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An integrated model for closed-loop supply chain configuration and supplier selection: Multi-objective approach

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ABSTRACT

Reverse logistics consists of all operations related to the reuse of products. External suppliers are one of the important members of reverse logistics and closed loop supply chain (CLSC) networks. However in CLSC network configuration models, suppliers are assessed based on purchasing cost and other factors such as on-time delivery are ignored. In this research, a general closed loop supply chain network is examined that includes manufacturer, disassembly, refurbishing, and disposal sites. Meanwhile, it is managed by the manufacturer. We propose an integrated model which has two phases. In the first phase, a framework for supplier selection criteria in RL is proposed. Besides, a fuzzy method is designed to evaluate suppliers based on qualitative criteria. The output of this stage is the weight of each supplier according to each part. In the second phase, we propose a multi objective mixed-integer linear programming model to determine which suppliers and refurbishing sites should be selected (strategic decisions), and find out the optimal number of parts and products in CLSC network (tactical decisions). The objective functions maximize profit and weights of suppliers, and one of them minimizes defect rates. To our knowledge, this model is the first effort to consider supplier selection, order allocation, and CLSC network configuration, simultaneously. The mathematical programming model is validated through numerical analysis.

1. Introduction

Reverse logistics is defined as the process of planning, implementing and controlling the inbound flow and storage of secondary goods and related information opposite to the traditional supply chain directions for the purpose of recovering value and proper disposal (Fleischmann, 2001). The design of reverse logistics network is a difficult problem because of economic aspects and the effects of it on other aspects of human life, such as the environment and sustainability of natural resources (Francas & Minner, 2009; Lee & Dong, 2009). Reverse logistics options consist of reuse, resale, repair, refurbishing, remanufacturing, cannibalization, and recycling (Thierry, Salomon, Nunen, & Wassenhove, 1995). In the remanufacturing process, used products are disassembled in disassembly sites. Then they are divided to two kinds of parts. Usable parts are cleaned, refurbished, and they are transmitted into part inventory. Then the new products are manufactured from the old and new parts (Kim, Song, & Jeong, 2006). The purpose of refurbishing is to increase the quality of products. Quality standards are less rigorous than those for new products. Military and commercial aircraft are examples of these products. Although the quality of products is improved by refurbishing, remaining service life is generally less than the average service life of new ones (Thierry et al., 1995).

The purchasing costs are more than 50% of all companies' expenses (Aissaoui, Haouari, & Hassini, 2007). Therefore, purchasing function is a prominent task. In reverse logistics, the new parts are bought from external suppliers. Not only the cost of purchase is important, but also other criteria of suppliers play a prominent role. For instance, late delivery can affect the production and increase the final costs tremendously. As a result, suppliers should be assessed based on several criteria that purchasing cost is one of them. In other words, supplier selection should be examined. Supplier selection is a multi-criteria decision making problem which consists of both qualitative and quantitative factors (Amin & Razmi, 2009).

Although several investigations have been performed for supplier selection in open loops, supplier selection in CLSC network is a novel subject. There are some differences between supplier selection in open loops and closed loops networks. The importance of some criteria is higher in closed loops supply chains rather than open ones. Generally, several factors such as quality, delivery, capacity, and price are considered in supplier selection (Weber, Current, & Benton, 1991). Kahraman, Cebeci, and Ulukan (2003)

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categorized supplier selection criteria into four groups including supplier criteria, product performance criteria, service performance criteria, and cost criteria. In closed loops, product performance criteria would have more importance rather than open loops because the products should have some characteristics such as durability, strength, and lightweight to be reusable and recoverable. In addition, the number of disposed products depends on product performance criteria and has influence on the total cost. Environmental criteria are another group of characteristics that should be emphasized in closed loop configuration. Recycling, clean technology, pollution reduction capacity, and environmental costs are examples of environmental factors. It is noticeable that conservation of environment is one of the goals of CLSC configuration. Recently, a few papers have considered green supplier selection; however, they have not focused on RL. In addition, order allocation and CLSC network configuration are not taken into account in them. Another difference between supplier selection in closed loops and open loops referred to the sources of uncertainty. Demand and supply usually are the sources of uncertainty in open loops. Supplier selection helps the researchers and practitioner to overcome the uncertainty in supply. However, in CLSC the return is added to the sources of uncertainty. Thus, the manufacturer should set a balance between supply, demand, and return and he/she should buy new parts according to the uncertain return. In other words, supplier selection and order allocation should be performed concurrently with CLSC configuration to prevent overstocking and under-stocking costs in purchasing process.

In this paper, we configure a general closed loop supply chain network that includes disassembly, refurbishing, and disposal sites. The manufacturer uses refurbished and new parts to produce new products. Therefore, he buys new parts from external suppliers. The main objective of network configuration is to determine the optimal number of products and parts in each section of the network. We propose an integrated model that has two phases. In the first phase, a new framework for supplier selection criteria is proposed which is based on supplier-related, part-related and process-related categories. The framework enables decision makers to determine the importance of each category. Moreover, it includes both qualitative and quantitative metrics. Then, suppliers are assessed by a proposed fuzzy model. To this aim, qualitative criteria are utilized. Fuzzy sets theory enables us to consider uncertainty in human's judgement. In the second phase, a closed loop supply chain is formulated as multi-objective mixed-integer linear programming model. The first objective function maximizes profit. In addition, second one minimizes defect rates (defect rate and profit are quantitative factors in supplier selection). Finally, the weight of suppliers (that is obtained in previous phase) is maximized in the third objective function. Not only the proposed model can help decision-makers for supplier and refurbishing sites selection (strategic decisions), but also it determines the amount of products and parts in each part of the network (tactical decisions). For solving multi objective problem, fuzzy AHP method is combined with compromise programming to determine the weights of each objective function precisely. To our knowledge, the proposed model is the first one that takes into account supplier selection, order allocation, and CLSC network configuration, at the same time. The model is designed for multiple products, parts, suppliers, and refurbishing sites. The multi objective MILP model is solved by GAMS. Besides, it is validated through computational testing.

The paper is organized as follows. The literature review is presented in Section 2. Section 3 introduces fuzzy sets theory. In Section 4, the problem is defined. Section 5 is devoted to the proposed model. In Section 6, we present a numerical example to validate the model. Finally, in Section 7 conclusion is presented.

