improve the recycling efficiency, as well as benefit the collection of ELVs along with sorting, dismantling and recycling.

2.2. Hybrid Multi-Criteria Decision-Making (MCDM) Methods

The multi-criteria decision-making methods, such as the analytic hierarchy process (AHP) [22], analytical network process (ANP) [25,26], data envelopment analysis (DEA) [27], the Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) [25,28], VIKOR [29] and the Decision Making Trial and Evaluation Laboratory (DEMATEL) [30] methods, are usually adopted to evaluate the alternatives in sustainability and green practices. MCDM methods would be used in recycling practices to select the best ELV recycling merchant. Vinodh [31] proposed an integrated MCDM method using the fuzzy AHP-TOPSIS technique to resolve the plastic recycling method selection. The evaluation model takes the optimal recycling method with multiple criteria into consideration. Yang [32] proposed the hybrid decision model integrating balanced scorecard (BSC) and DEA for the information technology project ranking. In addition, the hybrid MCDM method has been considered a complex decision-making method and an effective tool involving both quantitative data and qualitative information [33], which is usually integrated with fuzzy set theory. Zhuo [34] applied the fuzzy number and fuzzy operators (2-tuple weighted averaging operator and 2-tuple ordered weighted averaging operator) into a decision model for the green procurement process, and a green supplier selection case was implemented to illustrate the proposed framework. Vahabzadeh [29] proposed the green decision-making model with fuzzy VIKOR and interval-valued trapezoidal fuzzy numbers for reverse logistics during the recycling process. To solve the problem, the hybrid MCDM method is usually generated by combining several basic decision-making techniques. The recent developed hybrid MCDM methods in green supply chain practice are summarized in Table 1.

Table 1. Representative literatures on sustainable practice by the hybrid MCDM method.

Hybrid MCDM Method	Application Area	First Author
Systematic DEA	Sustainable supply chain	Shi [27]
Expert system and AHP	Environmental automotive material selection	Ali [22]
Fuzzy Delphi and ANP	Regeneration project selection	Wang [26]
Fuzzy AHP and TOPSIS	Plastic recycling method selection	Vinodh [31]
Fuzzy set and fuzzy TOPSIS	Site selection from sustainability perspective	GUO [28]
Fuzzy logic and Systems Dynamic	Sustainable supplier selection	Orji [35]
DEMATEL and VIKOR	Green supplier selection	Kuo [30]
Fuzzy logic and fuzzy operators	Product component EOL option	Ma [36]
TOPSIS and Entropy	Vulnerability assessment of water use	Kwangjai [37]
ANP and VIKOR	Vendor selection	Hsu [38]
Neural network (NN), ANP and DEA	Green supplier selection	Kuo [39]
TOPSIS and fuzzy set (FS)	Sustainability performance evaluation	Kannan [40]
FS and VIKOR	Reverse logistics (recycling)	Vahabzadeh [29]
FS and grey theory	Green supply chain management	Tseng [7]
ANP and Fuzzy Delphi and TOPSIS	Sustainable supplier selection	Wu [25]
ANP and grey relation analysis (GRA)	Green supplier of automotive organization	Hashemi [41]
Fuzzy AHP and Group decision	Green supplier selection	Buyukozkan [42]

The MCDM method has grown as a sub-branch of operations research that provides assistance for managers and decision-makers in unraveling the uncertainty and vagueness of evaluation information. As can be seen from Table 1, it has been proved that the methods mentioned above have come into use more frequently in green supply chain practices. Besides, VIKOR has been proven to be an effective MCDM method to rank the alternatives by comprehensively considering the group utility and individual regret value. Mardani [43] has summarized the recent sustainable application in green areas using the VIKOR method. As for the vagueness and ambiguity of decision information, the fuzzy-based techniques are usually embedded into the typical MCDM methods [44]. The linguistic variables and fuzzy operators are normally used to obtain the subjective weight of decision-making. To reflect the objective information, the concept of Shannon entropy is introduced and it has shown the advantage in objective weight calculation. In order to consider the vague information of decision-makers comprehensively, the combined weight including subjective and objective items is calculated integrating fuzzy-based techniques. Linguistics variables facilitate the collection of the evaluation information given by the expert panel, and fuzzy techniques make contributions to the quantification of qualitative criteria. In addition, the combined weighting technique is explored to determine the criteria weight. The previous researchers show little relative experience in green supply chain practice using the hybrid MCDM method integrated with the VIKOR technique, Shannon entropy and the fuzzy aggregation technique. Being different from previous research [29,42,43], the present research proposes the hybrid MCDM method integrating the fuzzy aggregation, Shannon entropy and fuzzy VIKOR techniques, which reflects the subjectivity and objectivity of the expert panel's judgment. Furthermore, the novel approach shows the flexibility of decision-making by adjusting the experiment parameters based on the preferences of the decision-makers.

2.3. Research Gap

Literature review shows that researchers and practitioners have applied hybrid MCDM methods in different practical areas implementing sustainability and green philosophy. In addition, in the automotive industry, green activities are conducted both in green supply chain management [6,14] and in the green performance on each process such as environmental material study [8,22], green procurement [6], site selection [28], ELV management project selection [45] and recycling practice [5].

However, the application of integrated MCDM methods in the context of ELV recycling service providers has proven scant. Most research and practices focused on the front of the supply chain instead of the end of the supply chain activity of green recycling. To some extent, it is regarded as the beginning of the re-manufacturing recovery and re-using industry [45]. The recycling service provider selection would be regarded as a multiple criteria complex problem with qualitative and quantitative information simultaneously. How to evaluate and recognize the best ELV recycling service provider taking qualitative and quantitative information into account is really a great challenge for auto-makers. The attributes influencing the alternative selection should be developed, and a systematic recycling service provider selection framework needs to be explored with the application of the novel hybrid MCDM method. As there is no methodology that meets all requirements for ELV recycling service provider selection, this present research explicitly focuses on that topic. To provide the best solution for recycling service provider selection and fill this application gap, a new hybrid MCDM method based on the combination of Shannon entropy, fuzzy aggregation and the FVIKOR technique is developed. The proposed hybrid MCDM method resolved the illustrative problem under a fuzzy atmosphere for the uncertainty and vagueness of criteria values and preferences of decision-makers in practice. The main contributions of the present research are as follows:

(1) This research initiates green practice in ELV recycling service provider selection considering economic, environmental and social dimensions, which makes a contribution to green supply chain practice.
(2) The combined weight has been proposed based on fuzzy aggregation and Shannon entropy techniques to obtain the criteria weight, which is embedded into fuzzy VIKOR procedures. The case study shows the effectiveness and flexibility of the proposed approach compared with Shemshadi's and Rostamzadeh's methods.
(3) The results of the sensitivity analysis on the relative importance of the decision-maker, the group utility weight and the importance of subjectivity demonstrate the high robustness of the proposed hybrid MCDM method.
(4) The applications of linguistic variables and fuzzy techniques in the proposed hybrid MCDM method facilitate the practitioner in collecting the evaluation information from the expert panel.

