Sustainability **2015**, *7*, 15527-15547; doi:10.3390/su71115527

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Article

Identifying Critical Factors in the Eco-Efficiency of Remanufacturing Based on the Fuzzy DEMATEL Method

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Academic Editor: Matthias Finkbeiner

Received: 2 September 2015 / Accepted: 13 November 2015 / Published: 20 November 2015

Abstract: Remanufacturing can bring considerable economic and environmental benefits such as cost saving, conservation of energy and resources, and reduction of emissions. With the increasing awareness of sustainable manufacturing, remanufacturing gradually becomes the research priority. Most studies concentrate on the analysis of influencing factors, or the evaluation of the economic and environmental performance in remanufacturing, while little effort has been devoted to investigating the critical factors influencing the eco-efficiency of remanufacturing. Considering the current development of the remanufacturing industry in China, this paper proposes a set of factors influencing the eco-efficiency of remanufacturing and then utilizes a fuzzy Decision Making Trial and Evaluation Laboratory (DEMATEL) method to establish relation matrixes reflecting the interdependent relationships among these factors. Finally, the contributions of each factor to eco-efficiency and mutual influence values among them are obtained, and critical factors in eco-efficiency of remanufacturing are identified. The results of the present work can provide theoretical supports for the government to make appropriate policies to improve the eco-efficiency of remanufacturing.

Keywords: remanufacturing; eco-efficiency; fuzzy DEMATEL; end-of-life products

1. Introduction

In recent years, the manufacturing industry in China has been experiencing a boom. For example, in 2014, the production and sales of automobiles in China reached a volume of about 23 million, ranking first in the world [1]. Tremendous demand and sustainable growth of automobiles bring enormous end-of-life products, the disposal of which will result in resource waste and serious environmental pollution. One of the solutions to such problems is remanufacturing, which includes a series of processes like collecting, dismantling, cleaning, inspection classification, processing, assembly, machine testing, and packaging [2].

The remanufacturing industry in China is in the initial stage but its development is very rapid. For example, the output value of automotive parts remanufacturing reached 8 billion yuan in 2012, and the reuse rate of recycled parts was 71.2% [3]. Furthermore, remanufacturing industry, as an important role of green economy, has been included in the "China manufacturing 2025" strategy. Chinese government has formulated a series of policies, regulations and measures to promote it [4].

Compared with the manufacturing of new products, remanufacturing requires only 50% of the usual costs, and the consumption of energy and materials can be reduced to 60% and 70%, respectively [5], thus greatly declining environmental damages and promoting the recycling and reusing of resources.

As for eco-efficiency, which places emphasis on the compromise between economic benefits and environmental performance, its fundamental principle is to achieve maximal economic efficiency with minimal resource consumption and environmental disruption [6,7]. Consequently, research on eco-efficiency in remanufacturing will contribute to the solution of resources exhaustion and environmental failure and will push the construction of ecological civilization in China.

There are many factors that may affect the development of remanufacturing in China, including policy guidance, resource reserves like remanufacturing technology and equipment, and social acceptance of remanufactured products [8–10]. However, which factors exert significant influence on the eco-efficiency of remanufacturing, and how can the economic and environmental benefits of remanufacturing be achieved? These are crucial issues that should be addressed in order to realize sustainable remanufacturing and the circular economy in China.

Statistical approaches and expert evaluation methods have been applied to recognize critical factors in this complicated system. Nevertheless, remanufacturing in China is still in the preliminary stage of development. Due to the lack of sufficient samples on remanufacturing, some statistical methods (such as regression analysis and factor analysis) are very limited regarding the analysis of the eco-efficiency of remanufacturing. Furthermore, many traditional expert evaluation methods (such as Analytic Hierarchy Process, AHP) are based on the independence assumption, ignoring the interdependence and feedback among elements of the system. The ANP (Analytic Network Process) method can solve the interactions and feedback among elements, but it employs average methods to obtain the weighted super-matrix, and the results of assessed weights would be higher or lower than the real situation. Consequently, the treatments of inner dependences among factors are incomplete and imperfect [11,12]. DEMATEL (Decision Making Trial and Evaluation Laboratory) has been considered an effective way to handle the inner dependences within criteria. It can show the causal relationships as well as the influencing strength among elements by structural modeling techniques, and is thus suitable for identifying critical factors in complex system [11,13–18].

In this paper, a fuzzy DEMATEL method is proposed to analyze factors influencing the eco-efficiency of remanufacturing, which will be useful for the government to make suitable policies to regulate the remanufacturing market and guide the sustainable development of the remanufacturing industry in China.

2. Literature Review

2.1. Factors Influencing Remanufacturing

There are many factors affecting the development of remanufacturing. Zhang *et al*. [8] proposed crucial factors influencing automotive remanufacturing in China, and pointed out that different driver patterns should be exploited in different phases to improve the development of remanufacturing. Xia *et al*. [9] reported that shortage of funds for technology research, lack of tax incentives, and insufficient cores were the three most important barriers for automotive parts remanufacturers in China. Wei *et al*. [19] argued that the environmental and ethical responsibility, customer orientation, and strategic advantage brought by remanufacturing activities were the three main factors for Chinese remanufacturers to implement remanufacturing practices, and the low acknowledgement of recycled products by customer were the most serious barriers for remanufacturing in China. Yang *et al*. [20] analyzed factors affecting the eco-efficiency of remanufacturing on the basis of product design and the remanufacturing closed-loop supply chain. Abdulrahman *et al*. [21] and González *et al*. [22] made empirical analysis on critical elements of reverse logistics in Chinese manufacturing industry.

2.2. Evaluation on the Eco-Efficiency of Remanufacturing

Eco-efficiency involves economic and ecological benefits. Sabharwal and Garg [23] conducted an analysis on the economic viability of remanufacturing with the graph theoretic method and obtained the maximum and minimum value of remanufacturing cost benefits. Schau *et al*. [24] evaluated the cost of remanufactured alternators from the perspectives of remanufacturers with the LCC (Life Cycle Costing) method. Sundin and Lee [25] summarized the measuring methods for remanufacturing environmental performance. Kerr *et al*. [6] quantified eco-efficiency in remanufacturing through specific cases. Several researchers explored the impacts of remanufacturing on resources and the environment through different models [5,26,27]. Golinska and Kuebler [28] assessed the sustainability and maturity of remanufacturing enterprises from economic, environmental, and social dimensions. Quariguasi and Bloemh of [7] analyzed the eco-efficiency in the remanufacturing processes of electronic products. Rathore *et al*. [29] studied the sustainability of remanufacturing with a specific case in India.