2. Literature review

Some literature reviews have been published for reverse logistics and closed loop supply chain configuration. Fleischmann et al. (1997) examined reverse logistics from operations research view point. They categorized the papers into three main groups including distribution planning, inventory, and production planning. Guide and Van Wassenhove (2009) categorized CLSC networks to five phases: (1) The golden age of remanufacturing. (2) From remanufacturing to valuing the reverse-logistics. (3) Coordinating the reverse supply chain. (4) Closing the loop. (5) Prices and markets. In addition, they stated that in reality, end of use, end of life, and commercial returns are the most important kinds of returns. Melo, Nickel, and Saldanha-da-Gama (2009) examined the application of facility location models in the supply chain management. In one of the categories, they divided the literature of reverse logistics to closed loop, and recovery networks. Pokharel and Mutha (2009) focused on all aspects of reverse logistics from networking and inventory analysis, collection of used products, determining the pricing, use, resale, and remanufacturing. They also came to conclusion that research publication on RL is increased specially after 2005.

2.1. Network configuration in RL

Network configuration is one of the main research streams in RL. The majority of authors use facility location models to formulate CLSC networks. However, no one has utilized supplier selection techniques during CLSC configuration. Jayaraman, Guide, and Srivastava (1999) proposed a mixed-integer programming model. The model can determine the location of remanufacturing/distribution facilities, the transhipment, production, and stocking of the optimal quantities of remanufactured products and used parts. Fleischmann, Beullens, Bloemhof-Ruwaard, and Van Wassenhove (2001) proposed a general model for closed loop supply chain network. The model is designed based on forward facility location model. Copier remanufacturing and paper recycling are utilized to show the efficiency of the model. Kim et al. (2006) presented a mathematical model to determine the quantity of products/parts processed in the remanufacturing facilities and the amount of parts purchased from suppliers. They maximized manufacturing cost saving. However, the model is designed for a single supplier. Ko and Evans (2007) proposed a mixed-integer nonlinear programming model that is a multi period, two-echelon, multi commodity, and capacitated network design problem. They considered forward and reverse flows simultaneously. Srivastava (2008) proposed a framework for analyzing a network. The model determines the disposition decision for various grades of different products concurrently with location-allocation and capacity decisions for facilities for a time horizon. Pati, Vrat, and Kumar (2008) formulated a mixed-integer goal programming model to determine the facility location, route and flow of different varieties of recyclable wastepaper in the multi-item, multi-echelon and multi-facility decision making framework. Lee, Gen, and Rhee (2009) formulated a mathematical model for a general CLSC network by prosing a heuristic approach (genetic algorithm). Although the model can determine the optimal numbers of disassembly and processing centers, the supplier selection is not taken into account. The authors supposed that there is only one supplier. Shi, Zhang, and Sha (2011) investigated a CLSC network which demand and return are uncertain. Shi, Zhang, Sha, and Amin (2010) proposed a mathematical model to maximize the profit of a remanufacturing system. They developed a solution approach based on Lagrangian relaxation method, and sub gradient algorithm.

2.2. Supplier selection

In the field of supplier selection and evaluation, a lot of articles have been published. Weber et al. (1991) sent a questionnaire to several companies. They identified the most important criteria including price, delivery, quality, facilities, geographic location, and technology. De Boer, Labro, and Morlacchi (2001) presented a literature review for all phases in the supplier selection process from initial problem definition, over the formulation of criteria, the qualification of potential suppliers, and final choice among the qualified suppliers. Humphreys, Wong, and Chan (2003) presented a new framework to select the best suppliers based on environmental criteria such as solid waste, chemical waste, air emission, water waste disposal, and energy. Lee, Kang, and Hung (2009) defined green supplier selection criteria by Delphi method and evaluated suppliers by fuzzy AHP model. The green supply chain ranges from simple open loops to CLSC networks. Hsu and Hu (2009) present an analytic network process model to incorporate the issue of hazardous substance management into supplier evaluation. Aissaoui et al. (2007) presented a literature review especially on the final selection stage that consists of two sections: determining the best vendors, and allocating orders among them. Recently, Ho, Xu, and Dey (2010) have reviewed the literature of the multi-criteria decision making approaches for supplier selection and evaluation. They focused on the papers from 2000 to 2008.

Some researchers have investigated application of fuzzy sets theory in supplier selection. For instance, Bottani and Rizzi (2006) applied fuzzy TOPSIS for selecting the best suppliers. Besides, Chan and Kumar (2007) used fuzzy AHP method. Chou and Chang (2008) presented a strategy-aligned fuzzy approach for solving the vendor selection problem from the strategic management view point. Their method is designed based on operations management and triangular fuzzy numbers. Wang, Cheng, and Huang (2009) combined fuzzy TOPSIS and AHP methods to select the best suppliers. Recently, Amin and Razmi (2009) proposed a general framework for supplier selection, evaluation, and development. In addition, they applied a fuzzy-QFD based algorithm for selecting the best internet service provider (ISP).

Ghodsypour and O'Brien (1998) proposed a new model to select the best supplier and determine the order allocation. They used analytical hierarchy process (AHP) to consider qualitative criteria. On the other hand, linear programming (single objective) was utilized to take into account quantitative metrics. After this paper, a lot of investigations have been performed using this idea. Table 1 shows some of them. All of these models are formulated as multi-objective programming, because it is desirable to maximize and minimize some objective functions, simultaneously. The main differences between these papers are related to the application of decision techniques. However, all of them are written for open loop supply chain networks. In addition, the majority of them only are examined constraints of demand and capacity of suppliers. On the other hand, one of the key elements of closed loop supply networks is external supplier. To date, suppliers are selected based on single criterion (purchasing cost) in closed loop supply chain networks. But, other factors such as quality and delivery and responsiveness of suppliers also are essential. In this paper, we propose an integrated fuzzy model to configure a closed loop supply chain network and select the best suppliers.

3. Fuzzy sets theory

The term fuzzy was proposed by Zadeh (1965). The fuzzy sets theory (FST) is introduced to improve the oversimplified model by developing a more robust and flexible model in order to solve real-world complex systems involving human aspects (Lai & Hwang, 1995). In addition, FST can help us to overcome uncertainty in human thought. A fuzzy number is illustrated by membership function that is a number between 0 and 1.