3. The Hybrid MCDM Method for Recycling Service Provider Selection

The problem is regarded as a typical *MCDM* problem, which has a set of K decision-makers $D = (D_1, D_2, \ldots, D_k, \ldots, D_K)$, $K \geqslant 2$, and the multi-criteria called $C = (C_1, C_2, ..., C_j, ..., C_n)$, $n \geqslant 2$. There are m alternatives $A = (A_1, A_2, \ldots, A_i, \ldots A_m)$ in the options for ELV recycling services. In addition, each criterion has a discrepant combinational weight to the final decision, which has been divided into the subjective and objective aspect. Let the relative subjective weights of criteria be presented as $\boldsymbol{w}^s = (w_1^s, w_2^s, \ldots, w_j^s, \ldots w_n^s)$, and the objective weights of criteria as $\boldsymbol{w}^o = (w_1^o, w_2^o, \ldots, w_j^o, \ldots, w_n^o)$. Let the φ value be the relative importance of subjectivity, and the combination of the criterion weight $\boldsymbol{w}^c = (w_1^c, w_2^c, w_j^c, \ldots, w_n^c)$ can be calculated based on the subjective weight and objective weight.

Suppose x_{kij} is the rating of the i-th alternative subject to the j-th criterion of the k-th decision-maker, and λ_k is the relative importance of each decision-maker, which satisfies $\sum_{1}^{K} \lambda_k = 1$, and $\lambda = (\lambda_1, \lambda_2, \ldots, \lambda_k), \lambda_k \geqslant 0$ for $k = 1, 2, \ldots, K$. This paper has proposed a novel hybrid MCDM method to tackle this particular problem for ELV recycling service selection subjects with economic, environmental and social considerations.

In this section, we briefly introduce some unit decision techniques, whose main segments in this section are fuzzy aggregation for trapezoidal fuzzy numbers (TFNs), the Shannon entropy method, and the FVIKOR technique. The linguistic variable is applied to describe the preferences of decision-makers, as well as for qualitative decision information. Besides, the fuzzy aggregation is utilized to obtain the subjective weights, and the entropy method is applied for objective weight calculation. After the combination of the two weights, we use the FVIKOR method to obtain a compromising solution from the optional alternatives.

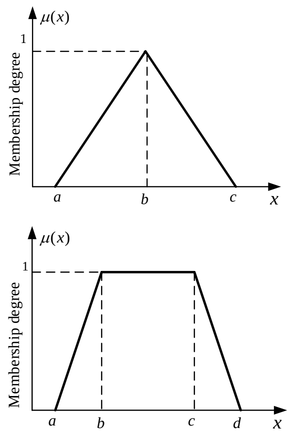
3.1. Trapezoidal Fuzzy Number and Fuzzy Aggregation for Subjective Weight

The fuzzy set theory is introduced in this part mainly to reflect the subjective judgments of decision-makers and deal with vague evaluation information [44,46]. The fuzzy set theory, introduced by Zadeh [47], has been developed and applied in many areas, especially for intelligent evaluation and decision matters. It was considered to deal with the vague and impressive cognitive human judgments on certain criteria with its mathematical advantages of membership function, especially for those variables that can be calculated or numbered by specific crisp values. The uncertain and vague information of alternatives subject to multi-criteria are quantified by linguistic variables or fuzzy numbers [46]. Based on the previous illustration, what comes next is a brief introduction to fuzzy set theory and linguistic variables.

(1) Fuzzy numbers

Definition 1: (Fuzzy set) Let x be the universe of discourse. The fuzzy set A can be regarded as order pairs, and it is linked by a membership function that maps each element with a specific number. The function value is the membership degree for x. The fuzzy number is a particular case of a fuzzy set, which is used to represent the vague scale ratings of the alternatives.

Definition 2: According to the shape of the membership function, the fuzzy numbers can be divided into several forms. The most notable types of fuzzy numbers are triangular and trapezoidal fuzzy numbers. Assume $A = (a, b, c)$ is the triangular fuzzy number and $B = (a, b, c, d)$ is the trapezoidal fuzzy number; the two membership functions of these two fuzzy numbers can be illustrated as Figure 1 shows.



$$\mu_A(x) = \begin{cases} (x-a)/(b-a), a \le x \le b \\ (c-x)/(c-b), b \le x \le c \\ 0, \quad \textit{otherwise} \end{cases} \tag{1}$$

$$\mu_A(x) = \begin{cases} (x-a)/(b-a), & a \le x \le b \\ 1, & b \le x \le c \\ (d-x)/(d-c), & c \le x \le d \\ 0, & \textit{otherwise} \end{cases} \tag{2}$$

Figure 1. Membership functions of triangular fuzzy number and trapezoidal fuzzy number.

As for the trapezoidal fuzzy number, when $b = c$, it will become the triangular fuzzy number. Therefore, the triangular fuzzy number is the special trapezoidal fuzzy number.

(2) Linguistic variables

Linguistic variables, proposed by Zadeh in 1974 [48], have been utilized for the description of evaluation information, especially for uncertain subjective judgments. It can transform the linguistic description into mathematic information on the basis of the membership function. The trapezoidal fuzzy number has been used to describe the qualitative information in this paper due to its popularity and generality. The corresponding rating scales with linguistic variables and trapezoidal fuzzy numbers (TFNs) can be illustrated as Table 2 shows, and the membership function is shown in Figure 2.

Table 2. Linguistic variables and TFNs.

Linguistic Variables	TFN
Very Low/Very Poor (VL/VP)	(0,0,1,2)
Low/Poor (L/P)	(1,2,2,3)
Medium Low/Medium Poor (ML)	(2,3,4,5)
intermediate (M)	(4,5,5,6)
Medium High/Medium Good (MH/MG)	(5,6,7,8)
High/Good (H/G)	(7,8,8,9)
Very High/Very Good (VH/VG)	(8,9,10,10)

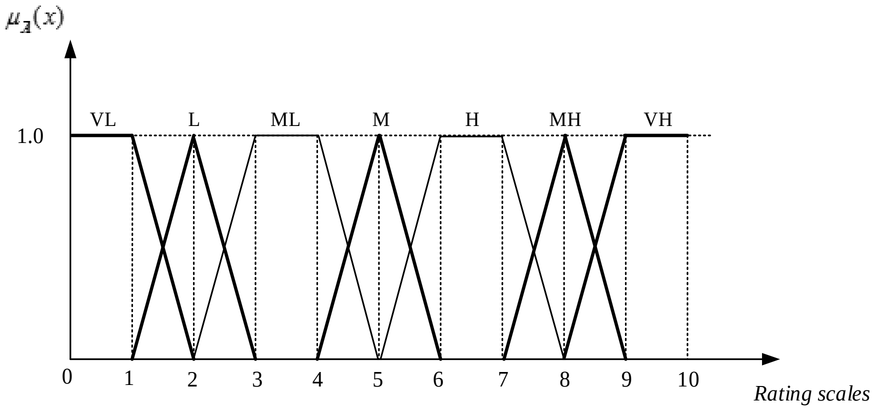


Figure 2. Membership function of triangular fuzzy number with correspondence for seven rating scales.