2.3. The Application of DEMATEL Method in Identifying Important Factors

DEMATEL is a method for applying graph theories and matrix tools to examine elements in complicated and structural systems. In this method, essential elements are recognized through causal relationships among elements and the degree of importance that elements exert on the system target [9,16,17].

Xia *et al*. [9] and Zhu *et al*. [10] applied the grey-DEMATEL approach to identify barriers of remanufacturing in China from different perspectives. Falatoonitoosi *et al*. [30] proposed evaluation indicators about the green supply chain and then adopted DEMATEL to evaluate the greenness of suppliers. The DEMATEL method was also used to evaluate the green corporate social responsibility of manufacturing enterprises [31] and to analyze critical criteria for the decision making of an equity investment [18]. In order to reduce subjective bias in the DEMATEL method, fuzzy set theory has been introduced in this method. Zhou *et al*. [13] and Govindan *et al*. [14] respectively utilized the fuzzy DEMATEL approach to identify crucial success factors of emergency management and to evaluate the driving force of corporate social responsibility in the mining industry. Lin [15] made an assessment on green supply chain management considering supply chain management practices, organizational performance and external drivers based on the fuzzy DEMATEL approach. Chang *et al*. [32] investigated the critical elements on the performance evaluation of the supplier with the DEMATEL method, and provided a reference for decision-making in supplier selection.

2.4. Gap Analysis and Research Highlights

From the literature review above, many studies focus on the analysis or evaluation of remanufacturing benefits, and it has been demonstrated that remanufacturing can yield tremendous benefits, drawing more people to participate in the remanufacturing industry. However, little effort has been made to investigate critical factors affecting the eco-efficiency of remanufacturing. Some early studies examined factors of remanufacturing, but without considering the eco-efficiency of remanufacturing. The DEMATEL method has been employed in the evaluation of green performance in different fields; however, it is rarely utilized in the remanufacturing field. To the best of our knowledge, there has been no research report on its application in the identification of curial factors in remanufacturing eco-efficiency.

To fill this gap, our study proposes a set of factors influencing the eco-efficiency of remanufacturing. Considering factors are unequal and independent, a fuzzy DEMATEL method is adopted to examine remanufacturing eco-efficiency from the perspective of multi-level and causal relationships. By exploring the contribution of each factor on eco-efficiency and interdependence relationships among factors, critical factors are obtained to improve the eco-efficiency of remanufacturing.

3. Factors regarding the Eco-Efficiency of Remanufacturing

With a focus on remanufacturing enterprises, the internal and external factors influencing the eco-efficiency of remanufacturing are proposed, and indicators regarding eco-efficiency are selected from economic and environmental dimensions. Table 1 shows 15 factors influencing remanufacturing eco-efficiency and nine indicators reflecting the eco-efficiency. The number in brackets in the table indicates the referenced document.

Table 1. Factors regarding remanufacturing eco-efficiency.

Dimensions	Factors	Dimensions	Factors
Internal factors	F1. Quantity of cores [9,10]	*External factors*	F10. Design for remanufacturing [16,21,30]
	F2. Quality of cores [8,16]		F11. OEMs information sharing [8,16,33]
	F3. Recycling system [9,23]		F12. Policy guidance [8,10,19,21,34–36]
	F4. Information system [9,16,22]		F13. Laws and regulations system [15,19,21,33]
	F5. Quality management [10,28]		F14. Standards of remanufacturing industry [9,37]
	F6. Pollution control [28]		F15. Social awareness of recycling and remanufacturing [8,21,22]
	F7. Remanufacturing equipment [9,21]		
	F8. Key remanufacturing technology [2,8,37]		
	F9. Remanufacturing technology R&D [10,38]		
Economic benefits	G1. Cost saving [23,28,38,39]	*Environmental benefits*	G5. Emission reduction [14,15,25,26]
	G2. Remanufacturing profits [26,28]		G6. Compliance rate of waste discharge [40]
	G3. Market occupancy [15,19,26]		G7. Recycle and reuse rate of end-of-life products [23,39]
	G4. Green image of corporation [14,28]		G8. Resources conservation [15,27,38]
			G9. Resource efficiency [28,38,40]

3.1. Factors Affecting the Eco-Efficiency of Remanufacturing

3.1.1. Internal Factors

F1: quantity of cores (used or discarded products which are the raw material of remanufactures). It is a fundamental guarantee for implementing remanufacturing practices. An insufficient number of cores is a critical barrier for remanufacturers in China [9,10]. Therefore, this factor should be considered in the eco-efficiency of remanufacturing.

F2: quality of cores. It represents mainly the remanufacturing ratio of cores, which has a great impact on the eventual reuse rate of cores [8].

F3: construction of a recycling system. It involves many bodies in recycling processes such as the owners of cores and recyclers, and it includes the establishment of recycling channels and reverse logistics systems. A completed recycling system improves the effective classification management of recycled products and makes the collection capacity coordinate with the remanufacturing scale [23].

F4: establishment of an information system. It contains information during a series of processes like scrapping end-of-life products, collecting, transport, disassembly, remanufacturing, storage, and final disposal, as well as information about stakeholders in these procedures, such as original manufacturers, core owners, recyclers, and remanufacturers [9,16,22].

F5: quality management. Quality management is not only to make products satisfy the quality standards and to ensure product safety and reliability, but also to make the remanufacturing process more economic and environmental [10]. Therefore, quality management has a direct impact on consumer decision-making and economic benefits of remanufacturers [28].

F6: pollution control. The environmental contamination during recycling and remanufacturing processes is controlled through advanced equipment, technologies, and other measures in order to reduce emissions and achieve cleaner production [28].

F7: remanufacturing equipment. It is the basis for implementing remanufacturing activities and reflects, to some extent, the capacity of the remanufacturing system [9,21].

