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In this paper, a general closed-loop supply chain (CLSC) network is configured which consists of multiple customers, parts, products, suppliers, remanufacturing subcontractors, and refurbishing sites. We propose a three-stage model including evaluation, network configuration, and selection and order allocation. In the first stage, suppliers, remanufacturing subcontractors, and refurbishing sites are evaluated based on a new quality function deployment (QFD) model. The proposed QFD model determines the relationship between customer requirements, part requirements, and process requirements. Besides, fuzzy sets theory is utilized to overcome the uncertainty in decision making process. In the second stage, the closed-loop supply chain network is configured by a stochastic mixed-integer nonlinear programming model. It is supposed that demand is an uncertain parameter. Finally in the third stage, suppliers, remanufacturing subcontractors, and refurbishing sites are selected and order allocation is determined. To this aim, a multi objective mixed-integer linear programming model is presented. An illustrative example is conducted to show the process. The main novel innovation of the proposed model is to consider CLSC network configuration and selection process simultaneously and under uncertain demand and uncertain decision making environment.

Keywords: reverse logistics (RL); closed-loop supply chain (CLSC); uncertainty; mixed-integer nonlinear programming (MINLP); fuzzy sets theory (FST)

1. Introduction

The products may be returned by customers after use. Reverse logistics is defined as the activities of the collection and recovery of product returns in supply chain management (SCM). Economic features, government directions, and customer pressure are three aspects of reverse logistics (Melo *et al.*, 2009). Generally, there are more supply points than demand points in reverse logistics networks when they are compared with forward networks (Snyder, 2006).

Several investigations have been performed about closed-loop supply chain (CLSC) configuration. In the majority of them, the parameters are deterministic (such as Krikke *et al.*, 2003; Kannan *et al.*, 2009; Amin and Zhang, 2012a). On the other hand, the minority of authors considered uncertainty (such as Listes, 2007). It is noticeable that a few of them have taken into account two or more sources of uncertainties (Snyder, 2006; Peidro *et al.*, 2009; Amin and Zhang, 2012b).

Uncertainties in supply and demand are two main sources of uncertainty in SCM. Uncertainty in supply is appeared because of the faults or delays in the supplier's deliveries. On the other hand, demand uncertainty is defined as inexact forecasting demands or as volatility demands. Therefore, it is crucial to take into account uncertain demands from both practical and research viewpoints (Davis, 1993; Peidro *et al.,* 2009; Zhang and Ma, 2009).

On the other hand, selection problem (especially supplier selection) is a subject of a lot of papers. A suitable decision making approach should be able to consider qualitative and quantitative factors. Among the qualitative techniques, quality function deployment (QFD) has absorbed a significant attention because it can consider the relationship between criteria (Amin and Razmi, 2009). In QFD, decision makers assess the alternatives subjectively, thus there is uncertainty in decision making process. To deal with this situation, an appropriate technique such as fuzzy sets theory should be combined with QFD. In addition, the most of papers have used first matrix of QFD. Among the quantitative techniques, mathematical programming frequently is applied. In selection problems, we usually deal with several factors such as cost and on-time delivery which have different natures. As a result, multi objective techniques should be utilized to select the best alternative and determine the order allocation. Even though CLSC configuration and selection problem are important issues, no investigation has examined an integrated model for selection of the best alternatives and configure the CLSC network particularly in uncertain environment.

Kim *et al.* (2006) configured a general CLSC network by maximizing the manufacturer's profit (in one stage). The network starts with returned products from customers. Then, they are collected in the collection site. The returned products are disassembled. The products that are beyond the capacity of disassembly site are sent to the remanufacturing subcontractor. The disassembled parts are categorized to reusable parts and wastes. The reusable parts are carried to the refurbishing site to be cleaned and repaired. Then, according to the number of refurbished and remanufactured parts, new parts are purchased from external supplier. In this paper, we investigate this network because it is a general network (not case-based). But, our approach and assumptions are different. In the paper of Kim *et al.* (2006), it is assumed that all of parameters such as demand and supply are certain and deterministic. In addition, they assumed single customer, supplier, remanufacturing subcontractor and refurbishing site. In this paper, a three-stage model is developed to configure the general CLSC network. In the first stage (evaluation), a new QFD model is proposed to take into account qualitative factors in the evaluation process. Unlike the majority of investigations that use house of quality (HOQ) method, the proposed QFD model consists of two matrices. Therefore, it can consider the relationship between customer requirements, part requirements, and process requirements. We also combine fuzzy sets theory in decision making process to overcome the uncertainty in human's judgments. The proposed QFD model is used to evaluate external suppliers, remanufacturing subcontractors, and refurbishing sites. The output of stage one is the weight (importance) of alternatives. The QFD can only handle qualitative criteria and another quantitative method such as mathematical programming should be added. In the second stage (network configuration), a stochastic mixed-integer nonlinear programming model is proposed to configure the CLSC network. The objective is to maximize the expected profit. Furthermore, the demands of customers are stochastic variables and uncertain. As a result, over stocking and under stocking costs are taken into account. In the third stage (selection and order allocation), a multi objective mixed-integer linear programming model is developed to select the best suppliers, remanufacturing subcontractors, and refurbishing sites. The model maximizes weights and on-time deliveries, while it minimizes total costs and defect rates. We also use two multi objective techniques including compromise, and equal weights to obtain different efficient solutions. To the best of our knowledge, the proposed model is among the first investigations in the literature that explores the selection process and CLSC configuration simultaneously, and in uncertain environment.

The paper is arranged as follows: Section 2 presents a literature review of reverse logistics and selection problem. In Section 3, the problem is defined. Then, a new model is proposed in Section 4. Section 5 presents an illustrative example. Besides, discussions are presented in Section 6. Finally, Section 7 presents conclusions.

2. Literature review

Several papers have been published about reverse logistics (RL) and closed-loop supply chain networks. Fleischmann *et al.* (1997) presented a literature review for RL. They examined the related papers based on three main categories including distribution planning, inventory, and production planning. Rubio *et al.* (2008)

presented a literature review of the papers on RL published in the scientific journals within the period 1995-2005. Melo *et al.* (2009) presented a literature review for the application of facility location models in supply chain management. They stated that the goal of the majority of models is to determine the network configuration by minimizing the total cost. However, profit maximization and multiple objectives have received less attention. Moreover, they implied that a few papers use stochastic parameters combined with other aspects such as multi-layer network structure. Guide and Van Wassenhove (2009) stated that the evolution of closed-loop supply chain networks can be examined in five phases including the golden age of remanufacturing, reverse logistics process, coordinating the reverse supply chain, closing the loop, and prices and markets. Akcali and Cetinkaya (2011) reviewed several papers of RL and CLSC. They also categorized decision techniques.

2.1. Reverse logistics under uncertainty

Uncertainty of demand and return is one the major obstacles in reverse logistics (Salema *et al.*, 2007). Peidro *et al.* (2009) identified three dimensions of uncertainty in supply chain management: the source of uncertainty (demand, supply, process), the problem type (strategic, tactical, operational), and the modelling approach (analytical, artificial intelligence-based, simulation, hybrid approaches). Listes (2007) proposed a stochastic model for the design of networks including both supply and return channels in a CLSC. They described a decomposition approach for solving the model based on the branch-and-cut method. Salema *et al.* (2007) presented a general model for reverse logistics network when there are capacity limits, and uncertain demands and returns. Lieckens and Vandaele (2007) proposed a mixed-integer nonlinear programming model based on queuing theory and stochastic lead time. However, it is designed for a single product. Pokharel and Mutha (2009) reviewed papers in reverse logistics context. They came to conclusion that mathematical modelling in RL is focused on deterministic methods and there are limited research papers considering stochastic demand. Francas and Minner (2009) studied the network design problem of a company that manufactures new products and remanufactures returned products in its facilities. They examined the capacity decisions and expected performance of manufacturing network configurations under uncertain demand and return. Pishvaee *et al.* (2009) proposed a stochastic model to configure a CLSC. They considered uncertainty in parameters. Shi *et al.* (2010) proposed a mathematical model to maximize the profit of a remanufacturing system by developing a solution approach based on Lagrangian relaxation method. Hasani *et al.* (In Press) developed an optimization model under uncertain demand and purchasing cost. Table 1 shows a summary of these papers.