As can be seen from the Table 2, there are seven scales for the membership degree description of a certain criterion.

(3) Fuzzy operators and defuzzification for TFNs

Assume there are two TFNs, $A_1 = (a_1, b_1, c_1, d_1)$ and $A_2 = (a_2, b_2, c_2, d_2)$; the algebraic operations are implemented according to the fuzzy operators "$\oplus\ominus\otimes\oslash$", proposed in the previous references [46]. The common operations between these TFNs can be formulated as follows.

Addition operator: $\mathrm{A}_1 \oplus \mathrm{A}_2 = (a_1 + a_2, b_1 + b_2, c_1 + c_2, d_1 + d_2)$

Subtraction operator: $\mathrm{A}_1 \ominus \mathrm{A}_2 = (a_1 - a_2, b_1 - b_2, c_1 - c_2, d_1 - d_2)$

Multiplication operator: $\mathrm{A}_1 \otimes \mathrm{A}_2 = (a_1 \times a_2, b_1 \times b_2, c_1 \times c_2, d_1 \times d_2)$

Division operator: $\mathrm{A}_1 \oslash \mathrm{A}_2 = (a_1/d_2, b_1/c_2, c_1/b_2, d_1/a_2)$

Fuzzy numbers usually must be transferred into crisp values for ranking and prioritization purposes, and this process is called defuzzification [46]. Defuzzification, as the necessary step in the fuzzy context, has been implemented in a great deal of research [49,50]. Many techniques for defuzzification have been developed, such as the area defuzzification technique, the left and right fuzzy ranking, the centroid-based Euclidean distance technique and so on, but there is no universal consensus [50]. The prevailing approach is based on the centroid, whose center of gravity of a specified curve is calculated. Suppose a trapezoidal fuzzy number $\tilde{x}_{ij} = (a, b, c, d)$ and the formula for defuzzification of the TFN can be calculated with the following general operation (Equation (3)).

$$x_{ij} = defuzzy\left(\tilde{x}_{ij}\right) = \frac{\int \mu\left(x\right) x dx}{\int \mu\left(x\right) dx} = \frac{(d+c)^2 - (b+a)^2 + ab - cd}{3\left[(d+c) - (a+b)\right]} \quad (3)$$

(4) Fuzzy aggregation

The subjective weight of each criterion shows the preference of the decision-maker, which can be obtained from the fuzzy aggregation and fuzzy operation [49] by integrating the judgments. The relative importance of the multi-criteria can be calculated and aggregated by experts' opinions via a seven-point scale (Table 3). It can help to handle experts' judgments and to make an evaluation based on multiple attributes. In general, the trapezoidal fuzzy numbers are used for the subjective weight calculation. Suppose the subjective weight of the criteria given by the *k*-th decision-maker is $\boldsymbol{w^s_{kij}} = \left(w^L_{kij}, w^{M1}_{kij}, w^{M2}_{kij}, w^U_{kij}\right)$, and the fuzzy aggregated subjective weight by a TFN is $\boldsymbol{w_{ij}} = \left(w^L_{ij}, w^{M1}_{ij}, w^{M2}_{ij}, w^U_{ij}\right)$.

Table 3. Linguistic variables for rating the weights of criteria and TFNs.

Linguistic Variables	TFN
Very Low (VL)	(0,0,0.1,0.2)
Low (L)	(0.1,0.2,0.2,0.3)
Medium Low (ML)	(0.2,0.3,0.4,0.5)
Intermediate (M)	(0.4,0.5,0.5,0.6)
Medium High (MH)	(0.5,0.6,0.7,0.8)
High (H)	(0.7,0.8,0.8,0.9)
Very High (VH)	(0.8,0.9,1,1)

$$w^L_{ij} = \sum_{k=1}^{K} \lambda_k w^L_{kij}, w^{M1}_{ij} = \sum_{k=1}^{K} \lambda_k w^{M1}_{kij}$$

$$w^L_{ij} = \sum_{k=1}^{K} \lambda_k w^L_{kij},\ w^{M1}_{ij} = \sum_{k=1}^{K} \lambda_k w^{M1}_{kij}, \quad (4)$$

According to the defuzzification operation (Equation (3)) and normalization operation (Equation (5)), the subjective weight of each criterion based on the preferences of decision-makers can be calculated as $\boldsymbol{w^s} = \left(w^s_1, w^s_2, \ldots, w^s_n\right)$.

3.2. Shannon Entropy Technique for Objective Weight

Shannon entropy is an effective method for uncertain information measurement formulated in terms of possibility theory. It has been widely used to decide the relative importance of criteria based on the evaluation information given by the decision-makers [51]. The relative importance of each criterion would be reflected by the intrinsic decision information, and the objective weights would be calculated based on the entropy value. Liu [49] has applied this technique into an MCDM problem for the weight acquisition. The objective weights based on the entropy value can be reached through the following steps.

Step 1: Normalization of the decision-making matrix. The elements of the matrix can be calculated according to Equation (5).

$$\mathrm{P}_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \quad (5)$$

where x_{ij} is the element of the decision matrix, calculated by fuzzy aggregation on evaluation information.

Step 2: Calculation for the information entropy of each criterion based on Equation (6).

$$e_j = -k \sum_{i=1}^{m} p_{ij} ln p_{ij} = -\frac{1}{lnm} \sum_{i=1}^{m} p_{ij} ln p_{ij} \quad (6)$$

Step 3: The objective weight of each criterion can be obtained through Equation (7).

$$\mathrm{w}_j^o = \frac{1 - e_j}{\sum_{j=1}^{n}\left(1 - e_j\right)} \tag{7}$$

3.3. Fuzzy VIKOR Method

The VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje) method has proven to be an effective method for the multi-criteria prioritization problem, as well as for the multi-criteria decision-making (MCDM) issues [52]. The compromised solution can be calculated and obtained for the prioritization issues based on the ranking list, which focus on priorities ranked from the set of alternatives considering multiple conflicting criteria. The FVIKOR is the extended VIKOR method when the determination information is qualitative and uncertain. The VIKOR-based methods are performed based on the particular measurement of "closeness" to the "ideal" solution [51], starting with the following formula of $L_p - metric$, and ranking orders of alternatives can be obtained based on the following measurement [29].

$$L_{p,i} = \left\{ \sum_{j=1}^{n} \left[\frac{w_j\left(f_j^* - f_{ij}\right)}{f_j^* - f_j^-} \right]^p \right\}^{1/p}, \ 1 \leqslant p \leqslant +\infty, \ i = 1,\ 2, \ldots, m \tag{8}$$

Within the VIKOR method $L_{1,i}$ (as S_i in Equation (10)) and $L_{\infty,i}$ (as R_i in Equation (10)) are used to rank the alternatives. The best choice obtained by the minimum S_i is based on the maximum group utility value (majority rule), while the best solution obtained by the minimum R_i is on the basis of the minimum individual regret value (opponent). The compromise solution can be the base for negotiation on the group utility and individual regret. It could be ranked by the index to choose the compromise solution [43]. The final ranking index value is the aggregation of all influential criteria, the relative importance of the criteria and the integration of group and individual satisfaction. In order to deal with the qualitative and vague information, fuzzy set theory is integrated with the typical VIKOR procedure called the fuzzy VIKOR (FVIKOR) approach. The steps of the FVIKOR method are implemented as follows.