F8: critical remanufacturing technology. It includes technology such as residual service-life prediction, nondestructive testing, economical and environment-friendly disassembly, cleaning and repairing *etc*. [2,8]. Sophisticated remanufacturing technology ensures quality of remanufactured products and the recovery and reuse rate of cores [37].

F9: remanufacturing technology research and development. Zhu *et al*. [10] and Jiang *et al*. [38] assumed that in sufficient technology research and development is an essential internal barrier for remanufacturers in China. In addition, research and development capability heavily depends on research funds and remanufacturing professionals.

3.1.2. External Factors

F10: Design for remanufacturing (DFR). It means design concepts that promote the remanufacture and reuse of end-of-life products at the beginning of the product life cycle, namely designing for disassembly, utilization of renewable or recycled materials, and exploiting remanufacturing labeling, *etc.* [16,21,30].

F11: Original Equipment Manufacturers (OEMs) information sharing. It includes the sharing of product material information, such as the material type and its purity, and whether the material is recyclable or not. Information sharing facilitates recyclers or remanufacturers to deal with precious metals and toxic materials properly and to improve the recycling rate of cores [8,16,33].

F12: policy guidance. The policies that exert influences on remanufacturing can be classified into two categories: financial incentives and restrictive policies. The former mainly includes subsidies and tax preferences for remanufacturing practices [21,34–36], while the latter includes authorization of components/products that can be recycled or remanufactured, and the permission of remanufacturers entering remanufacturing market [8,10,19]. Restrictive policies reduce the recovery and reuse ratio of cores and limit the scale of remanufacturers, while the reasonable policy guide is essential for stakeholders to achieve their own benefits.

F13: establishment and improvement of laws and regulatory systems. It includes laws and regulations that directly related with the recycling and remanufacturing of end-of-life products, and those related with the environment or circular economy that have an indirect impact on recycling and remanufacturing, and laws and regulations clearly defining the conception of extended producer responsibility and the scope of intellectual property rights [15,19,21,33].

F14: standards of the remanufacturing industry. It contains remanufacturing technology standards, quality inspection standards, remanufacturing product certification standards, *etc.* Xu *et al*. [37] argued that strict industry standards should be established for the rapid development of the remanufacturing industry in China.

F15: social awareness of recycling and remanufacturing. It includes the recycling perception, the cognition of remanufacturing benefits and the recognition of remanufactured products of stakeholders such as core owners, OEMs, remanufacturers, the government, and remanufactured product purchasers [8,21,22].

3.2. Indicators on Eco-Efficiency of Remanufacturing

The eco-efficiency of remanufacturing is mainly embodied in two aspects: one is the cost saving brought by the reduction in energy and resources and the profits created by remanufacturing activities; the other is that remanufacturing achieves the recycling of resources and lowers waste emissions and resource consumption, lessening the negative impact on the environment [20].

3.2.1. Economic Benefits

Economic benefits of remanufacturing are mainly reflected in costs and revenues. The former includes the expenditure on collecting cores (such as information and logistics costs, fees paid to the owners of cores), costs in remanufacturing procedures such as resources, costs, and operating costs. It also contains environmental expenses on disposal of waste [23,28,38,39]. Revenues consist of profits, market occupancy, and indirect revenues yielded by the green image of the corporation [14,15,19,23,26,28]. Economic benefits here are reflected through indicators of cost saving, remanufacturing profits, market occupancy, and the green image of the corporation.

3.2.2. Environmental Benefits

Environmental benefits are expounded through impacts of emissions on the environment and resource utilization in the remanufacturing processes [20,26]. Emissions include gas waste, liquid waste, and solid waste in the remanufacturing processes [14,15,25]. Waste emissions, waste disposal and the eventual compliance rate of waste discharge can be used to determine whether the main factor affecting environmental performance is emissions or processing capacity [40]. Impacts of remanufacturing on resources are mainly reflected in two aspects: one is resource recycling brought by remanufacturing end-of-life products, the other is resource conservation and resource efficiency during remanufacturing processes [15,23,27,28,38–40]. Therefore, indicators of emission reduction, compliance rates of waste discharge, the recycle and reuse rate of end-of-life products, resource conservation and resource efficiency are chosen as a representation of economic performance.

4. Application of the Fuzzy DEMATEL Method in the Eco-Efficiency of Remanufacturing

In most cases, the DEMATEL method directly adopts crisp values to assess the degree of influence among elements, which ignores the fact that experts generally make fuzzy linguistic assessments according to their experience instead of crisp value evaluation [13,32]. To reduce uncertainty in the subjective evaluation by experts, this paper introduces fuzzy theory in the DEMATEL method to analyze elements influencing the eco-efficiency of remanufacturing. Specific steps are shown as follows:

Step 1: based on the factors above, 24 factors affecting the eco-efficiency of remanufacturing are determined, represented by the set $S = \{s_1, s_2, \ldots s_{24}\}$. To make an assessment on interdependent relationships among these factors, a consultative group of experts is established, which consists of four academic experts in remanufacturing research and three senior management staff serving in a remanufacturing enterprise. This enterprise mainly engages in the manufacture and research of construction engineering, environmental engineering, and infrastructure such as agricultural machinery. It is also one of the "demonstration remanufacturers of construction machinery" released by the Ministry of Industry and Information Technology in China.

Step 2: the relationship between factors is measured with five linguistic terms including "no influence", "very low influence", "low influence", "high influence" and "very high influence", denoted as 0,1,2,3 and 4, respectively. According to the suggestion of the consultative group of experts, a direct-relation matrix reflecting the direct relationship among factors can be attained, as shown in Table 2.

Table 2. Direct-relation matrix of factors.