Triangular fuzzy number (TFN) is one of the most important fuzzy numbers. TFNs can be denoted as $X = (a,n,b)$ and $Y = (c,m,d)$, where n and m are the central values, a and c are the left spreads, and b and d are the right spreads (see Fig. 1). Then $C = (a + c, n + m, b + d)$ is the addition of these two numbers. Besides, $D = (a - c, n - m, b - d)$ is the subtraction of them. Moreover, $E = (a \times c, n \times m, b \times d)$ is the multiplication of them (Lai & Hwang, 1995; Zimmermann, 2001)

$$\mu X(x) = \begin{cases} 0 & x < a \\ \frac{x-a}{n-a}, & a \leqslant x \leqslant n \\ \frac{b-x}{b-n}, & n \leqslant x \leqslant b \\ 0, & x > b \end{cases}$$

4. Problem definition

In this study, a CLSC network is investigated that consists of disassembly, refurbishing and disposal sites. Fig. 2 shows the network. The network is managed by manufacturer. The manufacturer produces products according to the demand. After using the products by customers, some of them are returned. The returned products are taken to disassembly site. Then, they are separated to reusable parts and wastes. The wastes go to the disposal site. On the other hand, reusable parts are taken to refurbishing site to be cleaned and refurbished. These parts are added to part inventory as new parts. It is noticeable that capacities of disassembly, disposal, and refurbishing sites are limited. According to the demand and refurbished parts, the manufacturer purchases new parts from external suppliers. Not only the cost of parts is important for manufacturer, but also he should consider other criteria such as delivery, and quality. The manufacturer encounters two types of decisions. First, he is interested to know the number of optimal products and parts in each section of the network. For instance, the number of returned parts is one of the variables. These factors are called tactical decisions. Network configuration provides information for tactical decisions. On the other hand, some strategic decisions should be considered. Supplier selection is one of them. Supplier selection is helpful to assess suppliers based on several factors. In CLSC networks, the parts are supplied from returned and new parts. The coordination and cooperation of these two sources can affect the rate of production, and ultimately change the cost of finished products. Besides, the lack of supply in new or returned parts can increase the holding costs of part inventory. Refurbishing site selection is another strategic decision. When there are some alternatives for refurbishing parts, the manufacturer prefers to select the site which has the lowest cost.

5. Proposed model

In this section, the proposed model is described. Fig. 3 shows the framework of our approach. First, the manufacturer identifies potential suppliers and defines appropriate criteria. Then, decision makers evaluate suppliers by proposed fuzzy model. The results of this phase are the weights (importance) of suppliers based on qualitative metrics. In the next phase, the closed loop supply chain (CLSC) network is formulated as multi-objective mixed-integer linear programming model. In this stage, the related variables (strategic and tactical decision variables) are calculated.

5.1. Evaluation of suppliers

In this section, a new method based on linguistic variables and triangular fuzzy numbers (TFNs) is proposed for supplier

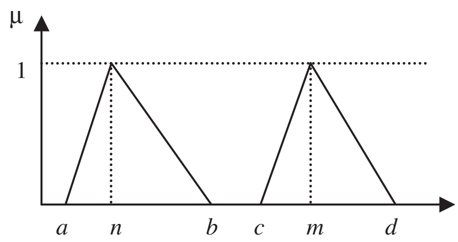

Fig. 1. Triangular fuzzy numbers.

assessment. The outputs of this stage are weights of suppliers. Although Fuzzy Analytic Hierarchy Process (FAHP) has some advantages in evaluating suppliers, we did not use this method in this stage, because in this problem, suppliers are assessed based on different parts and therefore, a lot of pairwise comparisons should be performed. In other words, FAHP needs more time than the proposed fuzzy model.

In the proposed model, the manufacturer determines the decision making group. Three or five managers can contribute in decision making process. Suppose that there are N decision makers ($n = 1,2,\ldots,N$), and M criteria ($m = 1,2,\ldots,M$). Moreover, there are K eligible suppliers ($k = 1,2,\ldots,K$) that produce I parts ($i = 1,2,\ldots,I$). The manufacturer assembles parts to produce products. The steps of this phase are as follows:

Step 1: Define suitable criteria: In this paper, we propose a new framework for defining supplier selection criteria, especially in the field of reverse logistics. The framework is designed based on supplier-related (Ca_1), part-related (Ca_2), and process-related (Ca_3) categories. Fig. 4 illustrates the framework. The majority of supplier selection studies have focused on supplier related criteria such as delivery, cost, financial ability and experience. These metrics are enough when the suppliers are assessed without considering specific parts and processes. Between part-related criteria, price and quality (defect rates) are frequently used. For instance, Dickson (1966) identified 23 different criteria based on a questionnaire sent to 273 purchasing agent and managers from North America. The most important ones were quality, delivery, performance history, warrant and claim policy, production facilities and capacity, net price, and technical capabilities.

In reverse logistics, other characteristics of parts also should be considered such as weight, strength, and durability. In addition, recyclable and reusable parts can be used in remanufacturing process. Not only the parts and suppliers criteria should be taken into account, but also process-related metrics such as process capability and process flexibility are essential. Furthermore, environmental-related criteria play an important role. Reduction of pollutions and clean technology are examples of green criteria in the field of supplier selection. It is noticeable that one of the goals of reverse logistics is to conserve the environment. Therefore, in the supplier selection process in RL, a considerable weight should be assigned to process- related factors.

Step 2: Let U = {VL, L, ML, M, MH, H, VH} be the linguistic set used to express opinions on the group of criteria. This scale is adopted from (Amin & Razmi, 2009). The linguistic variables of U can be quantified using triangular fuzzy numbers (please refer to Fig. 5). Each decision maker establishes a level of importance for each category by using linguistic variables and TFNs (Ca_x represents importance of category x, $x = 1, 2, 3$). Then, they are combined by Eq. (1) and the weights of categories are calculated

$$Ca_x = \frac{Ca_{x1} + Ca_{x2} + \cdots + Ca_{xN}}{N} \tag{1}$$

Step 3: Let w_{xmN} represents the importance of criterion m in category x by decision maker N. Decision makers establish a level of importance by Eq. (2)

$$w_{xm} = \frac{w_{xm1} + w_{xm2} + \cdots + w_{xmN}}{N} \tag{2}$$

Step 4: Let Su_{xmikN} represents the assessment of supplier k that manufactures part i based on criterion m in category x which is performed by decision maker N. Each decision maker establishes a level of importance. The aggregated weight of supplier k based on criterion m and part i in category x (Su_{xmik}) is calculated by Eq. (3)

$$Su_{xmik} = \frac{Su_{xmik1} + Su_{xmik2} + \cdots + Sux_{xmikN}}{N} \tag{3}$$

Step 5: In this step, weights of categories are multiplied by weights of criteria and aggregated weights. Eq. (4) shows the formula. In this equation, a_{ik} is a TFN. Now, the numbers should be defuzzified. In this paper, a simple method is applied to defuzzify the numbers. A deffuzzified number of $a_{ik} = (a,n,b)$ is calculated by Eq. (5) (Chou & Chang, 2008)

$$a_{ik} = \sum_{x=1}^{3} \sum_{m=1}^{M} Ca_x \times w_{xm} \times Su_{xmik} \tag{4}$$

$$be_{ik} = \frac{a + n + b}{3} \tag{5}$$

Step 6: The normalized weights (importance) of suppliers based on each criterion is calculated by Eq. (6). Now, the suppliers can be ranked

