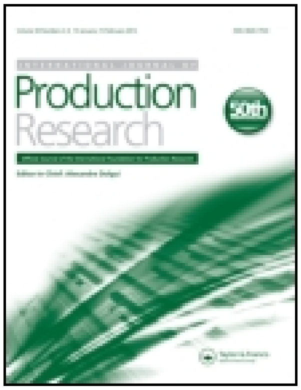

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A three-stage model for closed-loop supply chain configuration under uncertainty

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A three-stage model for closed-loop supply chain configuration under uncertainty

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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. In addition, the fuzzy sets theory is utilised to overcome the uncertainty in the 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 end, 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 the CLSC network configuration and selection process simultaneously, under uncertain demand and in an 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

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 on closed-loop supply chain (CLSC) configuration. In the majority of them, the parameters are deterministic (as in Krikke *et al.* 2003, Kannan *et al.* 2009, Amin and Zhang 2012b). On the other hand, a 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 2012a). Uncertainties in supply and demand are two main sources of uncertainty in SCM. Uncertainty in supply appears because of 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, the 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 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 the decision-making process. To deal with this situation, an appropriate technique such as fuzzy sets theory should be combined with QFD. In addition, most papers have used the 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 utilised to select the best alternative and determine order allocation. Even though CLSC configuration and selection problems are important issues, no investigation has examined an integrated model for the selection of the best alternatives and configured the CLSC network particularly in an uncertain environment.

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Kim *et al*. (2006) configured a general CLSC network by maximising 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 the disassembly site are sent to the remanufacturing subcontractor. The disassembled parts are categorised into 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 an external supplier. In this paper, we investigate this network because it is a general network (not case-based). Yet our approach and assumptions are different. In Kim *et al*. (2006), it is assumed that all of parameters such as demand and supply are certain and deterministic. In addition, they assumed a 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 the decision-making process to overcome the uncertainty in human judgment. 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 maximise 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 maximises weights and on-time deliveries, while it minimises 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 an uncertain environment.

The paper is arranged as follows: Section 2 presents a literature review of reverse logistics and selection problems. In Section 3, the problem is defined. Then, a new model is proposed in Section 4. Section 5 presents an illustrative example. 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 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 was to determine the network configuration by minimising the total cost. However, profit maximisation 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 categorised decision techniques.

2.1 *Reverse logistics under uncertainty*

Uncertainty of demand and return is one of 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 a 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 a 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 maximise the profit of a remanufacturing system by developing a solution approach based on the Lagrangian relaxation method. Hasani *et al*. (2011) developed an optimisation model under uncertain demand and purchasing cost. Table 1 shows a summary of these papers.

More directly related 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 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 have investigated the problem of selection and evaluation of the best third-party reverse logistics. For example 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) categorised the supplier selection process into four phases, including initial problem definition, formulation of criteria, qualification, and final selection. Aissaoui *et al*. (2007) presented a review of the papers related to supplier selection. After a description of the 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 using the idea (e.g. 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

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 centres	Multiple capacity levels	Multiple distributors	Multiple disposal centres	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

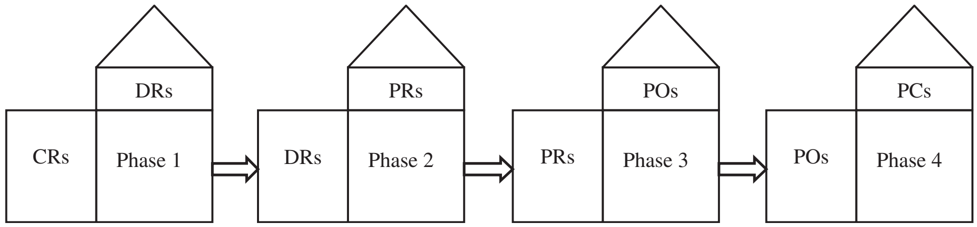

Figure 1. Quality function deployment including customer requirements (CRs), design requirements (DRs), part requirements (PRs), process operations (POs), and production characteristics (PCs).