	F1	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**	**F9**	**F10**	**F11**	**F12**	**F13**	**F14**	**F15**	**G1**	**G2**	**G3**	**G4**	**G5**	**G6**	**G7**	**G8**	**G9**
F1	0	0	3	2	3	2	3	2	2	0	0	3	2	0	2	4	3	2	1	2	0	0	3	3
F2	0	0	1	1	3	0	0	3	0	3	0	2	0	0	0	3	4	1	0	3	1	3	3	0
F3	4	3	0	3	0	0	2	0	0	0	0	2	0	0	0	4	3	0	3	0	0	2	1	1
F4	3	2	4	0	3	2	0	3	2	0	2	2	3	1	0	3	3	2	0	3	2	3	3	2
F5	0	0	0	3	0	3	0	2	1	2	2	1	2	4	4	4	4	3	4	3	2	2	2	2
F6	0	0	0	0	2	0	2	2	2	3	2	2	3	3	0	2	2	0	4	4	3	0	3	2
F7	0	0	0	0	2	1	0	2	1	0	0	1	0	0	0	3	1	0	0	2	1	2	1	3
F8	0	2	3	2	4	3	3	0	3	3	2	3	2	3	0	4	3	3	2	3	2	4	3	3
F9	0	1	0	0	0	0	2	4	0	2	0	2	0	0	0	3	1	1	2	2	1	3	3	3
F10	0	4	0	2	3	3	0	2	2	0	3	3	2	3	0	4	1	1	3	3	1	4	3	2
F11	0	3	0	4	4	4	0	3	3	4	0	3	4	2	2	3	2	0	2	3	1	3	3	2
F12	4	3	2	3	2	2	3	4	3	3	3	0	3	3	4	4	2	3	3	3	2	3	3	1
F13	3	1	2	0	3	3	0	1	0	4	4	3	0	4	3	2	0	1	2	4	3	4	2	0
F14	0	0	0	0	4	3	1	4	4	2	3	3	2	0	1	2	1	2	3	4	1	2	3	2
F15	4	3	2	2	4	0	0	2	2	3	3	3	2	2	0	3	1	3	3	2	1	1	2	2
G1	2	2	2	2	0	0	1	2	2	2	1	0	0	0	0	0	4	3	3	1	0	3	3	2
G2	1	1	0	0	2	0	0	0	0	0	0	2	0	0	0	3	0	2	0	0	0	2	0	2
G3	0	0	0	1	2	0	0	0	0	0	0	2	0	0	1	0	3	0	1	0	0	0	0	0
G4	3	2	0	0	3	3	0	1	2	2	1	0	0	0	1	3	3	3	0	3	3	1	2	1
G5	0	0	0	0	1	3	1	2	2	1	0	0	2	1	0	2	1	0	4	0	4	0	3	0
G6	0	0	0	0	1	2	1	0	2	0	0	1	2	0	2	2	1	2	4	3	0	0	0	0
G7	0	1	0	2	2	0	2	2	3	2	2	2	0	1	0	4	3	2	3	3	1	0	4	2
G8	0	0	0	0	2	0	1	2	1	2	2	1	0	0	0	4	3	3	3	4	2	0	0	2
G9	0	0	0	0	2	0	2	2	2	0	0	0	0	0	0	3	3	0	3	3	1	0	4	0

Step 3: converting vague language into triangular fuzzy numbers. According to Karsak and Tolga [41], triangular fuzzy numbers can effectively quantify the uncertainty of complicated systems with simple calculations, and are thus utilized in this paper to deal with linguistic evaluation. A set of triangular fuzzy numbers is set a as A (m, n, r), in which m and r respectively denote the lower and upper limits of fuzzy value, n is the most possible value. The membership function $u_A(x)$ is defined as follow:

$$u_A(x)\begin{cases}\frac{x-m}{n-m};\ (m<x<n)\\ \frac{x-r}{n-r};\ (n<x<r)\\ 0;\ \text{the rest}\end{cases}$$

where, $0 \le u_A(x) \le 1$, m, n and r are real numbers

With it, the linguistic evaluations can be converted into triangular fuzzy numbers, as shown in Table 3.

Table 3. Fuzzy linguistic scale.

Linguistic Evaluation	Influencing Numbers	Triangular Fuzzy Numbers
Very high influence	4	(0.7,0.9,1.0)
High influence	3	(0.5,0.7,0.9)
Low influence	2	(0.3,0.5,0.7)
Very low influence	1	(0.1,0.3,0.5)
No influence	0	(0,0.1,0.3)

Step 4: Fuzzifying the direct-relation matrix

Due to the simplicity of the centroid method and the fact that it unnecessarily considers the preference of decision-makers [42], it is employed in this paper to transform triangular fuzzy numbers into crisp values. Equation (1) shows the centroid method, where f represents the obtained crisp value, and r, m, n denote the parameters in the triangular fuzzy number A defined in Step 3. After the defuzzification of the linguistic evaluation, a matrix is constructed, where y_{ij} represents the transformation value of the direct impact that factor y_i exerts on factor y_j.

$$f = \frac{(r-m)+(n-m)}{3} + m \tag{1}$$

Step 5: Normalizing the matrix Y. The normalized direct-relation matrix is determined by Equation (2), where $0 < b_{ij} < 1$. With Equation (2), at least rows or columns in matrix Y can be standardized, so that the calculation accuracy can be improved [17].

$$B = \frac{Y}{\max\left(\max\sum_{i=1}^{n} y_{ij}, \max\sum_{j=1}^{n} y_{ij}\right)} \tag{2}$$

Step 6: Calculating the total relation matrix. The total relation matrix $T = B + B^2 + B^3 + \ldots + B^n$ reflects the indirect relationship between elements. T can be calculated with Equation (3)

$$T = (t_{ij})_{n\times n} = \sum_{i=1}^{\infty} B^i = B(E - B)^{-1} \quad (3)$$

where E represents the unit matrix, and t_{ij} denotes the indirect influence of t_i on t_j.

To simplify the process of identifying critical factors, it is necessary to set a threshold value to eliminate minor influence values and remain larger ones. Generally, threshold value is obtained by the value of average or the value of it plus standard deviation of the total-relation matrix [9,10,16]. Owing to the large number of factors in this paper, a relatively high threshold value (sum of the average and the standard deviation) is set to cope with influence values in matrix T [9]. Thus, the threshold value equals 0.101170. Values greater than the threshold are represented in bold, and the total relation matrix is obtained and shown in Table 4.