Table 1. Summary of some papers about reverse logistics

References	**Number of stages**	**Multiple products**	**Multiple scenarios**	**Multiple manufacturers**	**Multiple customers**	**Multiple warehouses**	**Multiple disassembly centers**	**Multiple capacity levels**	**Multiple distributors**	**Multiple disposal centers**	**Multiple processing facilities**	**Multiple recovery facilities**
Listes (2007)	2		y	y	y							y
Salema *et al.* (2007)	1	y	y	y	y	y	y					
Lieckens and Vandaele (2007)	1				y			y			y	
Francas and Minner (2009)	2	y		y								
Pishvaee *et al.* (2009)	1		y		y				y	y		y

More directly to our model, Kim *et al.* (2002) developed a nonlinear programming (NLP) model to configure a supply network with uncertain demand. They applied stochastic programming to formulate the problem. The supply planning network includes a manufacturer and the suppliers. However, the model is designed for open loop networks. In addition, it does not take into account selection problems. Our paper extends their work for a general CLSC network. In addition, the proposed model can select the best suppliers, remanufacturing subcontractors, and refurbishing sites.

2.2. Selection problem

Each person deals with selection problems. Selection problems consist of two elements: criteria and alternatives. Some researchers investigated the problem of selection and evaluation the best third-party reverse logistics. Efendigil *et al.* (2008) presented a two-phase model based on artificial neural networks and fuzzy logic to select the most suitable third-party reverse logistics provider.

A lot of researchers have focused on evaluation and selection of the best external suppliers. De Boer *et al.* (2001) categorized supplier selection process into four phases including initial problem definition, formulation of criteria, the qualification, and final selection. Aissaoui *et al.* (2007) presented a review of the papers related to supplier selection. After description of buying process, they developed a new classification. Ghodsypour and O'Brien (1998) combined a qualitative method (analytical hierarchy process) and a quantitative method (linear programming) to select the best supplier. After this paper, several investigations have been published by using the idea such as Amin *et al.* (2011). Some of the authors also use multi objective programming methods because there are some conflicting objectives in supplier selection. Efficient solutions are obtained by solving multi objective problems. The characteristic of efficient solutions is that the value of any objective function cannot be improved without sacrificing on at least one other objective value (Wadhwa and Ravindran, 2007).

Quality function deployment (QFD) is a useful method that frequently is utilized in design quality. QFD is a unique method that can consider the relationship between elements such as customer and design requirements. QFD also is helpful in selection problems. Figure 1 displays a typical QFD. Besides, the first matrix of QFD which is called house of quality (HOQ) is illustrated in Figure 2. Bevilacqua *et al.* (2006) used HOQ for supplier selection. However, they did not take into account quantitative factors such as on-time delivery. Amin and Razmi (2009) combined a quantitative method with HOQ to take into account qualitative and quantitative metrics to select the best internet service provider. Some of the QFD related papers are summarized in Table 2. It can be observed from the Table that the majority of authors have utilized one matrix (HOQ). Furthermore, they have applied prioritizing techniques such as fuzzy sets theory.

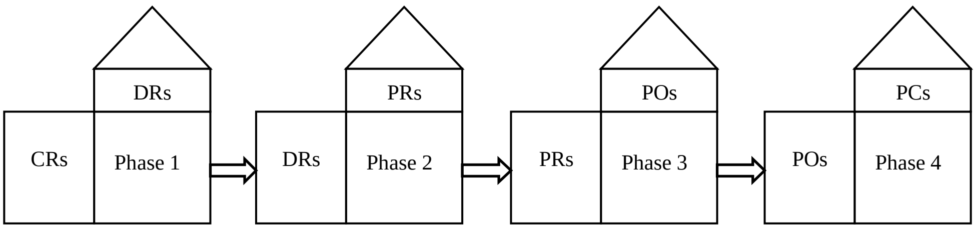

Figure 1. Quality function deployment including customer requirements (CRs), design requirements (DRs), parts requirements (PRs), process operations (POs), and production characteristics (PCs)

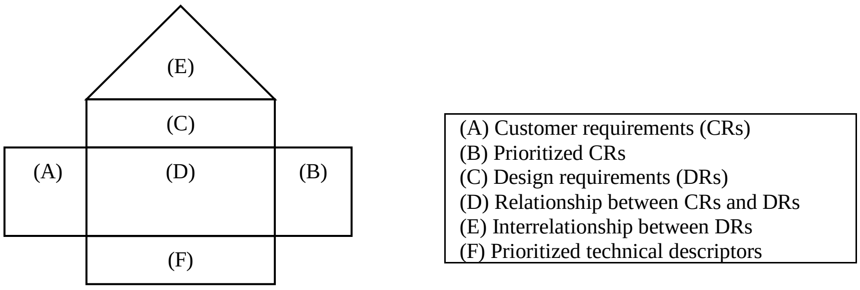

Figure 2. House of quality

Table 2. The summary of papers about QFD technique

References	**Application of QFD**	**Number of matrixes**	**Prioritizing techniques**
Han et al. (2004)	Developing a new type of pencil	1	Mathematical programming
Bevilacqua *et al.* (2006)	Supplier selection	1	Triangular fuzzy numbers
Fung *et al.* (2006)	Product development of packing-machine	1	Fuzzy numbers
Li and Kuo (2007)	Online playing games	1	Genetic chaotic neural network
Lee *et al.* (2008)	Product life cycle management (PLM)	1	Fuzzy and Kano models
Amin and Razmi (2009)	ISP selection & evaluation	1	Triangular fuzzy numbers
Delice and Gungor (2009)	Washing machine development	1	Mixed-integer linear programming
Chin *et al.* (2009)	Hypothetical writing instrument	1	Evidential reasoning (ER)
Ramanathan and Yunfeng (2009)	Design of security fasteners for a company	1	Data envelopment analysis
Zhang and Chu (2009)	Product development of HDD machine	1	Triangular fuzzy numbers
Liu (2009)	Stainless thermos	2	Triangular fuzzy numbers
Chen and Ko (2009)	Semiconductor packing case	2	Fuzzy numbers

3. Problem definition

Figure 3 shows a general closed-loop supply chain network which is designed by Kim *et al.* (2006). The manufacturer produces the products. Then they are sent to the customer. Some of the products are returned after use and they are carried to the collection site. The collected products are sent to the disassembly site. However, because of the limited capacity of disassembly site, some of the products must be carried to the remanufacturing subcontractor. In disassembly site, the products are divided into reusable parts and wastes. The reusable parts are refurbished in the refurbishing site. In addition, remanufacturing subcontractor and external supplier also supply parts. It is supposed that the objective is to maximize the profit of manufacturer, and the network is managed by manufacturer. The network configuration helps us to know how many parts and products exist in each section of the network.

In this paper, it is assumed that there are multiple customers, remanufacturing subcontractors, refurbishing sites, and external suppliers. Therefore, not only the CLSC network should be configured, but also all of the alternatives should be evaluated and selected. Besides, the order allocation should be determined. It is also important to take into account qualitative and quantitative criteria in evaluation process. Furthermore, an appropriate decision making technique should be utilized to handle the uncertainty because the decisions are made under uncertain environment. It is supposed that demand is uncertain, and at the beginning of the decision horizon, the manufacturer knows the statistical distribution of market demand of each product.

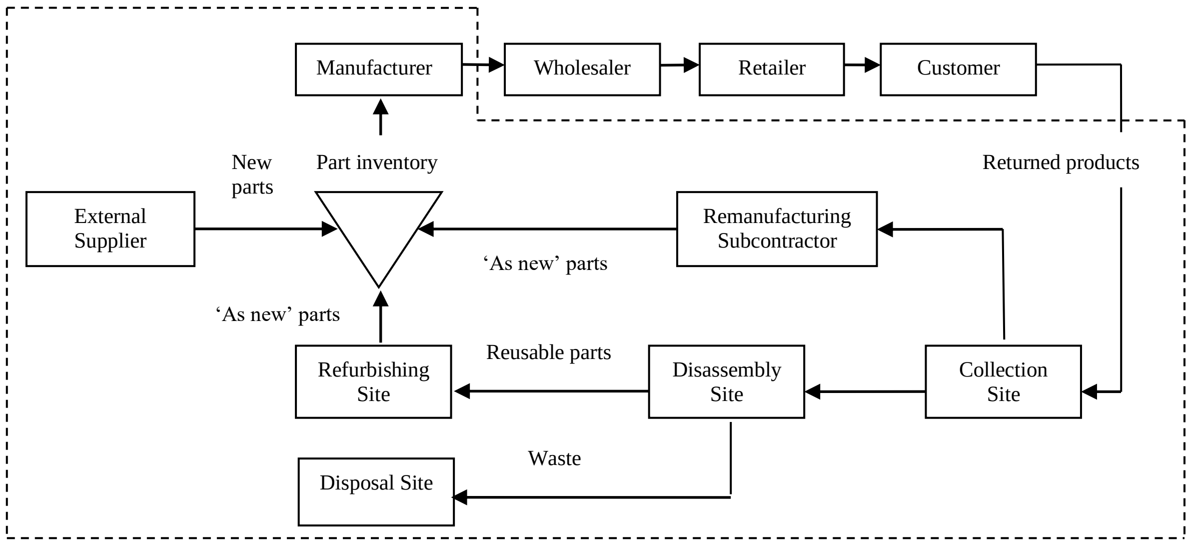

Figure 3. Framework for remanufacturing system – the dashed area (Kim *et al.*, 2006)

4. Proposed model

The objective of the proposed model is to help the manufacturer in the following issues:

- To configure the CLSC network. The objective function is maximization of the expected profit. The model should determine the units of products to be manufactured, collected, disassembled, and sent to remanufacturing subcontractors, and units of parts to be disposed, refurbished, and purchased from suppliers under uncertain demand.
- To evaluate and select the best suppliers, remanufacturing subcontractors, and refurbishing sites based on qualitative and quantitative criteria and in uncertain environment.