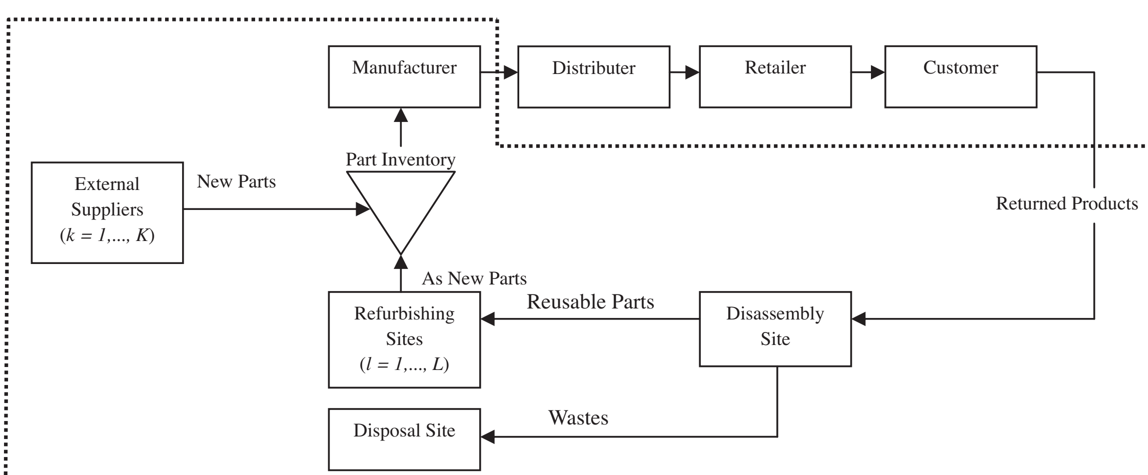

Fig. 2. A closes loop supply chain (dashed area).

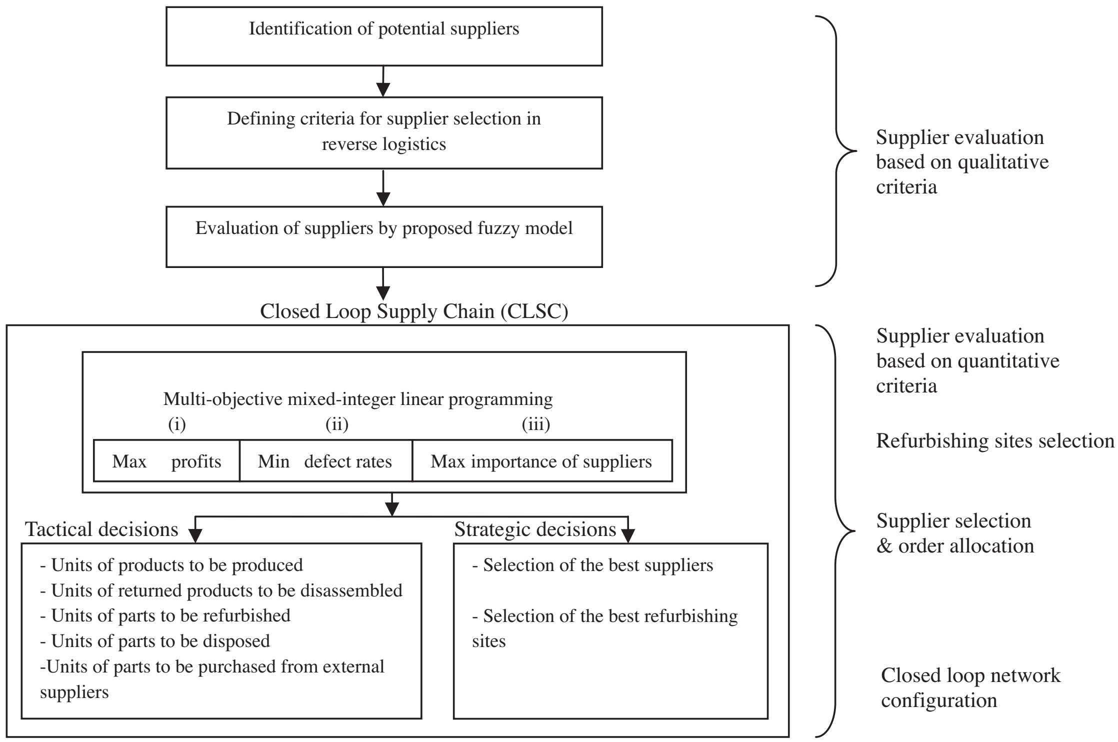

Fig. 3. Framework of the proposed model.