Step 7: Calculating the sum of each row and the sum of each column in matrix T. Let R be the sum of rows in matrix T, and D be the sum of columns calculated with Equations (4) and (5), respectively. The value of R_i denotes both the direct and indirect influence that factor i exerts on other factors, while D_j indicates the total direct and indirect effect that factor j receives from the others. Fori = j, $(R_i + D_i)$ represents the prominence of a factor in remanufacturing eco-efficiency, and the value has a positive correlation with prominence. In addition, the value of $(R_i - D_i)$ indicates the net impact of the factor on remanufacturing eco-efficiency. Final results are presented in Table 5.

$$R = (R_i)_{n\times 1} = \left(\sum_{j=1}^{n} t_{ij}\right)_{n\times 1} \quad (4)$$

$$D = (D_j)'_{1\times n} = \left(\sum_{i=1}^{n} t_{ij}\right)'_{1\times n} \quad (5)$$

Table 4. Total-relation matrix of factors affecting remanufacturing eco-efficiency.

	F1	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**	**F9**	**F10**	**F11**	**F12**	**F13**	**F14**	**F15**	**G1**	**G2**	**G3**	**G4**	**G5**	**G6**	**G7**	**G8**	**G9**
F1	0.0462	0.0479	0.0756	0.0699	0.1010	0.0748	0.0803	0.0849	0.0794	0.0569	0.0497	0.0912	0.0698	0.0474	0.0635	**0.1297**	**0.1066**	0.0814	0.0824	0.0958	0.0525	0.0609	**0.1060**	0.0919
F2	0.0370	0.0418	0.0445	0.0519	0.0915	0.0463	0.0385	0.0875	0.0499	0.0836	0.0434	0.0712	0.0412	0.0416	0.0348	**0.1073**	**0.1062**	0.0619	0.0622	0.0972	0.0552	0.0875	0.0957	0.0485
F3	0.0826	0.0736	0.0346	0.0730	0.0539	0.0415	0.0590	0.0503	0.0460	0.0444	0.0384	0.0676	0.0373	0.0352	0.0324	**0.1122**	0.0933	0.0479	0.0881	0.0578	0.0405	0.0711	0.0677	0.0561
F4	0.0829	0.0742	0.0890	0.0527	**0.1081**	0.0813	0.0504	**0.1029**	0.0857	0.0636	0.0765	0.0862	0.0873	0.0622	0.0453	**0.1284**	**0.1140**	0.0865	0.0804	**0.1163**	0.0798	**0.1013**	**0.1140**	0.0841
F5	0.0503	0.0543	0.0443	0.0863	0.0783	0.0964	0.0483	0.0930	0.0773	0.0882	0.0802	0.0755	0.0777	0.0984	0.0898	**0.1386**	**0.1239**	**0.1016**	**0.1270**	**0.1194**	0.0824	0.0901	**0.1039**	0.0855
F6	0.0433	0.0478	0.0381	0.0455	0.0910	0.0578	0.0666	0.0859	0.0822	0.0937	0.0737	0.0793	0.0839	0.0834	0.0420	**0.1071**	0.0914	0.0588	**0.1191**	**0.1219**	0.0899	0.0614	**0.1070**	0.0785
F7	0.0294	0.0321	0.0276	0.0325	0.0667	0.0465	0.0321	0.0649	0.0505	0.0389	0.0337	0.0477	0.0326	0.0326	0.0281	0.0907	0.0587	0.0400	0.0498	0.0723	0.0464	0.0631	0.0595	0.0735
F8	0.0541	0.0822	0.0822	0.0815	**0.1297**	**0.1025**	0.0905	0.0804	**0.1084**	**0.1073**	0.0854	**0.1067**	0.0824	0.0942	0.0507	**0.1527**	**0.1253**	**0.1078**	**0.1155**	**0.1302**	0.0888	**0.1222**	**0.1268**	**0.1058**
F9	0.0355	0.0504	0.0332	0.0390	0.0558	0.0442	0.0613	0.0967	0.0493	0.0701	0.0413	0.0687	0.0386	0.0387	0.0326	**0.1047**	0.0698	0.0595	0.0822	0.0843	0.0542	0.0851	0.0951	0.0820
F10	0.0487	0.0990	0.0442	0.0761	**0.1127**	0.0974	0.0504	0.0965	0.0905	0.0688	0.0928	0.0996	0.0780	0.0896	0.0465	**0.1415**	0.0927	0.0774	**0.1183**	**0.1228**	0.0718	**0.1150**	**0.1197**	0.0860
F11	0.0544	0.0948	0.0495	**0.1029**	**0.1307**	**0.1137**	0.0546	**0.1152**	**0.1082**	**0.1197**	0.0653	**0.1070**	**0.1064**	0.0847	0.0730	**0.1416**	**0.1109**	0.0736	**0.1143**	**0.1315**	0.0781	**0.1129**	**0.1276**	0.0926
F12	**0.1049**	0.1008	0.0776	0.0995	**0.1185**	0.0975	0.0951	**0.1323**	**0.1155**	**0.1151**	**0.1037**	0.0812	0.1012	0.0994	0.0996	**0.1629**	**0.1209**	**0.1156**	**0.1338**	**0.1390**	0.0943	**0.1195**	**0.1355**	0.0889
F13	0.0850	0.0666	0.0670	0.0565	**0.1148**	0.1003	0.0514	0.0842	0.0704	**0.1135**	**0.1048**	**0.1026**	0.0590	**0.1019**	0.0834	**0.1211**	0.0812	0.0779	**0.1097**	**0.1334**	0.0961	**0.1140**	**0.1075**	0.0648
F14	0.0468	0.0527	0.0421	0.0521	**0.1199**	0.0967	0.0599	**0.1154**	**0.1106**	0.0889	0.0909	0.0977	0.0770	0.0548	0.0561	**0.1163**	0.0883	0.0872	**0.1169**	**0.1293**	0.0708	0.0899	**0.1158**	0.0851
F15	0.0960	0.0907	0.0689	0.0787	**0.1241**	0.0640	0.0508	0.0958	0.0896	**0.1016**	0.0922	**0.1017**	0.0787	0.0774	0.0485	**0.1330**	0.0938	**0.1026**	**0.1174**	**0.1090**	0.0701	0.0814	**0.1067**	0.0870
G1	0.0607	0.0648	0.0574	0.0635	0.0596	0.0455	0.0496	0.0762	0.0723	0.0710	0.0522	0.0507	0.0400	0.0390	0.0338	0.0744	**0.1084**	0.0859	0.0948	0.0739	0.0448	0.0874	0.0969	0.0724
G2	0.0382	0.0400	0.0258	0.0308	0.0626	0.0320	0.0287	0.0384	0.0358	0.0351	0.0308	0.0570	0.0294	0.0294	0.0269	0.0844	0.0445	0.0591	0.0434	0.0440	0.0314	0.0593	0.0439	0.0570
G3	0.0265	0.0274	0.0234	0.0374	0.0591	0.0299	0.0249	0.0338	0.0314	0.0313	0.0283	0.0541	0.0276	0.0274	0.0352	0.0446	0.0726	0.0330	0.0478	0.0389	0.0290	0.0333	0.0374	0.0310
G4	0.0727	0.0646	0.0354	0.0426	0.0952	0.0835	0.0406	0.0663	0.0746	0.0740	0.0541	0.0521	0.0442	0.0427	0.0477	**0.1102**	0.0997	0.0880	0.0662	**0.1014**	0.0823	0.0634	0.0870	0.0614
G5	0.0343	0.0367	0.0305	0.0347	0.0623	0.0783	0.0454	0.0701	0.0681	0.0561	0.0396	0.0440	0.0603	0.0477	0.0325	0.0867	0.0641	0.0465	**0.1019**	0.0595	0.0880	0.0464	0.0892	0.0439
G6	0.0338	0.0347	0.0288	0.0330	0.0580	0.0621	0.0421	0.0443	0.0638	0.0422	0.0361	0.0506	0.0574	0.0347	0.0531	0.0803	0.0595	0.0645	0.0964	0.0870	0.0397	0.0425	0.0505	0.0396
G7	0.0421	0.0572	0.0381	0.0679	0.0879	0.0529	0.0656	0.0845	0.0917	0.0784	0.0703	0.0770	0.0462	0.0552	0.0390	**0.1273**	**0.1047**	0.0805	**0.1045**	**0.1071**	0.0619	0.0598	**0.1152**	0.0782
G8	0.0362	0.0405	0.0325	0.0395	0.0781	0.0464	0.0470	0.0735	0.0590	0.0697	0.0627	0.0566	0.0402	0.0392	0.0344	**0.1135**	0.0941	0.0839	0.0950	**0.1052**	0.0669	0.0504	0.0590	0.0690
G9	0.0321	0.0346	0.0290	0.0336	0.0707	0.0398	0.0557	0.0678	0.0648	0.0419	0.0357	0.0402	0.0342	0.0337	0.0297	0.0961	0.0870	0.0445	0.0873	0.0884	0.0502	0.0439	0.0963	0.0424