Figure 4 shows the framework of the proposed three-stage model. In the first stage, suppliers, remanufacturing subcontractors, and refurbishing sites are evaluated by a fuzzy QFD model due to uncertainty in decision making process (particularly for qualitative criteria). In the second stage, a stochastic programming model is used to configure the supply chain because of uncertain demand. Finally, the best alternatives are selected in the third stage by a multi objective model.

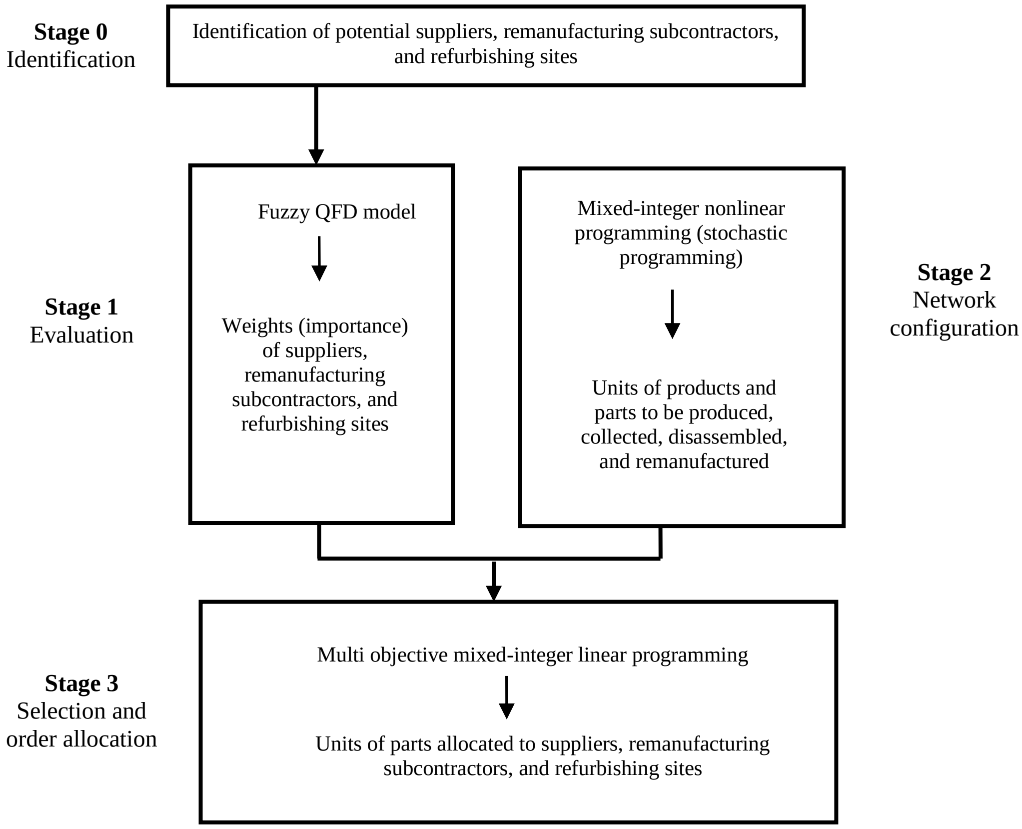

Figure 4. Framework of the proposed model

4.1. Evaluation

In the first stage, suppliers, remanufacturing subcontractors, and refurbishing sites are evaluated based on the proposed fuzzy QFD model. First, the members of decision making group should be selected. Three or five managers can contribute in decision making process. Suppose that there are E decision makers ($e = 1, 2,..., E$), and K alternatives ($k = 1, 2,..., K$). Let U = {VL, L, M, H, VH} be the linguistic set used to express opinions on the group of criteria. The linguistic variables of U can be quantified using triangular fuzzy numbers. Figure 5 displays the scale.

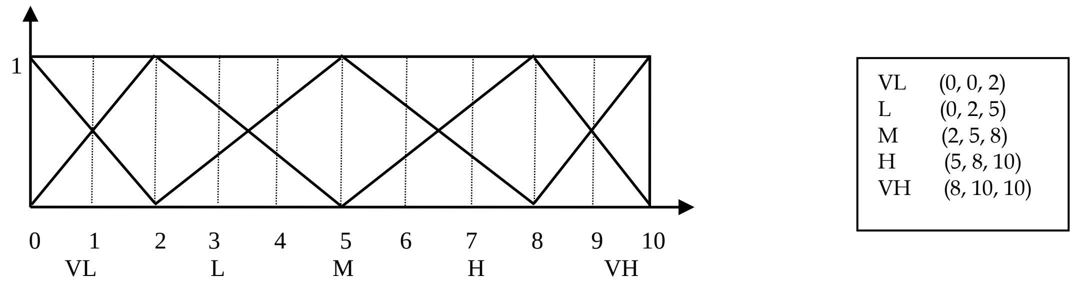

Figure 5. A linguistic scale for triangular fuzzy numbers

The QFD enables us to take into account relationship between customer requirements (CRs), design requirements (DRs), and process requirements (PRs). The main steps of the proposed model are as follows:

Step 1: List customer requirements (CRs), design requirements (DRs), and process requirements (PRs). CRs in manufacturing environment can be interpreted as product requirements such as reasonable cost, strength, and durability.

Step 2: Determine the importance of CRs. Each decision maker determines the weights of CRs. Triangular fuzzy numbers are used to quantify the linguistic variables.

Step 3: Determine weights of decision makers. Suppose that the weight of DM_e is r_e. This parameter can be determined by the manager of company. These variables are designed according to the authorities, experiences, and the responsibilities of different DMs. In addition, Eq. (1) should be satisfied where E is the number of decision makers (e = 1, 2,..., E).

$$\sum_{e=1}^{E} r_e = 1 \tag{1}$$

Step 4: Calculate aggregated weights for CRs. The assigned weights by decision makers for customer requirements should be aggregated. Aggregated weight (w_p) is calculated by Eq. (2) where P is the number of CRs (p = 1, 2,..., P).

$$w_p = (r_1 \otimes w_{p1}) \oplus ... \oplus (r_E \otimes w_{pE}) \tag{2}$$

Step 5: Determine the relationship between CRs and DRs. Each decision maker is asked to express opinion using the linguistic variables (for example low, medium, high) on the impact of each CR on each DR. Again, triangular fuzzy numbers are utilized to quantify the linguistic variables.

Step 6: Calculate aggregated weights between CRs and DRs. Aggregated weight (a_{ph}) is calculated by Eq. (3) where E is the number of decision makers (e = 1, 2,..., E), P is the number of CRs (p = 1, 2,..., P), and H is the number of DRs (h = 1, 2,..., H).

$$a_{ph} = (r_1 \otimes a_{ph1}) \oplus ... \oplus (r_E \otimes a_{phE}) \tag{3}$$

Step 7: Determine prioritized technical descriptors (in the first matrix). Now we can complete the first matrix by calculating the weights of each DR (f_h), from the aggregated weight for CR (w_p), and the aggregated weight between CR and DR (a_{ph}) according to the Eq. (4). These variables also are triangular fuzzy numbers.

$$f_h = \frac{1}{P} \otimes [(w_1 \otimes a_{1h}) \oplus ... \oplus (w_P \otimes a_{Ph})] \tag{4}$$

Step 8: Calculate aggregated weights between DRs and PRs. Aggregated weight (b_{hu}) is calculated by Eq. (5) where E is the number of decision makers (e = 1, 2,..., E), H is the number of DRs (h = 1, 2,..., H), and U is the number of PRs (u = 1, 2,..., U).

$$b_{hu} = (r_1 \otimes b_{hu1}) \oplus ... \oplus (r_E \otimes b_{huE}) \tag{5}$$

Step 9: Determine prioritized technical descriptors (in the second matrix). The second matrix can be completed by calculating the weights of each PR (g_u), from the weight of DR (f_h), and the aggregated weight between DR and PR (b_{hu}) according to the Eq. (6).