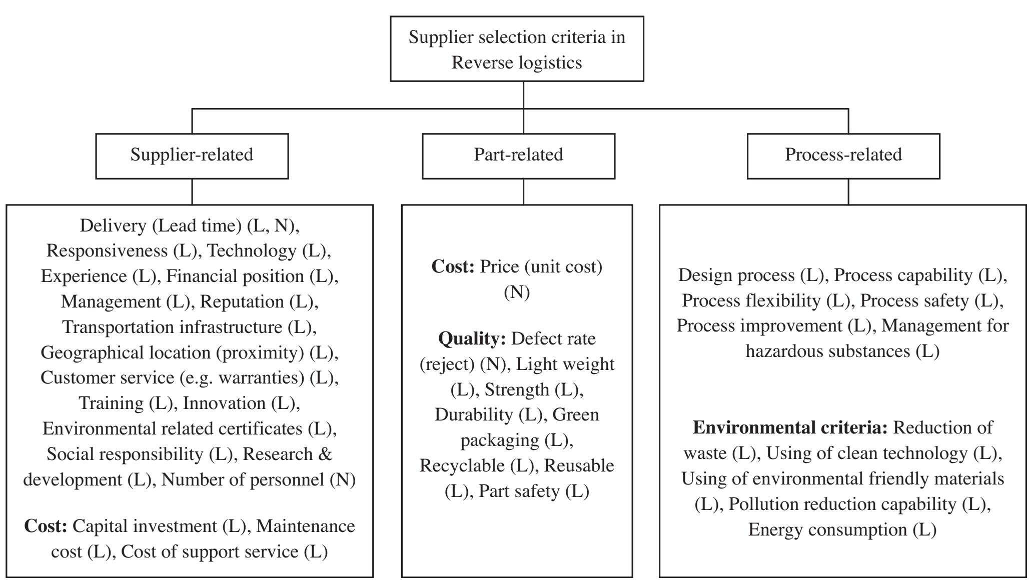

Fig. 4. Proposed supplier selection criteria in reverse logistics (L): qualitative criteria and (N): quantitative criteria.

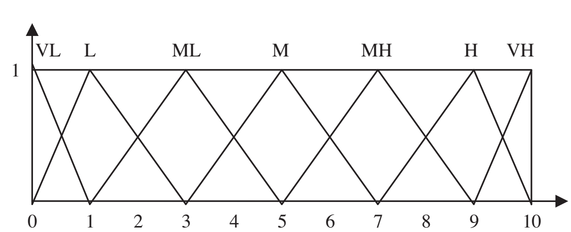

Fig. 5. A linguistic scale (Amin & Razmi, 2009).

$$t_{ik} = \frac{be_{ik}}{\sum_{k=1}^{K} be_{ik}} \tag{6}$$

5.2. Mathematical model for CLSC

The problem can be formulated as a mathematical model. The following assumptions are made in the development of the model:

– If the quantity of provided parts from refurbishing site is not enough for requirement of manufacturer, manufacturer should purchase parts from external suppliers.

Table 1
Summary of papers about supplier selection and order allocation.

Authors	Supplier selection techniques	Order allocation techniques
Ghodsypour and O'Brien (1998)	Analytical hierarchy process (AHP)	Linear programming
Xia and Wu (2007)	AHP and rough sets theory	Mixed-integer programming
Demirtas and Ustun (2008a)	Analytic network process (ANP)	Mixed-integer programming
Demirtas and Ustun (2008b)	ANP	Mixed-integer programming
Ustun and Demirtas (2008)	ANP	Goal programming
Sanayei, Mousavi, Abdi, and Mohaghar (2008)	Utility theory	Linear programming
Lin (2009)	Fuzzy preference programming	Linear programming
Demirtas and Ustun (2009)	ANP	Goal programming
Wu, Sukoco, Li, and Chen (2009)	ANP	Mixed-integer programming
Faez, Ghodsypour, and O'Brien (2009)	Fuzzy case-based reasoning	Mixed-integer programming
Razmi, Songhori, and Khakbaz (2009)	Fuzzy	Fuzzy linear programming
Amin, Razmi, and Zhang (2011)	Fuzzy SWOT analysis	Fuzzy linear programming

– The maximum capacity of disassembly and refurbishing sites and suppliers are known.
– The sum of disassembling and refurbishing costs is less than purchasing cost of a new part.
– The proposed model is a single period one.

Indices, decision variables, and parameters of the mathematical model are as follows:

Indices

i set of parts, $i = 1,\ldots,I$
j set of products, $j = 1,\ldots,J$
k set of suppliers, $k = 1,\ldots,K$
l set of refurbishing sites, $l = 1,\ldots,L$

Decision variables

P_j units of product j to be produced
R_j units of returned product j to be disassembled
Q_{ik} units of part i to be purchased from external supplier k
T_i units of part i that are obtained in disassembly site
X_{il} units of part i to be refurbished in refurbishing site l
V_i units of part i to be disposed
U_{il} binary variable for set-up of refurbishing site l for part i
F_j binary variable for set-up of disassembly site for product j
u_k binary variable for supplier k

Parameters

S_j unit selling price for the product j
a_j resource usage to produce one unit of product j
c_j unit direct manufacturing cost of product j
D_j demand for product j
d_j set-up cost of disassembly site for product j
E_i max capacity of disassembly site to dissemble part i
f_i unit disassembly cost for part i
h_i unit disposing cost for part i
e_i resource usage to disassemble one unit of part i
o_{il} unit refurbishing cost for part i in refurbishing site l
p_{il} set-up cost of refurbishing site l for part i
g_{il} resource usage to refurbish one unit of part i in refurbishing site l
G_{il} max capacity of refurbishing site l to refurbish part i
q_{ij} unit requirements for part i to produce one unit of product j
r_{ik} the cost of purchasing part i from external supplier k
b_{ik} internal resource usage of supplier k to produce one unit of part i
B_k max capacity reserved of external supplier k
v_k minimum purchase quantity from supplier k
H_j max percent of product j returns
O_i max percent of reusable part i
A max capacity of the manufacturer plant
C max number of refurbishing sites
s_{ik} defect rate for part i that is produced by supplier k
t_{ik} weight (importance) of supplier k for part i

Model formulation

$$Max Z_1 \quad \sum_{j=1}^{J}(S_j - C_j)P_j - \sum_{i=1}^{I}\sum_{k=1}^{K} r_{ik}Q_{ik} - \sum_{i=1}^{I} f_i T_i - \sum_{l=1}^{L}\sum_{i=1}^{I} o_{il}X_{il} - \sum_{i=1}^{I} h_i V_i - \sum_{l=1}^{L}\sum_{i=1}^{I} p_{il}U_{il} - \sum_{j=1}^{J} d_j F_j \tag{7}$$

$$Min Z_2 \quad \sum_{i=1}^{I}\sum_{k=1}^{K} s_{ik}Q_{ik} \tag{8}$$

$$Max Z_3 \quad \sum_{i=1}^{I}\sum_{k=1}^{K} t_{ik}Q_{ik} \tag{9}$$

Subject to

$$\sum_{j=1}^{J} q_{ij}P_j = \sum_{l=1}^{L} X_{il} + \sum_{k=1}^{K} Q_{ik} \quad \forall i \tag{10}$$