Step 1: Data collection. The decision information (linguistic variable) should be collected from the established decision expert group.

Step 2: Aggregating the fuzzy ratings of each alternative based on fuzzy aggregation. The relative importance of each decision-maker λ_k has been set in different scenarios. After that, the fuzzy determination matrix will be generated.

Let the fuzzy rating of the *i*-th alternative subject to the *j*-th attribute of the *k*-th decision-maker be the TFN $\tilde{x}_{kij} = (x_{kij}^L, x_{kij}^{M1}, x_{kij}^{M2}, x_{kij}^U)$. Therefore, the fuzzy rating of each alternative subjected to criterion C_j can be formulated as the aggregated TFN $\tilde{x}_{ij} = (x_{ij}^L, x_{ij}^{M1}, x_{ij}^{M2}, x_{ij}^U)$, where $i = 1, 2, \ldots, m$; $j = 1, 2, \ldots, n$; $k = 1, 2, \ldots, K$. The elements of the aggregated TFNs can be calculated as follows (Equation (9)):

$$x_{ij}^L = \sum_{k=1}^{K} \lambda_k x_{kij}^L,\ x_{ij}^{M1} = \sum_{k=1}^{K} \lambda_k x_{kij}^{M1},\ x_{ij}^{M2} = \sum_{k=1}^{K} \lambda_k x_{kij}^{M2},\ x_{ij}^U = \sum_{k=1}^{K} \lambda_k x_{kij}^U \tag{9}$$

Step 3: Defuzzification of the fuzzy decision matrix into the crisp values. According to Equation (3), the determination matrix $\boldsymbol{D}$ is obtained.

$$x_{ij} = defuzzy\,(\tilde{x}_{ij}) = \frac{(x_{ij}^U + x_{ij}^{M2})^2 - (x_{ij}^{M1} + x_{ij}^L)^2 + x_{ij}^L x_{ij}^{M1} - x_{ij}^{M2} x_{ij}^U}{3[(x_{ij}^U + x_{ij}^{M2}) - (x_{ij}^{M1} + x_{ij}^L)]}$$

Step 4: Based on the combination weight calculated from the fuzzy analytic hierarchy process (FAHP) and entropy techniques, the best value f_j^* and the worst value f_j^- of each criterion has been established.

$$f_j^* = \begin{cases} \max\limits_i x_{ij}, & \textit{the more the better} \\ \min\limits_i x_{ij}, & \textit{the less the better} \end{cases}, \quad f_j^- = \begin{cases} \min\limits_i x_{ij}, & \textit{the less the bad} \\ \max\limits_i x_{ij}, & \textit{the more the bad} \end{cases}$$

Step 5: Compute the maximum group utility value S_i and the minimum individual regret value R_i for every alternative. The relative importance between the subjective and objective weight of each criterion can be denoted as φ.

$$S_i = \varphi \sum_{j=1}^{n} w_j^s f_{ij} + (1-\varphi) \sum_{j=1}^{n} w_j^o f_{ij} = \sum_{j=1}^{n} f_{ij} [\varphi w_j^s + (1-\varphi) w_j^o] = \sum_{j=1}^{n} w_j^c f_{ij}$$

$$R_i = \max_j [\varphi w_j^s f_{ij} + (1-\varphi) w_j^o f_{ij}] = \max_j (w_j^c f_{ij}) \tag{10}$$

where $w_j^c = \varphi w_j^s + (1-\varphi) w_j^o$, which is the combination of the weights of each criterion, and $f_{ij} = \left[\frac{f_j^* - x_{ij}}{f_j^* - f_j^-} \right]$ is the normalized distance for the element x_{ij} according to the mapping function with the best and worst values.

Step 6: Calculate the comprehensive utility value $Q_i, i = 1, 2, \ldots, m$ for each alternative.

$$Q_i = v \frac{S_i - S^*}{S^- - S^*} + (1-v) \frac{R_i - R^*}{R^- - R^*} \tag{11}$$

where $S^- = \max\limits_i S_i, S^* = \min\limits_i S_i, R^- = \max\limits_i R_i, R^* = \min\limits_i R_i,\ v \epsilon (0,1)$ is the relative weight of the maximum group utility, while the $1 - v$ is the relative importance of the individual regret. Obviously, the value of v represents the attitude towards the decision-makers, which is similar to the optimistic and pessimistic decision-making.

Step 7: Alternatives ranking based on the three sorting values, S, R, and Q. The ranking has the same sequence with an ascending order, which is listed in the three columns of the ranking result.

Step 8: Ranking orders and compromised solution generation. The candidate $A^{(1)}$ will be regarded as the compromising solution, which has the minimum comprehensive group utility value Q if the following two conditions (acceptance advantage and its stability) can be satisfied:

C1 (*Acceptable advantage*): $Q\left(A^{(2)}\right) - Q\left(A^{(1)}\right) \geqslant DQ$ where $A^{(2)}$ is the second alternative in the ranking sequence by the Q value, and $DQ = 1/(m\text{-}1)$.

C2 (*Acceptable stability in decision-making*): The alternative $A^{(1)}$ must also be the best ranked by S or R. This compromise solution is stable within a decision-making process, which could be: "voting by majority rule" (when $v > 0.5$ is needed), or "by consensus" $v = 0.5$, or "with veto" $v < 0.5$. As in the interpretation mentioned above, the value of v represents the relative weight of the determination strategy of the maximum group utility.

If one of the conditions is not satisfied, then a set of compromise solutions is proposed, consisting of two situations, which is:

(1) Alternatives $A^{(1)}$, $A^{(2)}$, ..., $A^{(m)}$ will be the compromise solutions if the condition C1 is not satisfied, while $A^{(m)}$ is decided by the formula $Q(A^{(m)}) - Q(A^{(1)}) < DQ$ for maximum m (the alternatives ranking are "in closeness").

(2) Alternatives $A^{(1)}$ and $A^{(2)}$ will fall into the compromise solution set if the condition C2 is not satisfied.

3.4. The Hybrid MCDM Method Integrating Fuzzy Aggregation, Shannon Entropy and FVIKOR

The purpose of this study is to select the best alternative among a set of recycling service providers, and it presents an integration of fuzzy aggregation, Shannon entropy and FVIKOR techniques in this section. Fuzzy aggregation has been applied into the subjective weight calculation of each criterion and the Shannon entropy concept is used for the objective weight calculation [46]. In addition, the FVIKOR method has contributed to the calculation of the ranking priority of each alternative candidate based on the maximum group utility concept and the minimum individual regret value [53]. The hybrid MCDM method integrating the above-mentioned techniques has been depicted as illustrated in Figure 3.