$$g_u = \frac{1}{H} \otimes [(f_1 \otimes b_{1u}) \oplus ... \oplus (f_H \otimes b_{Hu})] \tag{6}$$

Step 10: Determine the impact of each alternative on the PRs. It is necessary to evaluate alternatives based on the attributes and combine said assessments with the weight of each attribute in order to establish final ranking. In the same way as before, the linguistic variables are used to quantify triangular fuzzy numbers. Then the Alternative Rating (AR) is calculated based on the Eq. (7) where K is the number of alternatives ($k = 1, 2, ..., K$).

$$AR_{ku} = (r_1 \otimes ar_{ku1}) \oplus ... \oplus (r_E \otimes ar_{kuE}) \tag{7}$$

Step 11: Calculate the fuzzy index (*FI*). The *FI* expresses the degree to which an alternative satisfies a given requirement. The *FI* is a triangular fuzzy number which is obtained from the previous scores. Eq. (8) illustrates the formula.

$$FI_k = \frac{1}{U} \otimes [(AR_{k1} \otimes g_1) \oplus ... \oplus (AR_{kU} \otimes g_U)] \quad (8)$$

Step 12: Defuzzifiy the numbers and rank the alternatives. A deffuzzified number of $FI_k = (a, b, c)$ is calculated by Eq. (9). Now, the alternatives can be ranked. Besides, the numbers are normalized. The normalized numbers can be interpreted as the weights (importance) of alternatives.

$$DI_k = \frac{a + 2b + c}{4} \quad (9)$$

4.2. CLSC network configuration

The second stage includes the network configuration. The indices, parameters, and decision variables of the second and third stages are illustrated in Appendix (Table 12).

4.2.1. Objective function

Expected profit: The objective function (10) maximizes the expected profit. The first part of the objective function represents expected value of profit from product *j* and customer *n* when the demand of the product *j* and customer *n* is less than the actual quantity produced. This is calculated by subtracting over-stocking cost from sales revenue. In contrast, the second part represents expected value of profit from product *j* and customer *n* when the realized demand of the product *j* and customer *n* is more than the actual quantity produced. It is calculated by subtracting under-stocking cost from sales revenue. The third part of this objective function represents cost of manufacturing. In addition, the fourth part represents the costs of parts purchasing from the external supplier. The fifth part represents the disassembly cost incurs from disassembly site. The costs of refurbishing and disposal sites are calculated in the sixth and seventh parts. The eights part represents the remanufacturing subcontractor cost. Furthermore, the collection cost is considered in the ninth part. Moreover, the tenth and eleventh parts represent the set-up costs of disassembly and refurbishing sites.

$$Max\ z_1 \quad \sum_{n=1}^{N}\sum_{j=1}^{J}\int_{0}^{P_{jn}^{m}}[S_{jn}X_{jn} - v_{jn}(P_{jn}^{m} - X_{jn})]f_{jn}(x)dX_{jn} + \sum_{n=1}^{N}\sum_{j=1}^{J}\int_{P_{jn}^{m}}^{\infty}[S_{jn}P_{jn}^{m} - u_{jn}(X_{jn} - P_{jn}^{m})]f_{jn}(x)dX_{jn}$$

$$-\sum_{j=1}^{J}C_j^m\sum_{n=1}^{N}P_{jn}^m - \sum_{i=1}^{I}C_i^pQ_i^p - \sum_{j=1}^{J}C_j^rP_j^r - \sum_{i=1}^{I}C_i^{re}Q_i^{re} - \sum_{i=1}^{I}C_i^dQ_i^d \qquad (10)$$

$$-\sum_{j=1}^{J}C_j^{sub}P_j^{sub} - \sum_{j=1}^{J}C_j^{coll}P_j^{coll} - \sum_{j=1}^{J}CS_j^rU_j^r - \sum_{i=1}^{I}CS_i^{re}U_i^{re}$$

4.2.2. Constraints

The constraints of the problem are formulated as follows:

Network constraints: Constraint (11) ensures that the numbers of manufactured parts are equal to the number of refurbished and purchased and remanufactured parts. Constraint (12) represents that the number of disassembled parts are equal to the number of refurbished parts and wastes. Constraint (13) shows that collected products are sent to the remanufacturing subcontractor and disassembly site. Constraint (14) reflects the maximum percent of return. Moreover, Constraint (15) shows the limitation of max percent of reusable parts.

$$\sum_{j=1}^{J}q_{ij}\sum_{n=1}^{N}P_{jn}^m = Q_i^{re} + Q_i^p + Q_i^{sub} \qquad \forall i \qquad (11)$$

$$Q_i^{re} + Q_i^d = Q_i^r \qquad \forall i \qquad (12)$$

$$P_j^{sub} + P_j^r = P_j^{coll} \qquad \forall j \qquad (13)$$

$$P_j^{coll} \le Z\sum_{n=1}^{N}P_{jn}^m \qquad \forall j \qquad (14)$$

$$Q_i^{re} \le E\ Q_i^r \qquad \forall i \qquad (15)$$

Product and part constraints: Constraints (16) and (17) ensure the relationship between parts and products in disassembly and remanufacturing sites.

$$Q_i^r = \sum_{j=1}^{J}q_{ij}P_j^r \qquad \forall i \qquad (16)$$

$$Q_i^{sub} = \sum_{j=1}^{J} q_{ij} P_j^{sub} \qquad \forall i \qquad (17)$$

Capacity constraints: Constraints (18) and (19) represent maximum capacity of manufacturer and disassembly sites.

$$\sum_{j=1}^{J} a_j \sum_{n=1}^{N} P_{jn}^{m} \leq W^{m} \qquad (18)$$

$$e_J^{r} P_j^{r} \leq W_j^{r} \qquad \forall j \qquad (19)$$

Set-up constraints: Constraints (20) and (21) are set-up constraints for set-up at the disassembly and refurbishing sites.

$$P_j^{r} \leq B\,U_j^{r} \qquad \forall j \qquad (20)$$

$$Q_i^{re} \leq B\,U_i^{re} \qquad \forall i \qquad (21)$$

Binary and non-negativity constraints:

$$U_j^{r}, U_i^{re} \in \{0,1\} \qquad \forall i, j \qquad (22)$$

$$P_{jn}^{m}, P_j^{r}, P_j^{coll}, P_j^{sub}, Q_i^{P}, Q_i^{sub}, Q_i^{r}, Q_i^{re}, Q_i^{d} \geq 0 \qquad \forall i, j, n \qquad (23)$$

4.3. Selection and order allocation

In the third stage, the best suppliers, remanufacturing subcontractors, and refurbishing sites are selected. In addition, the order allocation is determined. To this aim, a multi objective mathematical model is proposed. Because of two reasons, we cannot combine stage 2 and stage 3 as a one stage. Firstly, the demands of customers are stochastic variables and they are determined by minimizing the total cost. Therefore, the demands are not included in the objective functions of on-time delivery and defect rates. Secondly, we have assumed that products beyond the capacity of disassembly site are sent to the remanufacturing subcontractors. In other words, the cost of disassembly is less than the cost of remanufacturing by subcontractors. If we combine the second and third stages, for the objective function of on-time delivery or defect rates, all products are sent to the remanufacturing subcontractors because there is no associated cost in the objective function of on-time delivery or defect rates.

4.3.1. Objective functions

The objective is minimization of costs and defect rates, and maximization of weights, and on-time delivery, simultaneously. In this model, Q_i^p, Q_i^{re}, and P_j^{sub} are parameters that are calculated in Stage 2. The mathematical form for these objectives is:

Total cost: The objective function (24) minimizes the total cost. The first part of the objective function represents the purchasing costs. The second part shows the costs of refurbishing sites. Furthermore, the third part represents the costs of remanufacturing subcontractors. Fixed costs associated with suppliers, remanufacturing subcontractors and refurbishing costs are written in the fourth, fifth, and sixth parts.

$$Min\ z_1 \quad \sum_{i=1}^{I}\sum_{k=1}^{K} C_{ik}^{P} Q_{ik}^{P} + \sum_{l=1}^{L}\sum_{i=1}^{I} C_{il}^{re} Q_{il}^{re} + \sum_{m=1}^{M}\sum_{j=1}^{J} C_{jm}^{sub} P_{jm}^{sub} + \sum_{k=1}^{K} g_k s_k + \sum_{m=1}^{M} y_m t_m + \sum_{l=1}^{L} h_l w_l \qquad (24)$$

Weight: This objective function includes three parts. The weights (importance) of suppliers, refurbishing sites, and remanufacturing subcontractors should be maximized.

$$Max\ z_2 \quad \sum_{i=1}^{I}\sum_{k=1}^{K} WE_{ik}^{P} Q_{ik}^{P} + \sum_{l=1}^{L}\sum_{i=1}^{I} WE_{il}^{re} Q_{il}^{re} + \sum_{m=1}^{M}\sum_{j=1}^{J} WE_{jm}^{sub} P_{jm}^{sub} \qquad (25)$$