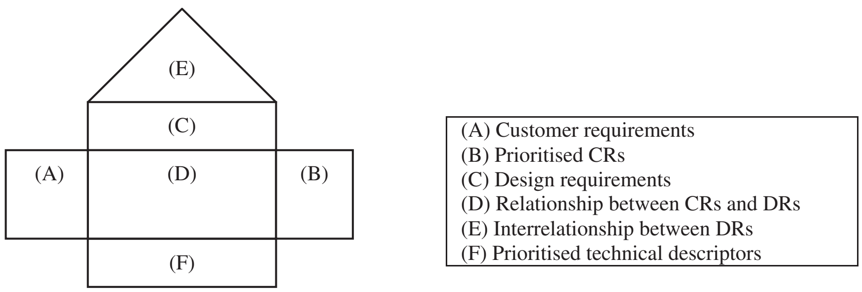

Figure 2. House of quality.

Table 2. Summary of papers on the QFD technique.

References	Application of QFD	Number of matrices	Prioritising 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 and 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

problems. The characteristic of efficient solutions is that the value of any objective function cannot be improved without sacrificing at least one other objective value (Wadhwa and Ravindran 2007).

Quality function deployment is a useful method that frequently is utilised 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. In addition, 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 summarised in Table 2. It can be observed from the table that the majority of authors have utilised one matrix (HOQ). Furthermore, they have applied prioritising techniques such as fuzzy sets theory.

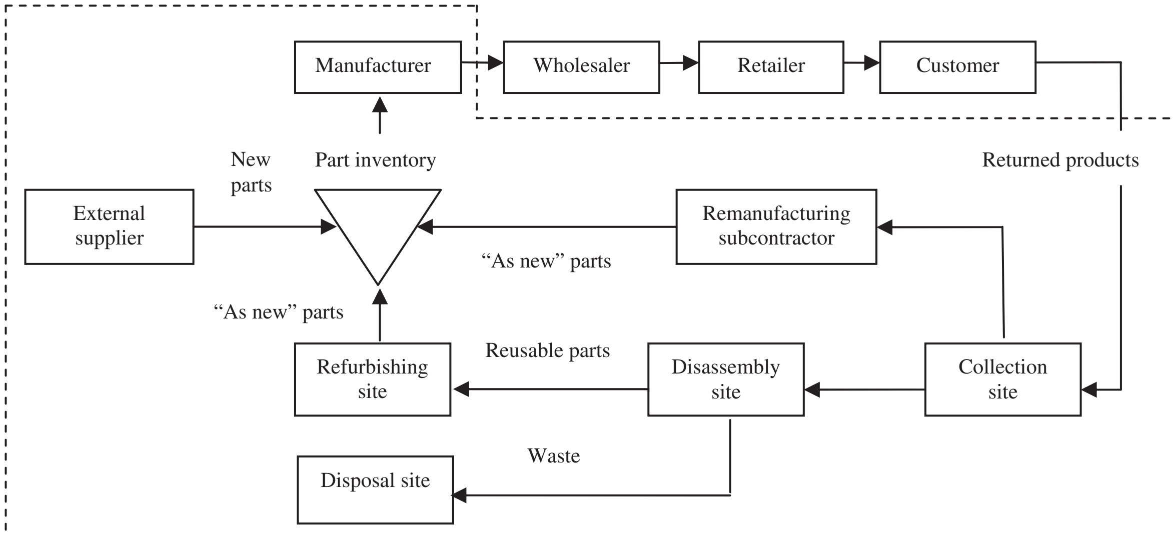

Figure 3. Framework for remanufacturing system – the dashed area (Kim *et al.* 2006).

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 the disassembly site, some of the products must be carried to the remanufacturing subcontractor. In the disassembly site, the products are divided into reusable parts and wastes. The reusable parts are refurbished in the refurbishing site. In addition, the remanufacturing subcontractor and external supplier also supply parts. It is supposed that the objective is to maximise the profits of the manufacturer, and the network is managed by the 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 the evaluation process. Furthermore, an appropriate decision-making technique should be utilised to handle the uncertainty because the decisions are made under an uncertain environment. It is supposed that demand is uncertain, and at the beginning of the decision horizon, the manufacturer knows the statistical distribution of the market demand of each product.