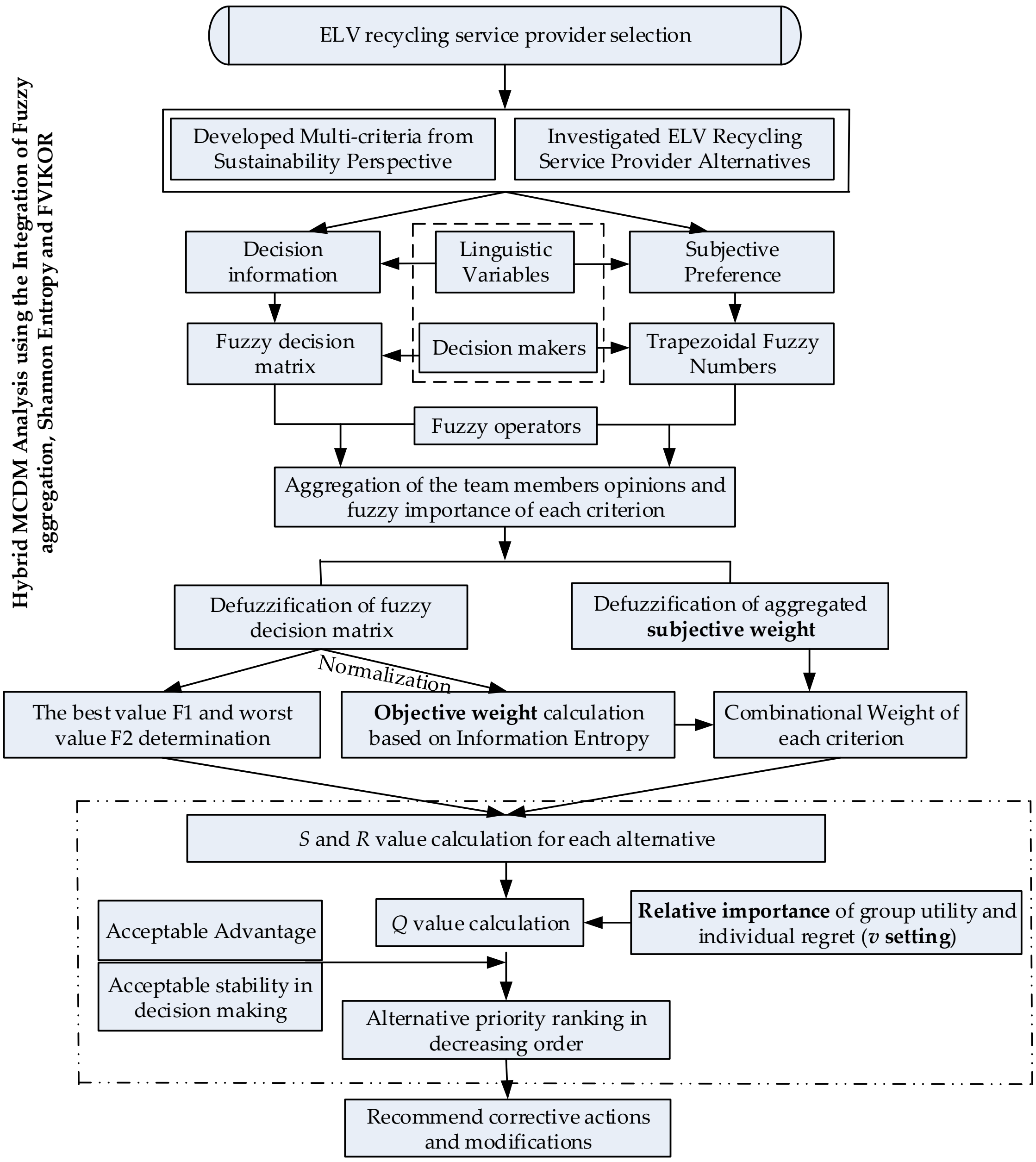


Figure 3. The hybrid multi-criteria decision making (MCDM) method.

4. Application of the Integrated Hybrid MCDM Method

A real numerical case for the application of the proposed hybrid MCDM method integrating the fuzzy aggregation, Shannon entropy and FVIKOR techniques is presented in this section, and it has been applied in an automotive enterprise (CA Company) in China. The enterprise is a famous vehicle-assembly organization with varieties of vehicle products such as sport utility vehicles (SUVs) and multi-purpose vehicles (MPVs) and, therefore, the responsibilities of ELV recycling are required. Compared with the automotive manufacturing industry, recycling industry development is slow and there are limited professionals and specialized recycling service providers. The existing recycling service provider selection for an automotive organization has focused on the economic aspect. This paper would like to explore further taking into account the sustainable perspective with social and environmental consideration. The recycling activity itself is a sustainable and green practice of the automotive industry, while little attention has been paid to the sustainability and green features of the recycling process and the recycling service conducted by the ELV recycling service providers. The sustainability recycling service providers are authorized organizations conducting the business of ELV recycling. Although many service providers exist in the ELV recycling business, the most sustainable one can be selected by the proposed hybrid MCDM method. Three (A1, A2, A3) authorized ELV recycling service organizations performing the automotive recycling work in Chongqing have distinctive pros and cons with different recycling patterns. A1 (A1 is short for Yushang Recycled Resources Co. Ltd, Chongqing, China) is the first organization that conducts the ELV recycling task under the authority of the local government, has and they have a very famous brand and reputation. After two years, the A2 and A3 recycling organizations have involved in ELV recycling operations as well. The ELV recycling industry is no longer monopolized by the Yushang organization.

In order to identify the best ELV recycling service provider, the integrated approach was used and two steps are included in the analytical framework: (i) the developed multi-criteria according to the three considerations, namely economic, social and environment dimensions; and (ii) the evaluation and selection of a compromised solution based on the hybrid MCDM method.

The previous studies for recycling practices applied the FVIKOR technique [30,40]. However, the specific practice in this paper focuses on the ELV recycling service provider selection problem with integrated FVIKOR and other MCDM methods. Furthermore, the criteria hierarchy is different than before, as is the analytical framework. Lastly, the evaluation model and its implementation procedures, discussed in this section, are relatively simple to put into practice for supporting the decision-making. The following illustrated case can interpret the discussion above.

4.1. Criteria Framework Development

The best choice of ELV recycling service provider would be calculated based on the established criteria framework, which will definitely be influenced by the different attributes. However, the present research tends to choose the best alternative recycling service supplier from the sustainability perspective. Salvado [1] proposed the sustainability indexes from economic, environmental and social dimensions. Besides, most of the MCDM problems in green supply chain practice develop the index system and construct the criteria framework from these three dimensions. This study organizes its influential attributes (13 criteria) from the typical three dimensions (economic, environmental and social perspectives) based on the previous literature and Table 4 illustrates the criteria sources and references. In addition, the criteria are verified and validated by the decision-makers of the case corporation. The input data and judgments for the three alternatives by the decision-makers are collected in terms of a series of linguistic variables through the Delphi investigation.