$$\sum_{l=1}^{L} X_{il} + V_i = T_i \quad \forall i \tag{11}$$

$$T_i = \sum_{j=1}^{J} q_{ij}R_j \quad \forall i \tag{12}$$

$$\sum_{j=1}^{J} a_j P_j \leqslant A \tag{13}$$

$$u_k v_k \leqslant \sum_{i=1}^{I} b_{ik}Q_{ik} \leqslant u_k B_k \quad \forall k \tag{14}$$

$$e_i T_i \leqslant E_i \quad \forall i \tag{15}$$

$$g_{il}X_{il} \leqslant G_{il}U_{il} \quad \forall i, l \tag{16}$$

$$P_j = D_j \quad \forall j \tag{17}$$

$$\sum_{l=1}^{L} X_{il} \leqslant O_i T_i \quad \forall i \tag{18}$$

$$V_i \leqslant (1 - O_i)T_i \quad \forall i \tag{19}$$

$$R_j = H_j P_j \quad \forall j \tag{20}$$

$$\sum_{l=1}^{L}\sum_{i=1}^{I} U_{il} \leqslant C \tag{21}$$

$$R_j \leqslant MF_j \quad \forall j \tag{22}$$

$$U_{il}, F_j, u_k \in \{0, 1\} \quad \forall i, j, k, l \tag{23}$$

$$P_j, R_j, Q_{ik}, T_i, X_{il}, V_i \geqslant 0 \quad \forall i, j, k, l \tag{24}$$

The objective function (7) maximizes the total profit. The first part of this objective function represents profit of selling products. The second part represents the costs of parts purchasing from external suppliers. The third part represents the disassembly cost incurs from disassembly site, and consists of unit disassembly cost multiplied by the amount of parts to be disassembled. The costs of refurbishing and disposal sites are calculated in the fourth and fifth parts. In addition, the sixth and seventh parts represent the set-up costs of refurbishing and disassembly sites. It is noticeable that refurbishing sites are selected based on maximum profit. The objective function (8) minimizes defect rates. Furthermore, the objective function (9) maximizes importance of external suppliers, which is calculated from the proposed fuzzy method including weights of external suppliers multiplied by the amount of parts purchased from them.

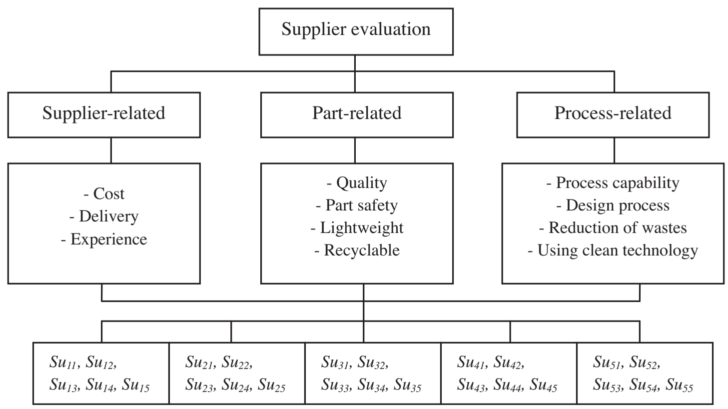

Fig. 6. Supplier evaluation based on qualitative criteria.

Table 2
Evaluation of suppliers based on qualitative criteria

Category	DM$_1$	DM$_2$	DM$_3$	TFN$_1$	TFN$_2$	TFN$_3$	Weights of categories
(a) Importance of categories							
Supplier-related	MH	M	M	(5,7,9)	(3,5,7)	(3,5,7)	(3.7,5.7,7.7)
Part-related	H	H	H	(7,9,10)	(7,9,10)	(7,9,10)	(7,9,10)
Process-related	VH	H	MH	(9,10,10)	(7,9,10)	(5,7,9)	(7.0,8.7,9.7)

Criteria	DM$_1$	DM$_2$	DM$_3$	Weights of criteria		DM$_1$	DM$_2$	DM$_3$	Aggregated weights
(b) Importance of criteria					*(c) Assessment supplier 1 based on part 1*				
Cost	VH	VH	H	(8.3,9.7,10.0)	Cost	H	MH	M	(5.0,7.0,8.7)
Delivery	MH	M	M	(3.7,5.7,7.7)	Delivery	M	MH	M	(3.7,5.7,7.7)
Experience	MH	M	MH	(4.3,6.3,8.3)	Experience	M	MH	MH	(4.3,6.3,8.3)
Quality	H	MH	VH	(7.0,8.7,9.7)	Quality	ML	L	M	(1.3,3.0,5.0)
Part safety	VH	H	MH	(7.0,8.7,9.7)	Part safety	VH	MH	H	(7.0,8.7,9.7)
Lightweight	MH	M	M	(3.7,5.7,7.7)	Lightweight	MH	MH	M	(4.3,6.3,8.3)
Recyclable	M	MH	MH	(4.3,6.3,8.3)	Recyclable	MH	M	M	(3.7,5.7,7.7)
Process capability	M	MH	M	(3.7,5.7,7.7)	Process capability	MH	MH	H	(5.6,7.7,9.3)
Design process	MH	H	VH	(7.0,8.7,9.7)	Design process	MH	M	MH	(4.3,6.3,8.3)
Reduction of wastes	H	MH	VH	(7.0,8.7,9.7)	Reduction of wastes	M	MH	MH	(4.3,6.3,8.3)
Using clean technology	M	ML	MH	(3.0,5.0,7.0)	Using clean technology	ML	MH	ML	(2.3,4.3,6.3)