Defect rate: This objective function consists of two parts. The units of purchased parts from external suppliers, and the units of refurbished parts are minimized according to the defect rate.

$$Min\ z_3 \quad \sum_{i=1}^{I}\sum_{k=1}^{K} DE_{ik}^{P} Q_{ik}^{P} + \sum_{l=1}^{L}\sum_{i=1}^{I} DE_{il}^{re} Q_{il}^{re} \qquad (26)$$

On-time delivery: This objective function takes into account the maximization of units of purchased parts from external suppliers, and the units of refurbished parts based on on-time delivery.

$$Max\ z_4 \quad \sum_{i=1}^{I}\sum_{k=1}^{K} OE_{ik}^{P} Q_{ik}^{P} + \sum_{l=1}^{L}\sum_{i=1}^{I} OE_{il}^{re} Q_{il}^{re} \qquad (27)$$

4.3.2. Constraints

The constraints of the problem are formulated as follows:

$$\sum_{i=1}^{I} b_{ik}^{P} Q_{ik}^{p} \leq W_{k}^{s} s_{k} \qquad \forall k \qquad (28)$$

$$\sum_{j=1}^{J} b_{jm}^{sub} P_{jm}^{sub} \leq W_{m}^{sub} t_{m} \qquad \forall m \qquad (29)$$

$$\sum_{i=1}^{I} e_{il}^{re} O_{il}^{re} \leq W_{l}^{re}\ w_{l} \qquad \forall l \qquad (30)$$

$$\sum_{k=1}^{K} Q_{ik}^{p} = Q_{i}^{p} \qquad \forall i \qquad (31)$$

$$\sum_{l=1}^{L} Q_{il}^{re} = Q_{i}^{re} \qquad \forall i \qquad (32)$$

$$\sum_{m=1}^{M} P_{jm}^{sub} = P_{j}^{sub} \qquad \forall j \qquad (33)$$

$$\sum_{k=1}^{K} s_{k} \leq G \qquad (34)$$

$$\sum_{m=1}^{M} t_{m} \leq T \qquad (35)$$

$$\sum_{l=1}^{L} w_{l} \leq F \qquad (36)$$

$$s_{k}, t_{m}, w_{l} \in \{0,1\} \qquad \forall k, m, l \qquad (37)$$

$$Q_{ik}^{P}, Q_{il}^{re}, P_{jm}^{sub} \geq 0 \qquad \forall i, j, k, l, m \qquad (38)$$

Constraints (28)-(30) represent the capacity of suppliers, remanufacturing subcontractors, and refurbishing sites, respectively. Constraints (31)-(33) show the total numbers of purchased and refurbished parts, and remanufactured products. Constraints (34)-(36) represent that the number of suppliers, remanufacturing subcontractors, and refurbishing sites must be less than or equal to the certain numbers.

4.3.3. Solution methodology

Multi objective problems can be solved using different methods. In this paper, weighted sums method, and compromise method are applied. The goal is to transform our problem so that it turns into a mono-objective optimization model.

Weighted sums method

The most popular but not really appropriate method for solving multi objective problems is the weighted sums method. In this method, decision makers determine the weights. The weights can be changed to generate different efficient solutions. The weighing method usually is utilized to approximate the efficient set. The Eq. (39) has to be solved for all $\lambda_c \in R^D$ with $0 \le \lambda_c \le 1$ and $\sum_c \lambda_c = 1$ where λ_c is the weight of objective function *c*, and *D* is the number of objective functions (Tanino *et al.,* 2003). It is supposed that all objective functions are minimization. Our problem is transformed to a single objective which is shown by Eq. (40).

$$Min \ \{\sum_{c=1}^{D} \lambda_c z_c(x) : x \in X\} \tag{39}$$

$$Min \quad \lambda_1 z_1 - \lambda_2 z_2 + \lambda_3 z_3 - \lambda_4 z_4 \tag{40}$$

Compromise method

Compromise programming tries to find a solution that comes as close as possible to the ideal values. Ideal solution corresponds to the best value that can be achieved for each objective, ignoring other objectives. "Closeness" is defined by the L_V distance metric which is shown in Eq. (41) where $z_c^* = min\ (z_c)$. It should be noted that all objective functions are minimization. Any point that minimizes L_V for $1 \le V \le \infty$ and $0 \le \lambda_c \le 1$ and $\sum_c \lambda_c = 1$ is called a compromise solution (Wadhwa and Ravindran, 2007). Therefore, the objective function of the problem can be written in the form of Eq. (42).

$$L_V = \left[\sum_{c=1}^{D} \lambda_c{}^V [\frac{z_c - z_c^*}{z_c^*}]^V \right]^{\frac{1}{V}} \quad \forall V = 1,2,\ldots,\infty \tag{41}$$

$$Min \quad [\lambda_1^V (\frac{z_1 - z_1^*}{z_1^*})^V - \lambda_2^V (\frac{z_2 - z_2^*}{z_2^*})^V + \lambda_3^V (\frac{z_3 - z_3^*}{z_3^*})^V - \lambda_4^V (\frac{z_4 - z_4^*}{z_4^*})^V]^{\frac{1}{V}} \quad \forall V = 1,2,...,\infty \quad (42)$$

5. An illustrative example

In this section, a numerical example is presented to show the proposed model. Suppose that a computer manufacturer assembles and sells 3 models of computer. In addition, each product is produced by 5 parts. The manufacturer is interested to know how many products and parts exist in each part of the closed-loop network. There are 5 alternatives of suppliers, remanufacturing subcontractors, refurbishing sites, and customers. Thus, it is important to select the best suppliers, remanufacturing subcontractors, and refurbishing sites. The data of the example is available based on request. The General Algebraic Modelling System (GAMS) is utilized to solve the model. GAMS is a high-level modelling software for mathematical programming and optimization. It has been run by default in this paper.

5.1. Stage 1

In the first stage, the suppliers, remanufacturing subcontractors, and refurbishing sites are evaluated by the proposed fuzzy QFD method. Figure 6 illustrates the selected qualitative criteria. In this example, the evaluation process of suppliers based on one part is examined. Furthermore, the linguistic set is utilized to express the opinions of experts. Each of the three decision makers establishes a weight for customer requirements. The results are shown in Table 3. The manager of company has determined a weight for each decision maker. In this example, there are three decision makers. Besides, one of them has more experience. Therefore, the manager has devoted the weights as r_1 = 0.4, r_2 = 0.3, and r_3 = 0.3. The aggregated weights are calculated in Table 4. In our case, P = 4, H = 4, U = 4, and K = 5. The opinions of the three decision-makers on the impact of CRs on DRs are shown in Table 5.

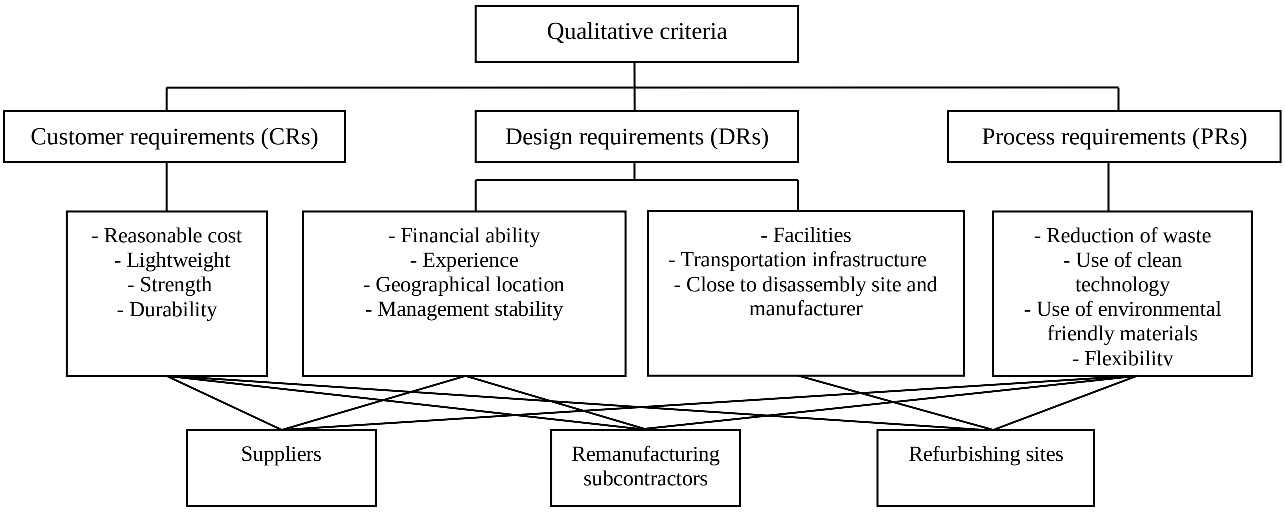

Figure 6. Qualitative criteria

Table 3. The importance of CRs

Customer requirements (CRs)	**DM$_1$**	**DM$_2$**	**DM$_3$**
Reasonable Cost	H	L	M
Lightweight	H	VH	H
Strength	H	M	H
Durability	M	L	L