Note: Figures in bold represent the influence values greater than the threshold (0.101170).

Table 5. Calculation results of the fuzzy DEMTEL.

Factors	R	D	R + D	R − D
F1: Quantity of cores	1.8456	1.2737	3.1193	0.5719
F2: Quality of cores	1.5265	1.4094	2.9359	0.1171
F3: Recycling system	1.4046	1.1192	2.5238	0.2854
F4: Information system	2.0532	1.3810	3.4341	0.6722
F5: Quality management	2.1106	2.1303	4.2409	−0.0197
F6: Pollution control	1.8494	1.6310	3.4804	0.2183
F7: Remanufacturing equipment	1.1502	1.2888	2.4390	−0.1386
F8: Key remanufacturing technology	2.4136	1.9408	4.3544	0.4728
F9: Remanufacturing technology R&D	1.4722	1.7752	3.2474	−0.3030
F10: DFR	2.1360	1.7541	3.8901	0.3818
F11: OEMs information sharing	2.3632	1.4817	3.8450	0.8815
F12: Policy guidance	2.6523	1.7662	4.4185	0.8862
F13: Laws and regulations system	2.1671	1.4306	3.5977	0.7365
F14: Standards of remanufacturing industry	2.0612	1.3906	3.4517	0.6706
F15: Social awareness of remanufacturing	2.1596	1.1585	3.3181	1.0010
G1: Cost saving	1.5753	2.7052	4.2804	−1.1299
G2: Remanufacturing profits	1.0080	2.2118	3.2198	−1.2039
G3: Market occupancy	0.8652	1.7658	2.6310	−0.9006
G4: Green image of corporation	1.6500	2.2545	3.9045	−0.6046
G5: Emission reduction	1.3667	2.3656	3.7323	−0.9990
G6: Compliance rate of waste discharge	1.2346	1.5653	2.7999	−0.3307
G7: The recycle and reuse rate of end-of-life products	1.7934	1.8618	3.6552	−0.0685
G8: Resources conservation	1.4925	2.2638	3.7562	−0.7713
G9: Resource efficiency	1.2798	1.7054	2.9852	−0.4256

Step 8: Constructing a casual diagram

With R + D being the horizontal axis, and R − D the vertical axis, a causal diagram is constructed to analyze the importance of each factor to remanufacturing eco-efficiency (Figure 1). When the factor is located above the horizontal axis, namely its value of R-D is positive, it means that the effect of this factor exerted on other factors is greater than that received from others. So the factor is a net causer and is then classified in the cause cluster. In contrast, when the value of R-D is negative, the factor is a net receiver and is then grouped in the effect cluster. Effect factors are affected by cause factors, influencing it the manufacturing eco-efficiency directly.

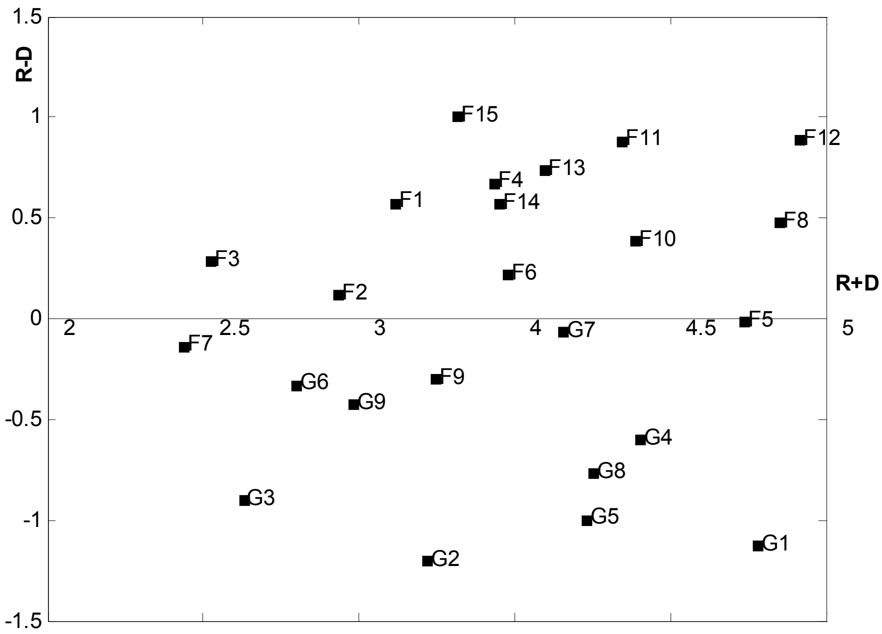

Figure 1. The causal diagram.