	Weights of categories	Weights of criteria	Aggregated weights	Final score
(d) Final score for supplier 1 based on part 1 (be_{11})				
Cost	(3.7,5.7,7.7)	(8.3,9.7,10.0)	(5.0,7.0,8.7)	(153,387,669)
Delivery	(3.7,5.7,7.7)	(3.7,5.7,7.7)	(3.7,5.7,7.7)	(50,185,456)
Experience	(3.7,5.7,7.7)	(4.3,6.3,8.3)	(4.3,6.3,8.3)	(68,226,530)
Quality	(7,9,10)	(7.0,8.7,9.7)	(1.3,3.0,5.0)	(63,234,485)
Part safety	(7,9,10)	(7.0,8.7,9.7)	(7.0,8.7,9.7)	(343,681,940)
Lightweight	(7,9,10)	(3.7,5.7,7.7)	(4.3,6.3,8.3)	(111,323,639)
Recyclable	(7,9,10)	(4.3,6.3,8.3)	(3.7,5.7,7.7)	(111,323,639)
Process capability	(7.0,8.7,9.7)	(3.7,5.7,7.7)	(5.6,7.7,9.3)	(145,381,694)
Design process	(7.0,8.7,9.7)	(7.0,8.7,9.7)	(4.3,6.3,8.3)	(210,476,780)
Reduction of wastes	(7.0,8.7,9.7)	(7.0,8.7,9.7)	(4.3,6.3,8.3)	(210,476,780)
Using clean technology	(7.0,8.7,9.7)	(3.0,5.0,7.0)	(2.3,4.3,6.3)	(48,187,427)
				a_{11} = (1516,3883,7045), be_{11} = 4147

i/k	1	2	3	4	5
(e) t_{ik} (Weight of supplier k for part i)					
1	0.21	0.19	0.20	0.20	0.20
2	0.18	0.21	0.20	0.20	0.21
3	0.20	0.24	0.19	0.17	0.20
4	0.21	0.20	0.20	0.21	0.18
5	0.18	0.18	0.23	0.20	0.21

Table 3
Results of CLSC configuration.

j	1	2	3	4	5
(a) Product-related variables (multi-objective problem)					
P_j	1400	1500	1400	1400	1500
R_j	700	750	700	700	750

i	1	2	3	4	5
(b) Part-related variables (multi-objective problem)					
T_i	7200	6550	7850	8650	8000
V_i	3600	3275	3925	4325	4000

i/l	1	2	3	4	5
(c) X_{il} (Units of part i to be refurbished in refurbishing site l)					
1	–	3600	–	–	–
2	–	–	–	3275	–
3	–	3925	–	–	–
4	–	4325	–	–	–
5	4000	–	–	–	–

First objective (Z_1)			Second objective (Z_2)			Third objective (Z_3)			Multi-objective (Z)		
i	k	Q_{ik}	i	k	Q_{ik}	i	k	Q_{ik}	i	k	Q_{ik}
(d) Q_{ik} (Units of part i to be purchased from external supplier k)											
1	4	10,800	1	2	10,800	1	1	6667	1	4	10,800
2	3	9825	2	2	9825	1	5	4133	2	5	9825
3	1	5000	3	2	11,775	2	5	9825	3	1	5000
3	5	6775	4	1	6667	3	2	11,775	3	5	6775
4	2	12,975	4	5	6308	4	4	12,975	4	2	12,975
5	4	12,000	5	3	12,000	5	3	12,000	5	3	12,000

Table 4
Product-related parameters.

j	1	2	3	4	5
S_j	150	200	220	230	250
a_j	1	2	2	2	3
C_j	30	35	30	30	35
D_j	1400	1500	1400	1400	1500
d_j	5	5	4	5	4

Table 5
Part-related parameters.

i	1	2	3	4	5
E_i	9000	10,000	8500	10000	9500
f_i	4	5.5	2.5	3.5	3.5
h_i	3	4	4	4	3
e_i	1	1	1	1	1

Constraint (10) ensures that the numbers of manufactured parts are equal to the number of refurbished and purchased parts. Constraint (11) represents that the number of disassembled parts are equal to the number of reusable parts and wastes. Constraint (12) ensures the relationship between parts and products. Constraints (13)–(16) represent minimum purchasing quantity from suppliers, and maximum capacity of manufacturer, external suppliers, disassembly, and refurbishing sites. Constraint (17) shows that the number of manufactured products is equal to demand. Constraints (18) and (19) reflect the maximum percent of reusable parts and wastes. Moreover, Constraint (20) shows the limitation of max percent of returns. Besides, Constraint (21) represents the limitation of the number of refurbishing sites.

6. Solution

For solving the proposed multi-objective model, the compromise programming method is adopted (Hwang & Yoon, 1981).

Table 6
Refurbishing site-related parameters.

i/l	1	2	3	4	5
(a) O_{il} (Unit refurbishing cost for part i in refurbishing site l)					
1	3	2	3	3	4
2	4	4	3	2	4
3	4	3	4	3	4
4	4	3	3	4	3
5	3	3	4	4	4

i/l	1	2	3	4	5
(b) P_{il} (Set-up cost of refurbishing site l for part i)					
1	4	5	4	4	4
2	4	4	4	4	5
3	5	5	4	5	5
4	4	5	5	5	5
5	4	4	4	5	4

i/l	1	2	3	4	5
(c) g_{il} (Resource usage to refurbish one unit of part i in refurbishing site l)					
1	1	1	1	1	1
2	1	1	1	1	1
3	1	1	1	1	1
4	1	1	1	1	1
5	1	1	1	1	1

i/l	1	2	3	4	5
(d) G_{il} (Max capacity of refurbishing site l to refurbish part i)					
1	9000	10,000	8500	10,000	9500
2	10,000	9000	8500	10,000	9500
3	9000	10,000	8000	9500	10,000
4	8500	9000	10,000	9500	8500
5	9000	9500	10,000	9000	8500

Table 7
q_{ij} (The usage of part i per unit of product j).

i/j	1	2	3	4	5
1	2	1	3	1	3
2	1	3	2	1	2
3	3	2	1	4	1
4	2	1	2	3	4
5	1	3	2	2	3

Table 8
Supplier-related parameters.

i/k	1	2	3	4	5
(a) r_{ik} (The cost of purchasing part i from external supplier k)					
1	14	14	18	12	19
2	16	21	14	16	14
3	13	23	20	15	14
4	15	14	18	19	14
5	18	15	14	13	15
(b) b_{ik} (Internal resource usage of supplier k to produce one unit of part i)					
1	1.5	2	3	1	3
2	2	1	1	3	1
3	2	1.5	1	3	2.5
4	1.5	3	2.5	2	3
5	3	2	3	2	1.5
(c) S_{ik} (Defect rate for part i that is produced by supplier k)					
1	0.10	0.05	0.10	0.07	0.11
2	0.05	0.05	0.10	0.10	0.05
3	0.10	0.05	0.10	0.05	0.07
4	0.05	0.10	0.07	0.10	0.06
5	0.10	0.11	0.05	0.10	0.10