Table 4. Criteria details for the ELV recycling service provider and its sources' illustration.

Dimension	Criterion		Description	Data Type	Source
Economic dimension (D1)	Recycling procurement cost	(C1)	The price offered to the last vehicle owner for buying an obsolete EOL vehicle	LB	[21,25,40]
	Operation cost	(C2)	The cost on the total recycling procedures that include the processing cost and expenditure on the reverse logistics	LB	[25,40]
	Quality utility assessment	(C3)	The average value of a unit EOL vehicle, which is influenced by specific recycling businesses (reuse and recycling operations)	HB	[25,27,54]
	Technical level	(C4)	Technology development of the supplier to meet current and future demand of the firm	HB	[40,54]
Environmental dimension (D2)	Resource consumption	(C5)	Resource consumption in terms of raw material, energy, and water during the recycling	LB	[1,40]
	Pollution production	(C6)	Average volume of air emission pollutant, waste water, solid wastes and harmful material releases per day during recycling	LB	[40]
	Energy efficiency	(C7)	The ELV recycling supplier is operating below or above industry norm compared with the other suppliers in the same industry	HB	[1,54]
	Environment management system	(C8)	The degree that it caters to the ISO 14001, and whether the organization has its environment issues controlled	HB	[2,6,7,40,55]
	Environmental equipment and facilities	(C9)	The equipment/apparatus for the green activities, which is also called the authorized treatment facility (ATF)	HB	[5]
Social dimension (D3)	Healthy and safety	(C10)	Health and safety incidents, health and safety practices	HB	[7,40]
	Local communities influence	(C11)	Service infrastructure, housing, health and safety incidents, regulatory/public services, supporting educational institutions, cultural properties, supporting community projects	HB	[1,28,40,54]
	Employee turnover rate	(C12)	The working condition and wage levels of a supplier relative to its local competitors can be indirectly measured by the turnover rate	LB	[40,54]
	Customer satisfaction	(C13)	The cognitive and perceived conformance performance, and denotes the ability of the organization to satisfy the customer needs	HB	[7,28]

Note: There are two types of the criteria [1].

4.2. Computation on Recycling Service Provider Selection Using Integrated FVIKOR

In this proposed study, we begin to evaluate the existing three alternatives (A1, A2 and A3) as subject to the established criteria framework. The decision-making team for the evaluation of criteria preference and alternative performance is composed of five experts from different areas (economy, environment, ELV recycling, automotive industry and green manufacturing area).

Step 1: Data collection. There are five expert members in the decision group from five fields. In order to obtain the required linguistic ratings, a questionnaire is prepared and distributed among the decision member team for the assessment of criteria and candidates, and each expert panel gives a judgment with a linguistic variable for the subjective weights of the criteria and the candidate's performance subject to each criterion. Therefore, the subjective preference and decision information are presented in Tables 5 and 6.

Table 5. Importance weight of multi-criteria from decision-makers with linguistic ratings.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
DM1	M	ML	H	M	H	VH	MH	M	ML	H	M	H	M
DM2	ML	H	MH	MH	VH	MH	H	H	ML	M	H	VH	ML
DM3	MH	MH	VH	H	M	H	VH	MH	L	MH	ML	M	L
DM4	M	M	MH	ML	MH	M	MH	H	MH	H	M	MH	MH
DM5	H	MH	H	H	H	M	H	VH	L	VH	MH	VH	L

Table 6. Linguistic ratings of the alternatives subject to each criterion.

		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
A1	DM1	VL	M	L	ML	MH	H	ML	M	ML	L	M	M	ML
	DM2	L	ML	VL	L	M	MH	M	ML	M	ML	ML	ML	ML
	DM3	VL	MH	VL	L	H	H	L	MH	M	ML	ML	M	L
	DM4	VL	M	ML	M	MH	H	L	MH	L	L	M	MH	ML
	DM5	L	MH	L	ML	M	M	M	ML	ML	L	MH	ML	L
A2	DM1	ML	M	MH	M	ML	M	H	MH	ML	H	MH	L	MH
	DM2	L	ML	H	MH	ML	M	MH	M	L	MH	M	VL	M
	DM3	ML	M	MH	M	L	MH	MH	H	M	H	M	L	H
	DM4	ML	ML	MH	ML	M	ML	VH	H	M	MH	MH	ML	MH
	DM5	M	MH	M	M	ML	ML	H	M	ML	VH	H	L	H
A3	DM1	M	H	H	ML	H	ML	L	ML	MH	L	L	ML	M
	DM2	ML	MH	VH	M	VH	M	ML	M	M	L	ML	L	MH
	DM3	ML	VH	MH	M	MH	M	ML	L	H	ML	L	L	M
	DM4	M	MH	H	L	H	ML	VL	M	H	ML	VL	ML	ML
	DM5	MH	H	MH	ML	H	MH	ML	ML	M	VL	ML	M	MH

Step 2: The fuzzy decision matrix can be obtained from the corresponding linguistic ratings, as well as the aggregated subjective importance weight provided by each decision-maker. When the decision-maker has an equal weight, the fuzzy decision matrix is presented as follows.

$$\tilde{A} = \left[\begin{array}{c} \begin{array}{ccccc} \mathrm{C1} & \mathrm{C2} & \mathrm{C3} & \mathrm{C4} & \mathrm{C5} \\ \begin{bmatrix} 0.4, & 0.8, & 1.4, & 2.4 \\ 2.2, & 3.2, & 3.8, & 4.8 \\ 3.4, & 4.4, & 5, & 6 \end{bmatrix}, & \begin{bmatrix} 4, & 5, & 5.6, & 6.6 \\ 3.4, & 4.4, & 5, & 6 \\ 6.4, & 7.4, & 8, & 8.8 \end{bmatrix}, & \begin{bmatrix} 0.8, & 1.4, & 2, & 3 \\ 5.2, & 6.2, & 6.8, & 7.8 \\ 6.4, & 7.4, & 8, & 8.8 \end{bmatrix}, & \begin{bmatrix} 2, & 3, & 3.4, & 4.4 \\ 3.8, & 4.8, & 5.2, & 6.2 \\ 2.6, & 3.6, & 4, & 5 \end{bmatrix}, & \begin{bmatrix} 5, & 6, & 6.4, & 7.4 \\ 2.2, & 3.2, & 3.8, & 4.8 \\ 6.8, & 7.8, & 8.2, & 9 \end{bmatrix}, \end{array} \\ \begin{array}{ccccc} \mathrm{C6} & \mathrm{C7} & \mathrm{C8} & & \mathrm{C13} \\ \begin{bmatrix} 6, & 7, & 7.2, & 8.2 \\ 3.4, & 4.4, & 5, & 6 \\ 3.4, & 4.4, & 5, & 6 \end{bmatrix}, & \begin{bmatrix} 2.4, & 3.4, & 3.6, & 4.6 \\ 6.4, & 7.4, & 8, & 8.8 \\ 1.4, & 2.2, & 3, & 4 \end{bmatrix}, & \begin{bmatrix} 3.6, & 4.6, & 5.4, & 6.4 \\ 5.4, & 6.4, & 6.6, & 7.6 \\ 2.6, & 3.6, & 4, & 5 \end{bmatrix}, & \ldots, & \begin{bmatrix} 1.6, & 2.6, & 3.2, & 4.2 \\ 5.6, & 6.6, & 7, & 8 \\ 4, & 5, & 5.6, & 6.6 \end{bmatrix} \end{array} \end{array}\right]$$

Step 3: The crisp values for the decision matrix and the weight for each criterion are calculated based on Equation (3). Then, according to Equations (4)–(7), the combined weights of the criteria can be obtained through the subjective weight and objective weight calculation.