5. Analysis on the Factors Affecting the Eco-Efficiency of Remanufacturing

5.1. Identifying Critical Factors

Generally, the values of (R + D) and (R − D) are used to examine the degree of importance of each factor on the system objective and the interdependence among factors. But these two parameters alone will likely lead to analysis results that are not consistent with the practical situation. Therefore, the value of R and D should be considered when critical elements are determined, in order to synthesize the impact of elements on system goals [9,16]. Specific analysis will be made in the following sections in accordance with Table 5 and Figure 1.

5.1.1. Cause Cluster

Social awareness of remanufacturing is shown to have the highest value of (R − D), which means that this factor is the primary causal criterion. In addition, the fifth ranking of R score and the relatively low ranking of D value indicate that the impact these factors are exerting on others is great while the effect it receives is minuscule. Consequently, social awareness of remanufacturing plays a leading role in the system.

Policy guidance is the second causal factor and its values of (R + D) and R are both on the top of all factors, indicating that policy guidance is of considerable significance to remanufacturing eco-efficiency.

OEMs information sharing is shown to have great effects on the target, with the comparatively top-ranking (R + D) and the third position of both (R − D) and R scores.

The laws and regulations system ranks fourth in both (R − D) and R values, which means this factor affects remanufacturing eco-efficiency mainly through causal relationships with others, exerting leading effects among other factors.

The information system factor has a fifth position in (R − D) values and a lower ranking of (R + D) and a medium R score, indicating that it has a comparatively small contribution to remanufacturing eco-efficiency and the degree of total influence on others is moderate. Thus, it cannot be recognized as a critical element. Similarly, standards of the remanufacturing industry and quantity of cores are not meaningful factors either.

Critical remanufacturing technology is demonstrated to be a net causer with the (R − D) value of 0.473. Furthermore, its (R + D) and R values rank second, indicating the contribution of this factor on eco-efficiency is considerable and the impact it is exerting on others is significant. Therefore remanufacturing technology can greatly contribute to the eco-efficiency of remanufacturing.

DFR have scores of (R + D), (R − D) and R ranking fourth among all factors, which illustrates that the degree of significance, the net effect on eco-efficiency, and the impact on other factors are all comparatively large. Therefore the DFR factor cannot be ignored in the analysis of important criteria of remanufacturing eco-efficiency.

Recycling system, pollution control, quality of recycled products, and other factors are placed in the cause group, providing some impact on the eco-efficiency of remanufacturing, but scores of (R − D) are relatively small, which indicates their net effects on eco-efficiency are limited. In addition, scores of (R + D) and R are not large. So these factors are not considered important.

5.1.2. Effect Cluster

The effect group is generally viewed as results from cause factors, so it is inappropriate to recognize them as significant criteria. However, there exist some special cases in which effect factors make great contributions to a system objective. As a consequence, an in-depth analysis should be made for effect factors to identify critical factors on remanufacturing eco-efficiency.

Quality management: With the (R − D) value slightly less than 0, the fourth ranking of (R + D) and a comparatively high value of R, quality management is slightly influenced by causal factors, but its significance to remanufacturing eco-efficiency is great. The impact of quality management cannot therefore be neglected when analyzing eco-efficiency of remanufacturing.

As for cost saving, although it has the third ranking of (D + R) score, its (R − D) is far less than zero and the D value is largest, meaning cost saving has a great contribution to remanufacturing eco-efficiency, but it can be easily influenced by other factors. For the same reason, the green image of a corporation is not the critical factor. But considering their prominence in the eco-efficiency of remanufacturing, it is necessary to conduct a further study on elements affecting these criteria, reversely reasoning crucial criteria that affect the eco-efficiency of remanufacturing. Accordingly, their great indirect effect can be fully achieved. With regard to the recycle and reuse rate of end-of-life products, its scores of (R − D), (R + D), R are −0.0685, 3.655 and 1.793 respectively, all of which are not high, so it cannot be classified as one of the critical factors. Similarly, other factors in the effect cluster are not essential to the eco-efficiency of remanufacturing.

5.2. Further Analysis on the Critical Factors

From previous analysis, seven crucial criteria which affect the eco-efficiency of remanufacturing are identified, which include six cause factors and one effect factor, namely, policy guidance, social awareness of remanufacturing, OEMs information sharing, laws and regulations system, critical remanufacturing technology, DFR, and quality management.

Regarding the social awareness of remanufacturing, the increasing remanufacturing awareness impels the government to develop appropriate incentive policies and legislations to regulate and guide behaviors of the remanufacturing stakeholders [8]. Meanwhile, the cognition of remanufacturing makes more remanufacturers enter the market to undertake remanufacturing activities. They adopt advanced technology to enhance the recovery and reuse ratio of cores, and exploit clean materials to realize the clean production during remanufacturing processes, while taking account of the environmental benefits while in pursuit of economic interests [9]. In addition, the perception and recognition of remanufacturing also actuate OEMs to design for remanufacturing and share their information to help other remanufacturers to implement remanufacturing businesses [27]. With respect to consumers, on one hand, as owners of cores, recycling consciousness motivates them to actively scrap end-of-life products, improving the recovery rate of these products; on the other hand, recognition of remanufactured products pushes consumers to make purchasing decisions, so the value of remanufactured products can be realized. Public awareness prompts remanufacturing stakeholders to join the remanufacturing industry with an active attitude and ensure the realization of remanufacturing eco-efficiency [19].