The aim is to minimize a function which is a measure to how close the decision maker can get to the ideal vector. A possible measure of closeness to the ideal solution is a family of L_p-metrics. Eq. (25)

shows the formula where Y is the number of objectives. The steps of this method are as follows:

$$L_p = \left[\sum_{y=1}^{Y} W_y^p \left|\frac{Z_y - Z_y^-}{Z_y^+ - Z_y^-}\right|^p\right]^{\frac{1}{p}} \tag{25}$$

1. Decision makers determine the importance of objective functions. Eq. (26) shows the formula for three objective functions

$$\sum_{y=1}^{3} W_y = 1, \quad W_y \geqslant 0 \quad (y = 1, 2, 3) \tag{26}$$

Decision makers should determine exact values of weights of objective functions. However, it is a challenging task to specify the precise weights. Fuzzy analytic hierarchy process (FAHP) can be helpful because it is based on pairwise comparisons. In addition, FAHP does not need a lot of time in this stage, because there are three objective functions. Thus, we combine FAHP and compromise programming model. The basic steps are as follows:

(I) Utilize pairwise comparison matrices: two objective functions are compared at each time to find out which one is more important. Fig. 5 can be utilized as a fuzzy scale.
(II) Synthesization is used to calculate weight of each objective function.
(III) Perform consistency test to check whether judgment of decision makers is consistent.

For more details about FAHP, you can refer to Kahraman et al. (2003) and Ho (2008).

2. The new objective function is constructed which is shown in Eq. (27) where Z_y^- and Z_y^+ ($y = 1, 2, 3$) denote the upper bound and lower bound of single objective functions subject to constraints (10)–(24). Obviously, the results differ depending on the value of p. Generally, p is 1 or 2. But, other values of p also can be used

$$Min Z \quad \left[W_1^p \times \left(\frac{Z_1^+ - Z_1}{Z_1^+ - Z_1^-}\right)^p + W_2^p \times \left(\frac{Z_2 - Z_2^-}{Z_2^+ - Z_2^-}\right)^p + W_3^p \times \left(\frac{Z_3^+ - Z_3}{Z_3^+ - Z_3^-}\right)^p\right]^{\frac{1}{p}} \tag{27}$$

3. The mixed-integer linear programming model with new objective function should be solved.

7. Numerical example

In this section, a numerical example is presented to show the proposed model. Suppose that a computer manufacturer assembles and sells five models of computer. In addition, each product is produced by five parts. The manufacturer is interested to know how many products and parts exist in each part of the closed loop network. Furthermore, it is important that which suppliers are eligible to supply required parts. In the first phase, manager of company forms a decision making group which is composed of three decision makers. They evaluate potential suppliers (5) based on each purchased part. Thus, the group selects appropriate criteria that are illustrated in Fig. 6. Then the members of group determine the importance of categories and criteria which are obtained by linguistic variables and triangular fuzzy numbers. The results are written in Table 2(a) and (b). In the next step, each supplier is assessed according to the criteria. Table 2(c) shows the process of assessment for supplier 1 who sells part 1. The process is repeated for other suppliers and parts. Then, the weights of categories are multiplied by weights of criteria and aggregated weights. Therefore, final scores can be calculated. Table 2(d) shows the results for supplier 1 and part 1. This process is repeated and scores are calculated for other alternatives. Now the weights (importance) of suppliers can be obtained by normalization. The results are illustrated in Table 2(e).

Table 9
B_k (the capacity of supplier k), v_k (minimum purchase quantity from supplier k), A (the capacity of manufacturer), H_j (max percent of product j returns), O_i (max percent of reusable part i), C (max number of refurbishing sites).

k	1	2	3	4	5
B_k	10,000	75,000	90,000	60,000	125,000
v_k	1000	1000	1000	1000	1000
A	200,000		H_j	0.5	
C	6		O_i	0.5	

In the second phase, the CLSC network is examined by using multi-objective MILP. In this paper, GAMS (General Algebraic Modelling System) is utilized to solve the model. This software is designed for modeling linear, nonlinear and mixed-integer optimization problems. The decision-making group determines the importance of objective functions as $W_1 = 0.7$, $W_2 = 0.1$, and $W_3 = 0.2$. The problem is solved for $p = 1$. The results of solving multi-objective functions problem are written in Table 3. Table 3 shows that the units of purchased parts from suppliers are different for each objective function. Aggregated objective function enables us to consider all of objective functions, simultaneously. Table 4 shows product-related parameters. Part related parameters are written in Table 5. Besides, refurbishing parameters are illustrated in Table 6. Table 7 is devoted to the usage of parts. Furthermore, supplier-related parameters and capacity parameters are written in Tables 8 and 9, respectively.

8. Conclusions

In this paper, we presented an integrated mathematical model for supplier selection, order allocation, and closed loop network configuration, as a novel innovation. The network consists of manufacturer, disassembly, refurbishing, and disposal sites. In the first phase, fuzzy sets theory is used to overcome the uncertainty in assessment of eligible suppliers. Therefore, the importance of suppliers can be calculated. Then, we designed multi objective mixed-integer linear programming model to optimize the supply chain network. The model not only determines the amount of parts and products in the nodes of CLSC network (tactical decisions), but also it selects the best suppliers and refurbishing sites (strategic decisions). GAMS is utilized to solve the proposed model. In addition, a numerical example is performed to analyze and validate the model. Computational results demonstrated the efficiency and effectiveness of the proposed model.

As this paper is the first one that introduces supplier selection and order allocation in closed loop supply chain configuration, there are many opportunities for future research. For instance, the authors can investigate application of supplier selection techniques in the CLSC configuration. However, it is noticeable that usually the complexity of closed networks is higher than open ones. Therefore, computational time is increased. In this situation, heuristics algorithms such as Genetic Algorithm and Scatter Search may be useful. In addition, it is valuable to investigate supplier selection and network configuration for general networks including refurbishing, recycling, repairing, collection, disassembly, and disposal sites. Furthermore, the remanufacturing capacity of factory is limited. Therefore, some of returned parts should be sent to remanufacturer subcontractor. According to the existence of some alternatives, selection of the best one is an important decision. Thus, a suitable decision making technique should be proposed for selection of remanufacturing subcontractor. Besides, it is supposed that the parameters are deterministic. However, in reality some factors such as demand and returns are uncertain. Stochastic, fuzzy, and robust programming can be helpful to overcome this obstacle. Moreover, the proposed model is a single period model. As a future research, multi period model can be investigated. In this situation, inventory and material flow also should be considered.

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