Step 4: The typical FVIKOR steps have been implemented in this procedure, including the best and worst values calculations. The ranking of the three alternatives subject to the established criteria by S, R, and Q in decreasing order is shown in Table 7.

Table 7. Ranking order of the three alternatives by S, R, Q values.

Alternative	S Value	R Value	Q Value	Ranking by S	Ranking by R	Ranking by Q
A1	0.7326	0.1321	0.9678	3	2	2
A2	0.1300	0.0650	0	1	1	1
A3	0.6987	0.1367	0.9718	2	3	3

Table 7 illustrates that the alternative A2 is the best one according to the Q values and should be selected as the ELV recycling service provider. This will be followed by the alternatives A1 and A3. As the results show in the above table, from the group utility, individual utility and comprehensive utility categories, A2 shows a better performance in the ELV recycling service with economic, environmental and social factors considered.

In order to testify the effectiveness and the advantage of flexibility of the novel proposed hybrid MCDM method, we explore the ranking results compared with Shemshadi's and Rostamzadeh's methods based on the practical case [51,56] presented in Table 8.

Table 8. Ranking results compared with Shemshadi's and Rostamzadeh's methods.

Alternative	Proposed Methodology		Shemshadi's Approach		Rostamzadeh's Method	
	Q Value	Ranking by *Q*	*Q* Value	Ranking by *Q*	*Q* Value	Ranking by *Q*
A1	0.9678	2	0.7292	3	1.4471	2
A2	0	1	0	1	0	1
A3	0.9718	3	0.7229	2	1.4695	3

The ranking results from the three methods are shown in Table 8. The result argues that A2 is the best choice of ELV recycling business for the CA Company. Furthermore, the ranking orders by the proposed hybrid MCDM method show its high conformity with Rostamzadeh's method. However, it shows a little inconsistency with Shemshadi's approach, the last alternative of which is A1 instead of A3. The different considerations account for the reason why the decision results differ. Shemshadi's approach only integrated the Shannon entropy technique into the fuzzy VIKOR procedure, taking the criteria's objective weight into consideration, while Rostamzadeh's method only applied the fuzzy aggregation technique in the fuzzy VIKOR implementation taking the subjective weight of the criteria into account. However, the novel hybrid MCDM method in this research proposes the combined weight, integrating the fuzzy aggregation and Shannon entropy techniques into the FVIKOR procedure, and the degree of subjectivity consideration is controlled by parameter $\varphi\,(0 \leqslant \varphi \leqslant 1)$. The novel hybrid MCDM method shows the flexibility of the decision procedure by adjusting the parameter based on the preference of the decision-makers.

4.3. Sensitivity Analysis

In order to investigate the robustness of the hybrid MCDM method integrated with the fuzzy aggregation, entropy and FVIKOR techniques, a sensitivity analysis is performed in this section. In general, the sensitivity analysis is used to understand how the variation of input affects the output of the analytical framework. In this research, the sensitivity analysis on the relative importance of the decision-maker (Table 9), group utility weight (Table 10) and subjectivity weight φ (Table 11) has been conducted by varying the assumed weight value in several scenarios. The sensitivity analysis scenario setting on v and φ is based on the domain range of the parameter $v \, \epsilon \, [0,1]$, $\varphi \, \epsilon \, [0,1]$). The scale unit of v is 0.2 and the scale unit of φ is 0.1. The scenario setting of λ ($\lambda \, \epsilon \, [0,1]$) is based on the weight combination of the five decision-makers and we established the six scenarios based on the possible decision situations in CA Company. The most common scenario is that each decision-maker has the same weight. Based on this analysis, the experiment parameter settings can be seen in the following the three tables (Tables 9–11). The decision results and ranking order of the three alternatives in different scenarios are observed and addressed in the next section.

Table 9. Weight combinations of decision-makers (six scenarios).

	λ(S1)	λ(S2)	λ(S3)	λ(S4)	λ(S5)	λ(S6)
DM1	0.20	0.40	0.15	0.15	0.15	0.15
DM2	0.20	0.15	0.40	0.15	0.15	0.15
DM3	0.20	0.15	0.15	0.40	0.15	0.15
DM4	0.20	0.15	0.15	0.15	0.40	0.15
DM5	0.20	0.15	0.15	0.15	0.15	0.40

Table 10. The weight of the group utility setting (seven scenarios).

	SS1	SS2	SS3	SS4	SS5	SS6	SS7
v	0	0.2	0.4	0.5	0.6	0.8	1
$1-v$	1	0.8	0.6	0.5	0.4	0.2	0

Table 11. The different importance of subjective weight compared to objective weight (11 scenarios).

	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SC9	SC10	SC11
φ	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1

5. Results and Findings

This section aims at presenting the sensitivity analysis resulting from different experiment scenarios, and it presents the variation of the best choice and the ranking orders of other alternatives.

(1) Sensitivity analysis on the relative importance of the decision-makers (six scenarios for λ)

The λ represents the significance of the decision-makers, which possibly influences the selection result dramatically. The Q value and ranking order are explored based on the six weight allocation cases for the decision-makers in Figure 4.

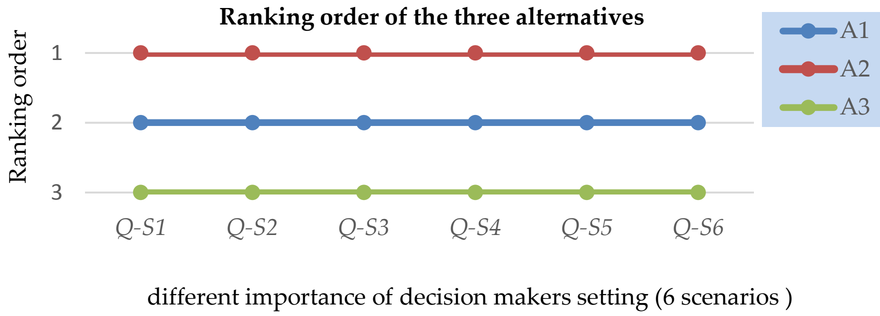


Figure 4. Sensitivity of the importance of decision-makers λ (six scenarios).