Table 4. Aggregated weights

	DM$_1$	**DM$_2$**	**DM$_3$**	
	0.4	0.3	0.3	Aggregated weights
Reasonable cost	(5, 8, 10)	(0, 2, 5)	(2, 5, 8)	(2.6, 5.3, 7.9)
Lightweight	(5, 8, 10)	(8, 10, 10)	(5, 8, 10)	(5.9, 8.6, 10)
Strength	(5, 8, 10)	(2, 5, 8)	(5, 8, 10)	(4.1, 7.1, 9.4)
Durability	(2, 5, 8)	(0, 2, 5)	(0, 2, 5)	(0.8, 3.2, 6.2)

Table 5. Impact of customer requirements (CRs) on design requirements (DRs)

DRs	Financial ability			Experience			Geographical location			Management stability		
CRs	**DM$_1$**	**DM$_2$**	**DM$_3$**	**DM$_1$**	**DM$_2$**	**DM$_3$**	**DM$_1$**	**DM$_2$**	**DM$_3$**	**DM$_1$**	**DM$_2$**	**DM$_3$**
Reasonable cost	VH	H	H	M	H	H	H	H	H	H	M	H
Lightweight	M	H	L	VH	VH	H	VL	VL	M	M	VL	M
Strength	M	H	H	M	M	H	L	M	L	M	L	L
Durability	L	M	M	H	H	H	L	M	M	M	M	M

The aggregated weights between CRs and DRs are calculated. Besides, prioritized technical descriptors are obtained. Figure 7 illustrates the first matrix. According to the model, the second matrix also is completed that is displayed in Figure 8. For example, (0.8, 3.2, 6.2) shows the impact of Management stability on Reduction of waste which is determined by decision makers and linguistic variables. These numbers are used to calculate the weight (importance) of each alternative. The impact of each alternative on the PRs is considered in Table 6. Then, alternative ranking and *FI* are calculated. The final results are written in Table 7. The normalized numbers represent the importance (weight) of alternatives. According to this Table, the fifth alternative (A_5) is the best one.

	Financial ability	Experience	Geographical location	Management stability	
Cost	(6.2, 8.8, 10)	(3.8, 6.8, 9.2)	(5, 8, 10)	(4.1, 7.1, 9.4)	(2.6, 5.3, 7.9)
Lightweight	(2.3, 5, 7.7)	(7.1, 9.4, 10)	(0.6, 1.5, 3.8)	(1.4, 3.5, 6.2)	(5.9, 8.6, 10)
Strength	(3.8, 6.8, 9.2)	(2.9, 5.9, 8.6)	(0.6, 2.9, 5.9)	(0.8, 3.2, 6.2)	(4.1, 7.1, 9.4)
Durability	(1.2, 3.8, 6.8)	(5, 8, 10)	(1.2, 3.8, 6.8)	(2, 5, 8)	(0.8, 3.2, 6.2)
	f_1	f_2	f_3	f_4	
	(11.6, 37.5, 71.2)	**(16.9, 46.1, 78.9)**	**(5, 22, 53.7)**	**(6, 26.6, 61)**	

Figure 7. The first matrix of QFD

	Reduction of waste	Use of clean technology	Use of environmental friendly materials	Flexibility	
Financial ability	(5.9, 8.6, 10)	(7.1, 9.4, 10)	(5, 8, 10)	(2.9, 5.9, 8.6)	(11.6, 37.5, 71.2)
Experience	(2, 5, 8)	(4.1, 7.1, 9.4)	(2.9, 5.9, 8.6)	(6.2, 8.8, 10)	(16.9, 46.1, 78.9)
Geographical location	(0.6, 2.3, 5)	(1.4, 4.1, 7.1)	(2.9, 5.9, 8.6)	(2.9, 5.9, 8.6)	(5, 22, 53.7)
Management stability	(0.8, 3.2, 6.2)	(0.6, 2.9, 5.9)	(1.4, 4.1, 7.1)	(4.1, 7.1, 9.4)	(6, 26.6, 61)
	g_1	g_2	g_3	g_4	
	(27.5, 172.2, 497.5)	**(40.6, 211.8, 548.7)**	**(32.5, 202.7, 571.4)**	**(44.4, 236.4, 609.1)**	

Figure 8. The second matrix of QFD

Table 6. The impact of alternatives on process requirements (PRs)

PRs	Reduction of waste			Use of clean technology			Use of environmental friendly materials			Flexibility		
Alternatives	**DM_1**	**DM_2**	**DM_3**	**DM_1**	**DM_2**	**DM_3**	**DM_1**	**DM_2**	**DM_3**	**DM_1**	**DM_2**	**DM_3**
A_1	M	M	L	M	L	L	M	M	M	H	VH	H
A_2	M	H	M	M	M	M	H	M	H	M	H	H
A_3	VL	VL	L	M	L	L	VH	L	VL	VH	H	VH
A_4	H	H	H	VH	H	M	M	H	H	M	L	M
A_5	H	M	H	VH	H	H	M	H	H	M	M	M

Table 7. Calculating the *FI* and normalization

	a	*b*	*c*	Score	Normalization	Rank
A_1	99	1108	4399	1678	0.188	4
A_2	116	1280	4911	1897	0.212	3
A_3	113	984	3605	1422	0.159	5
A_4	135	1350	4929	1941	0.217	2
A_5	144	1412	5073	2010	0.225	1

5.2. Stage 2

In the second stage, the closed-loop supply chain is configured. In this stage, it is supposed that there are single supplier, remanufacturing subcontractor, and refurbishing site. In addition, the demand is a stochastic parameter. Therefore, under stocking and over stocking costs should be considered. The results of mathematical programming model are written in Table 8. The first section shows the units of products that should be manufactured for each customer. For instance, the manufacturer should produce 483 units of product 1 for customer 1. The second section of Table 8 illustrates product related variables including the number of products that are collected, disassembled, and sent to the remanufacturing subcontractor. For example, due to capacity of disassembly site, 200 units of collected products (type 2) are disassembled and the rest of them (403), are sent to the remanufacturing subcontractors. The third section of Table 8 displays the part related variables. In other words, the numbers of disassembled, disposed and refurbished parts are calculated. For instance, from 1900 units of disassembled parts 1, 950 units are refurbished and 950 units are disposed. In addition, Table 8 shows how many parts should be purchased from external supplier.

Table 8. Results of Stage 2

P_{jn}^{m} (Units of product *j* to be produced for customer *n*)					
j / n	**1**	**2**	**3**	**4**	**5**
1	483	583	85	183	283
2	305	205	285	305	105
3	218	318	218	428	218

Product-related variables

j	**1**	**2**	**3**
P_j^{coll}	809	603	700
P_j^{r}	500	200	700
P_j^{sub}	309	403	-

Part-related variables

i	**1**	**2**	**3**	**4**	**5**
Q_i^{sub}	1021	1518	1734	1021	1518
Q_i^{r}	1900	1800	4702	3301	2501
Q_i^{re}	950	900	2351	1651	1250
Q_i^{d}	950	900	2351	1651	1250
Q_i^{P}	3872	4218	8786	5973	5269

5.3. Stage 3

The mathematical programming model is solved by some techniques including single objectives (first, second, and third objectives), equal weights, and compromise method. For example, we calculated the results in GAMS by considering the first objective. The number of products that are sent to subcontractors, the number of purchased parts from external suppliers, and the number of refurbished parts are calculated in Table 9. It can be seen that there are some differences between the solutions. For instance, the first part is purchased from supplier 4 based on the first objective because the cost of purchasing is minimum ($12). However, the results of second objective show that the part 1 is bought from supplier 1 due to the maximum weight (0.21).