Policy guidance: at present, the remanufacturing in China is still at the primary stage, accompanied with many barriers for realizing remanufacturing eco-efficiency. Chang *et al.* [35] argued that appropriate police guidance is required to conduct behaviors of stakeholders and promote the sustainable remanufacturing. For example, financial subsidies or tax breaks should be provided for customers who scrap end-of-life products or purchase remanufactured products, for the enterprises that engage in recycling and remanufacturing activities or adopt environmentally friendly materials and technology, and for OEMs because of its DFR or information sharing [8,14]. Meanwhile, reasonably loosening restrictions on remanufactured products and allowing more qualified remanufacturers to enter the remanufacturing market will promote the prosperity of the remanufacturing market [21].

OEMs information sharing: Du *et al.* [27] emphasized the importance of OEMs in remanufacturing practices. Information sharing promotes OEMs to design for remanufacturing, decreasing impacts on environment in the design phase; Besides, it helps remanufacturers choose appropriate techniques to remanufacture end-of-life products and make a reasonable decision on the disposal of these products. OEMs own intellectual property rights of original products and have a precise understanding of product structure, material composition, and the adopted technical standards, *etc.* [16]. Therefore, once OEMs limit the remanufacturing activities of remanufacturers through intellectual property rights, the recycling of discarded products will be directly affected and the economic and environmental benefits of remanufacturing will be difficult to achieve.

Laws and regulations system: in the current recycling market in China, a considerable quantity of end-of-life products have entered the market in informal channels, causing an enormous waste of resources and secondary environmental pollution [4]. In addition, refurbished and shoddy products capture the market of remanufactured products and lower public recognition of remanufactured products [33]. Hence, establishing a laws and regulations system to regulate the recycling and remanufacturing market becomes the top priority to enhance the eco-efficiency of remanufacturing. In addition, as for OEMs, the extended producer responsibility system should be concisely clarified in the form of laws and regulations rather than policies. Moreover, the producer obligations and the recycling rate should be clearly stipulated. Furthermore, the scope of intellectual property rights needs to be clearly defined to promote the sharing of product information [8].

Remanufacturing technology and DFR: technical factors of remanufacturing include DFR before remanufacturing and remanufacturing technology during remanufacturing processes. DFR has a direct impact on the remanufacturing rate and the reuse ratio, which will decrease costs and emissions during the remanufacturing process, and increase the eco-efficiency of remanufacturing [20]. Remanufacturing technology guarantees the safety and reliability of remanufactured products and promotes consumers choosing remanufactured products [2,5]. Accordingly, DFR ensures the formation of remanufacturing rates in the design stage while remanufacturing technology improves the achievement of remanufacturing rates in the remanufacturing processes [9], both of which make great contributions to cost saving and resource recycling.

Quality management: according to Yao *et al.* [43], concerns of consumers regarding product quality limit the market occupancy of remanufacturing products and hamper the implementation of economic performance generated in remanufacturing activities. Except for making remanufactured products meet the quality and performance requirements, the quality control of remanufacturing processes maximizes the recycling of resources and promotes resource conservation and emission reduction, which makes significant contributions to the sustainable remanufacturing [28].

From the seven critical factors discussed above, it can be concluded that at the current stage of remanufacturing in China, the eco-efficiency of remanufacturing is realized mainly through external factors such as the laws and regulations system, policy guidance, OEMs information sharing, and the growth of public awareness. In addition, to achieve eco-efficiency of remanufacturing, remanufacturers should master sophisticated remanufacturing technology to make a precise evaluation on the remanufacturing rate of cores and then implement it. They are also required to exploit appropriate techniques during the remanufacturing process to maximize the recycling and reusing ratio of cores and minimize the impact on the environment simultaneously. Additionally, remanufacturers need monitor the quality of remanufactured products, ensuring that customers can purchase products with a quality similar to new products and with less cost.

6. Conclusions

In order to achieve the potential economic and environmental benefits in remanufacturing and to provide the decision-making theoretical basis for the government to instruct the development of sustainable remanufacturing, this paper establishes a factor set affecting the eco-efficiency of remanufacturing on the basis of the current development of remanufacturing in China and the opinions of experts and scholars as well. Considering inter-connections among factors and subjective fuzziness in the expert evaluation process, we utilize the fuzzy DEMATEL approach to identify crucial factors affecting the eco-efficiency of remanufacturing. Firstly, the direct-relation matrix and total-relation matrix are built up according to mutual relationships among factors. Then, the contribution of each factor on the eco-efficiency of remanufacturing and the interdependence relationships among factors is obtained, by which seven essential factors are determined accordantly. The study in this paper shows that at the current stage in China, the eco-efficiency of remanufacturing is improved mainly through the external factors such as a completed legislation system, policy guidance, OEMs information sharing, and growth of public awareness; and through the internal factors such as advanced remanufacturing technology, and quality management of the remanufactured products.

Furthermore, these critical elements involve government, consumers, OEMs, remanufacturers, and other stakeholders. Hence, for achieving eco-efficiency of remanufacturing in China, the following suggestions are provided in accordance with different stakeholders. For government, on one hand, it should enact policies to strengthen the public consciousness of recycling and remanufacturing, and to guide the behaviors of remanufacturing stakeholders. On the other hand, legislation should be completed to regulate the recycling and remanufacturing market, and to clearly define the responsibilities and obligations of stakeholders. In order to assume the responsibility of recycling products, OEMs should consider environmental factors in the design stages and improve remanufacturing activities by information sharing and design for remanufacturing. Remanufacturers, as the primary implementer of remanufacturing, should possess sophisticated remanufacturing technology to improve the recycling rate of cores and promote resource conservation and emissions reduction in the remanufacturing processes. Quality management is also required to eliminate concerns of consumers about the quality of remanufactured products, thus expanding the market occupancy of these products.

Acknowledgments

This work is financially supported by the National Natural Science Foundation of China (71473077), the National High Technology Research and Development Program of China (2013AA040206), and the Hunan Provincial Natural Science Foundation of China (13JJA003).

Author Contributions

Qianwang Deng and Xiahui Liu proposed the idea, built the modeling, wrote the manuscript, and revised it. Haolan Liao provided guidance throughout the paper and revised the paper.

Conflicts of Interest

The authors declare no conflict of interest.

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