As can be seen from Figure 4, the best choice of ELV recycling service provider is always the alternative A2, no matter how the weight of the decision-makers is allocated. Furthermore, A1 and A3 then follow, which means the proposed hybrid MCDM method has a stable performance based on decision-making.

(2) Sensitivity analysis on the group utility weight (seven scenarios for v)

The group utility weight v has reflected the optimistic attitude and the Q value has been calculated in seven different scenarios (Table 12) whose ranking results can be seen in the Figure 5.

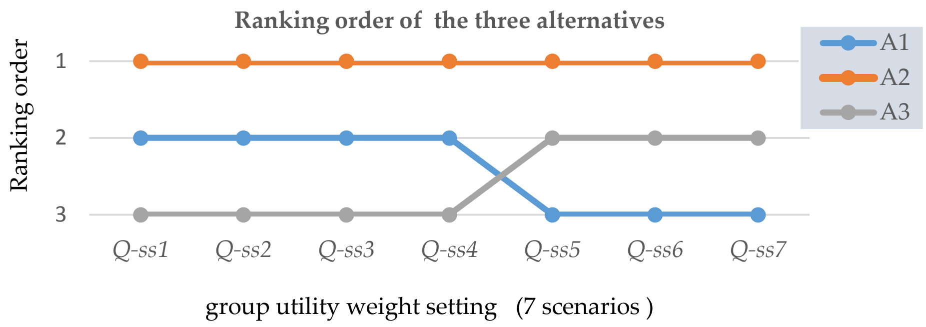


Figure 5. Sensitivity of the group utility weight v (seven scenarios).

Table 12. The Q value of different group utility weight settings.

Alternative	Q-SS1	Q-SS2	Q-SS3	Q-SS4	Q-SS5	Q-SS6	Q-SS7
A1	0.9356	0.9485	0.9613	0.9678	0.9742	0.9871	1
A2	0	0	0	0	0	0	0
A3	0.9774	0.9887	0.9774	0.9718	0.9662	0.9549	0.9436

The best candidate is A2 as calculated above, while the other two alternatives show a fluctuation with the varying of the v value. As can be seen, when the decision-makers pay more attention to group utility than to individual utility ($v \leqslant 0.5$), A1 shows its advantage over A3, and *vice versa*.

(3) Sensitivity analysis on the importance of subjective weight (11 scenarios for φ)

The subjectivity weight φ reflects the relative importance of subjectivity compared with the objectivity of decision-makers. When $\varphi = 0$ the decision-making problem only relies on the objective decision information, and $\varphi = 1$ means the obtained solution is based on the subjective cognition of decision-makers. Both of these situations cannot be seen as a rational decision method, which requires a combination of the φ value. The result of each alternative and the best choice obtained are presented in Figure 6.

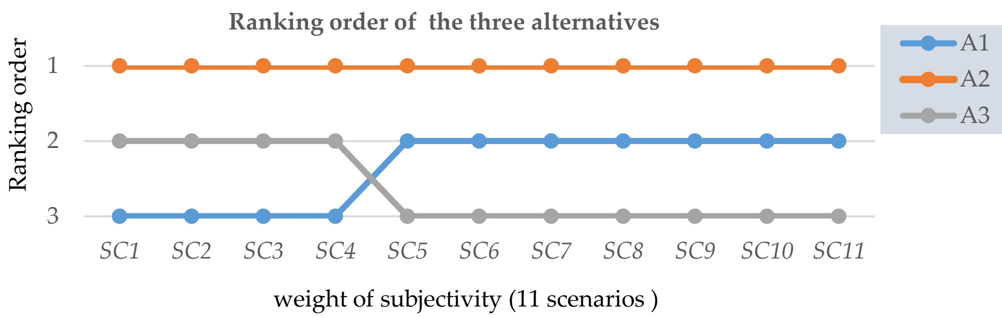


Figure 6. Sensitivity of the subjectivity weight φ (11 scenarios).

As Figure 6 illustrated, a similar fluctuation occurred in A1 and A3, while candidate A2 shows its stability with the top performance. Specifically, candidate A3 shows a better performance compared to A1 when the decision-making is obtained from the objective information ($\varphi \leqslant 0.4$), and the alternative A1 has a better performance when the subjectivity dominates.

From the above analysis, candidate A2 always shows the top priority regardless of the changes in the weight of the decision-makers, group utility and subjectivity. It indicates that alternative A2 is the best ELV recycling service provider by applying the proposed hybrid MCDM method.

6. Conclusions and Future Research

The present research takes economic, environmental and social merits into consideration when studying the ELV recycling service provider selection problem from the perspective of sustainability. The evaluation index system has been developed using the multi-criteria framework from three dimensions, namely the economic dimension, environmental dimension and social dimension. The three dimensions include four, five and four criteria, respectively, which are obtained from academic papers, practical interviews, expert recommendations and feasibility reports. Considering the vagueness and ambiguity of decision information, as well as the subjectivity and objectivity of decision-makers, the hybrid MCDM method integrating fuzzy aggregation, Shannon entropy and the FVIKOR technique has been employed to select the best ELV recycling service provider from all existing candidates. The weights and performances of all criteria were judged by the five groups of expert panels in the fields of automotive, economy, society, environment and the recycling industry. In addition, the relative importance of each decision-maker λ, the subjectivity weight φ and the group utility weight v, regarded as the decision parameters, have been analyzed for the best alternative selection. The computation result shows that alternative A2 should be selected as the best one for its stable top-ranking order. This paper not only illustrates the application procedure of the proposed hybrid MCDM method to ELV recycling service provider selection, but it conducts the sensitivity analysis on the three parameters illustrated above. The calculation results indicate A2 is always the best alternative no matter how the experiment parameters change, while the comprehensive scores of A1 and A3 show a slight fluctuation in different scenarios. The case implemented in this paper argues that the hybrid MCDM method is reasonably practical, effective and robust for the ELV recycling service provider selection problem. In addition, according to the preferences of practitioners, the integrated methodology would enable them to make decisions via adjusting the decision parameters.

7. Limitations and Scope for Future Research

It is worth mentioning that the weights of the criteria and even the established attributes probably need to be updated due to the variation of consideration and the preferences of decision-makers. Besides, the other weight calculation techniques such as the fuzzy ANP, DEA and BP neutral network could be employed to judge the considerable criteria. Other novel hybrid MCDM methods, including the integration of the fuzzy extended AHP, fuzzy TOPSIS and fuzzy ELECTRE, for ELV recycling service provider selection would be developed in a future study due to the limitation of the practical issue in mathematical models. In addition, the computation results from different hybrid MCDM methods would be compared, which promotes better interpretation of the criteria involved and determination procedures. Furthermore, the computer-based intelligent decision system would be explored to help implement the proposed integrated FVIKOR method. Furthermore, the dynamic decision-making and result analysis would be applied into practice via the man-machine interaction interface. Through computer-aided intelligent procedures, we can develop the sensitivity analysis on the combination of decision parameters under more established scenarios.

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