Table 9. Results of multi objective techniques

First objective			**Second objective**			**Third objective**			**Fourth objective**			**Equal weights**			**Compromise method**		
j	m	P_{jm}^{sub}	j	m	P_{jm}^{sub}	j	m	P_{jm}^{sub}	j	m	P_{jm}^{sub}	j	m	P_{jm}^{sub}	j	m	P_{jm}^{sub}
1	2	309	1	2	309	1	1	309	1	1	309	1	2	309	1	2	309
2	4	403	2	2	403	2	1	403	2	1	403	2	4	403	2	4	403
i	k	Q_{ik}^{p}	i	k	Q_{ik}^{p}	i	k	Q_{ik}^{p}	i	k	Q_{ik}^{p}	i	k	Q_{ik}^{p}	i	k	Q_{ik}^{p}
1	4	3872	1	1	3872	1	2	3872	1	5	3872	1	4	3872	1	2	3872
2	3	4218	2	5	4218	2	5	4218	2	1	4218	2	3	4218	2	5	4218
3	1	8786	3	2	8786	3	2	8786	3	1	8786	3	1	8786	3	4	8786
4	5	5973	4	1	5973	4	1	5973	4	3	5973	4	2	5973	4	1	5973
5	4	5269	5	3	5269	5	3	5269	5	5	5269	5	4	5269	5	3	5269
i	l	Q_{il}^{re}	i	l	Q_{il}^{re}	i	l	Q_{il}^{re}	i	l	Q_{il}^{re}	i	l	Q_{il}^{re}	i	l	Q_{il}^{re}
1	2	950	1	4	950	1	4	950	1	5	950	1	2	950	1	4	950
2	4	900	2	2	900	2	5	900	2	1	900	2	4	900	2	4	900
3	4	2350	3	2	2350	3	2	2350	3	2	2350	3	2	2350	3	2	2350
4	2	1650	4	2	1650	4	1	1650	4	3	1650	4	2	1650	4	2	1650
5	2	1250	5	5	1250	5	5	1250	5	1	1250	5	1	1250	5	5	1250

The values of objective functions for single objectives, equal weights, and compromise methods are shown in Table 10. Each of the cases represents a unique situation. Table 10 can be displayed to the management to produce information for the decision making situation. Management may also select the most suitable alternative depends on some other factors.

Table 10. Value of objective functions

Multi-objective methods	**z_1 (cost)**	**z_2 (weight)**	**z_3 (defect rate)**	**z_4 (on-time delivery)**
First objective	478649	7047	2905	31891
Second objective	572883	8006	1957	31891
Third objective	597675	7821	1747	31683
Fourth objective	558849	7222	2923	32823
Equal weights	478649	7283	3098	32265
Compromise method	521470	7288	1755	31832

6. Managerial implications and discussions

The following results can be observed from the application of the proposed model.

6.1. Comparison between the proposed model and HOQ

In the first stage, the new QFD method is utilized to evaluate the alternatives. The proposed model includes two QFD matrices. We also solve the problem by house of quality (HOQ) method that has one QFD matrix. The results are illustrated in Table 11. According to the Table, the ranks of suppliers are same. However, the weights of them have changed. For example, the weight (importance) of supplier 5 increased in

HOQ method. It is noticeable that not only the ranking is important, but also the weights have significant effects on the results because they are inputs of Stage 3.

Table 11. Comparison between the first stage and HOQ

	HOQ			The proposed model		
	Score	Normalization	Rank	Score	Normalization	Rank
A₁	212	0.178	4	1678	0.188	4
A₂	250	0.210	3	1897	0.212	3
A₃	172	0.144	5	1422	0.159	5
A₄	275	0.231	2	1941	0.217	2
A₅	283	0.238	1	2010	0.225	1

6.2. Sensitivity analysis of uncertain demand

In order to see the impact of demand uncertainty on the objective function (stage 2), we vary the standard deviations of demands and solve the problem. It is supposed that demand has normal distribution. Figure 9 shows the sensitivity analysis for the demand of customer 1. It is observable that expected profit decreases as the uncertainty of demand (standard deviation) increases.

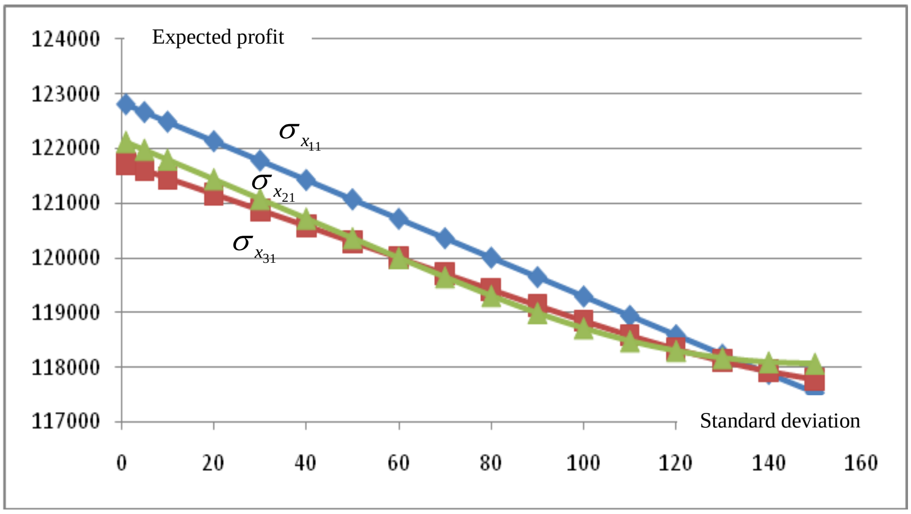

Figure 9. Expected profit as a function of standard deviations

6.3. Comparison of single and multiple sourcing policies

In single sourcing policy, the parts are purchased from one supplier. Figure 10 compares the optimal procurement of single and multiple sourcing policies. It can be seen that with the single sourcing policy, the manufacturer encounters higher cost (objective function) rather than multiple sourcing policy. Moreover, it is noticeable that supplier 4 cannot supply enough parts due to the limitation of its capacity. Therefore, in this situation a portion of demand cannot be supplied.

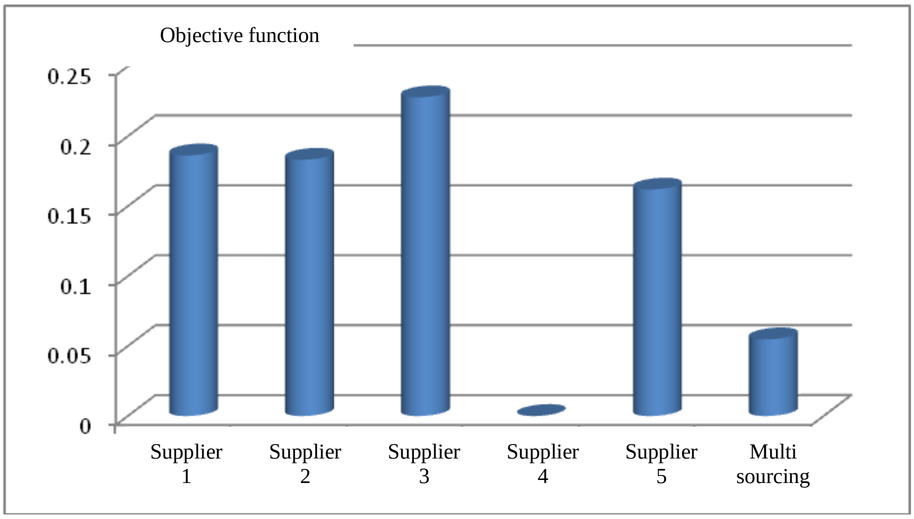

Figure 10. Value of objective function of single and multiple sourcing policies (compromise method)

6.4. Sensitivity analysis of capacity

We observed the changes of objective function by varying the capacity of remanufacturing subcontractors, while the other factors are fixed. Results are illustrated in Figure 11. This analysis shows that the minimum objective function can be obtained with a certain capacity of remanufacturing subcontractors. As a result, in practice, the capacity should be expanded to a particular level.

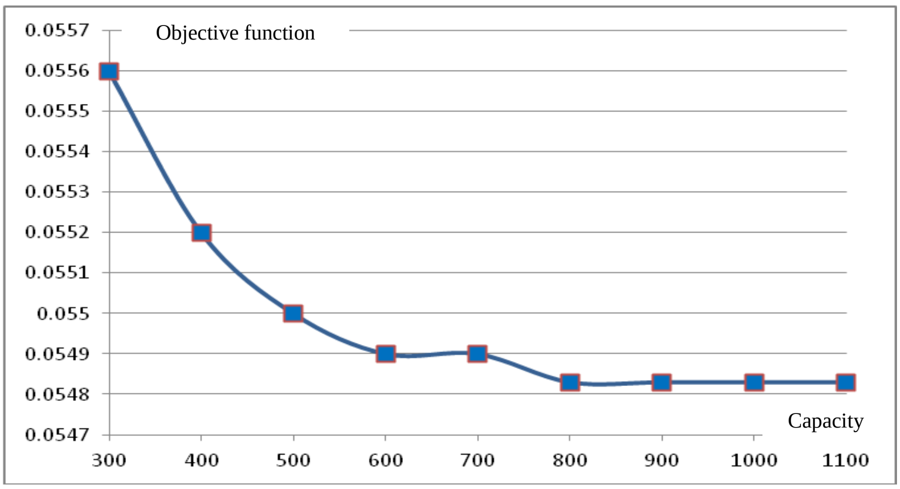

Figure 11. Sensitivity analysis for capacity of remanufacturing subcontractors

7. Conclusions

In this paper, a three-stage model is proposed to evaluate and choose the best suppliers, remanufacturing subcontractors, and refurbishing sites based on qualitative and quantitative criteria. In addition, the closed-loop supply chain network is configured. In the proposed model, the uncertainty in selection process and demand are taken into account. Moreover, the use of the model has been demonstrated through an illustrative example. The results show that the model is a viable tool and can be useful in decision making regarding the management of closed-loop supply chain network.

There are still some future lines of research. In the model, the return is a deterministic parameter. It is valuable to consider uncertain returns and examine the impacts of stochastic or fuzzy parameters. On the other hand, the model is designed for a general network. It is worthwhile to apply the model in real cases and see the effects. For example, some managers may not be interested in using the QFD model due to the shortage of time. Moreover, quantity discount can be the subject of future research. Quantity discount is a well-known approach which is employed by suppliers to promote their products. One difficulty is that the production level depends on product demands and it is unknown. But, the production level of each product is essential to determine the quantity of purchased parts. Another future research is investigating on the mathematical properties of the model to develop suitable solution approaches.

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Appendix A: Fuzzy sets theory

Nowadays, operations research is applied for solving decision making problems. Unfortunately, real world situations often are not deterministic. As a result, precise mathematical models are not enough to cover practical situations (Lai and Hwang, 1995). To deal with imprecision, fuzzy sets theory (FST) can be used. This concept was proposed by Zadeh (1965). FST considers the situations involving the human factor with all its vagueness of perception, subjectively, attitudes, goals and conceptions. Let X be the universe whose generic element be denoted by x. A fuzzy set A is a function $A: X \rightarrow [0,1]$.

There are several types of fuzzy numbers. Triangular fuzzy number (TFN) is one of them. A TFN A is denoted by triplet $A = (a_l, a, a_u)$ and has the shape of a triangle as shown in Figure 12. Moreover, its membership function μ_A is given by Eq. (43).

$$\mu_A(x) = \begin{cases} 0 & , x < a_1, x > a_u \\ \dfrac{x - a_1}{a - a_1} & , a_1 \le x \le a \\ \dfrac{a_u - x}{a_u - a} & , a < x \le a_u \end{cases} \tag{43}$$

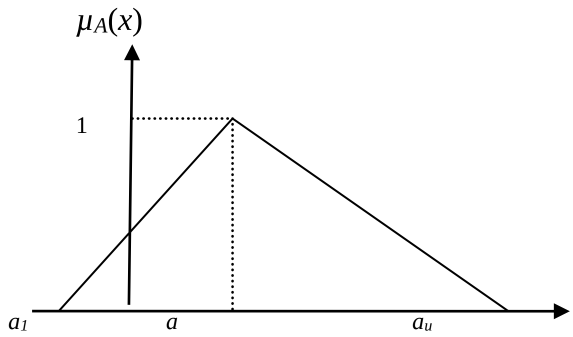

Figure 12. A triangular fuzzy number $A = (a_1, a, a_u)$

Let $A = (a_1, a, a_u)$ and $B = (b_1, b, b_u)$ be two TFNs then (Bector and Chandra, 2005):

(i) Addition of two fuzzy numbers $A \oplus B = (a_1 + b_1, a + b, a_u + b_u)$

(ii) Multiplication of two fuzzy numbers $A \otimes B = (a_1 \times b_1, a \times b, a_u \times b_u)$

(iii) Subtraction of two fuzzy numbers $A \Delta B = (a_1 - b_1, a - b, a_u - b_u)$

Appendix B

Table 12. The indices, parameters, and decision variables of the second and third stages

Indices

i	Set of parts, $i = 1,..., I$
j	Set of products, $j = 1,..., J$
k	Set of suppliers, $k = 1,..., K$
l	Set of refurbishing sites, $l = 1,..., L$
m	Set of remanufacturing subcontractors, $m = 1,..., M$
n	Set of customers, $n = 1,..., N$

Stochastic variables

X_{jn}	Random variable of the demand of product *j* for customer *n*
$f_{jn}(x)$	PDF of the demand of product *j* for customer *n*

Decision variables

P_{jn}^{m}	Units of product *j* to be produced for customer *n*
P_{j}^{r}	Units of returned product *j* to be disassembled
P_{j}^{coll}	Units of product *j* to be collected
P_{jm}^{sub}	Units of product *j* to be remanufactured by subcontractor *m*
P_{j}^{sub}	Units of product *j* to be remanufactured
Q_{ik}^{p}	Units of part *i* to be purchased from external supplier *k*
Q_{i}^{p}	Units of part *i* to be purchased
Q_{im}^{sub}	Units of part *i* to be remanufactured by subcontractor *m*
Q_{i}^{sub}	Units of part *i* to be remanufactured
Q_{i}^{r}	Units of part *i* that are obtained in disassembly site
Q_{il}^{re}	Units of part *i* to be refurbished in refurbishing site *l*
Q_{i}^{re}	Units of part *i* to be refurbished
Q_{i}^{d}	Units of part *i* to be disposed
U_{i}^{re}	Binary variable for set-up of refurbishing site for part *i*
U_{j}^{r}	Binary variable for set-up of disassembly site for product *j*
s_{k}	Binary variable for selection of supplier *k*
t_{m}	Binary variable for selection of subcontractor *m*
w_{l}	Binary variable for selection of refurbishing site *l*

Parameters

S_{jn}	Unit selling price of the product *j* for customer *n*
u_{jn}	Under stocking cost of product *j* for customer *n*
v_{jn}	Overstocking cost of product *j* for customer *n*
a_{j}	Resource usage to produce one unit of product *j*
C_{j}^{m}	Unit direct manufacturing cost of product *j*
CS_{j}^{r}	Set-up cost of disassembly site for product *j*
C_{j}^{coll}	Unit direct collection cost of product *j*
C_{j}^{r}	Unit disassembly cost for product *j*
C_{i}^{d}	Unit disposing cost for part *i*
e_{j}^{r}	Resource usage to disassemble one unit of product *j*
C_{il}^{re}	Unit refurbishing cost for part *i* in refurbishing site *l*
C_{i}^{re}	Minimum unit refurbishing cost for part *i*
CS_{i}^{re}	Set-up cost of refurbishing site for part *i*
e_{il}^{re}	Resource usage to refurbish one unit of part *i* in site *l*
W_{l}^{re}	Maximum capacity of refurbishing site *l*
q_{ij}	Unit requirements for part *i* to produce one unit of product *j*
C_{ik}^{p}	The purchasing cost of part *i* from external supplier *k*
C_{i}^{p}	The minimum purchasing cost of part *i*
C_{jm}^{sub}	Unit remanufacturing cost of subcontractor *m* for product *j*
C_{j}^{sub}	Minimum unit remanufacturing cost for product *j*
b_{ik}^{P}	Resource usage of supplier *k* for producing part *i*
b_{jm}^{sub}	Internal resource usage of remanufacturing subcontractor *m* to produce one unit of product *j*
W_{k}^{s}	Maximum capacity reserved of external supplier *k*
W_{m}^{sub}	Maximum capacity reserved of remanufacturing subcontractor *m*
Z	Maximum percent of returns
E	Maximum percent of reusable parts
W^{m}	Maximum capacity of the manufacturer plant
WE_{ik}^{P}	Weight (importance) of supplier *k* for part *i*
WE_{il}^{re}	Weight (importance) of refurbishing site *l* for part *i*
WE_{jm}^{sub}	Weight (importance) of remanufacturing subcontractor *m* for remanufacturing product *j*
DE_{ik}^{P}	Defect rate of part *i* that is produced by supplier *k*
DE_{il}^{re}	Defect rate of part *i* that is refurbished in site *l*
OE_{ik}^{P}	Rate of on-time delivery of part *i* by supplier *k*
OE_{il}^{re}	Rate of on-time delivery of part *i* in refurbishing site *l*
g_{k}	Fixed cost associated with supplier *k*
y_{m}	Fixed cost associated with subcontractor *m*
h_{l}	Fixed cost associated with refurbishing site *l*
G	Maximum number of external suppliers
T	Maximum number of remanufacturing subcontractors
F	Maximum number of refurbishing sites
B	A big number
W_{j}^{r}	Maximum capacity to dissemble product *j*
$\mu_{x_{jn}}$	Mean demand of product *j* for customer *n*
$\sigma_{x_{jn}}$	Standard deviation of demand of product *j* and customer *n*