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 the maximisation of the expected profit. The model should determine the units of products to be manufactured, collected, disassembled, and sent to remanufacturing subcontractors, and the units of parts to be disposed of, 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 an 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 the 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.

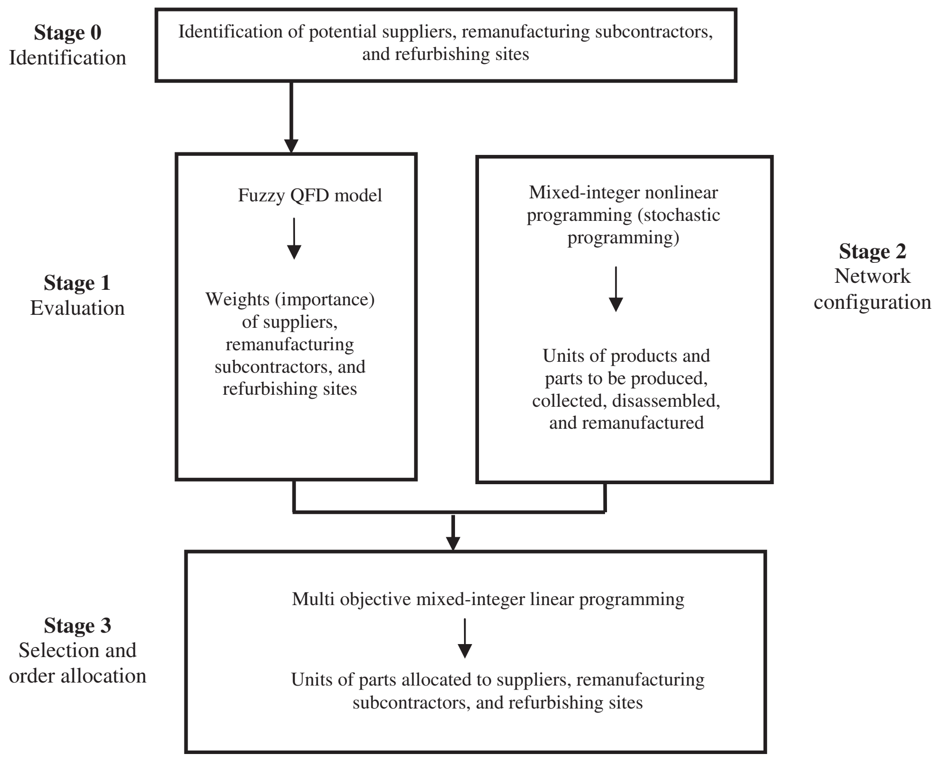

Figure 4. Framework of the proposed model.

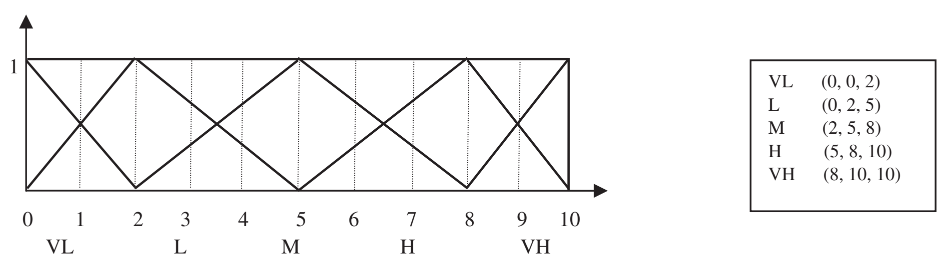

Figure 5. A linguistic scale for triangular fuzzy numbers.

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 a decision-making group should be selected. Three or five managers can contribute to the decision-making process. Suppose that there are E decision makers ($e = 1, 2, \dots, E$), and K alternatives ($k = 1, 2, \dots, K$). 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.

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

Step 1: List CRs, DRs, and PRs. CRs in a manufacturing environment can be interpreted as PR, for example 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 the company. These variables are designed according to the authorities, experiences, and the responsibilities of different DMs. In addition, Equation (1) should be satisfied where E is the number of decision makers ($e = 1, 2, \ldots, E$).

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

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 Equation (2) where P is the number of CRs ($p = 1, 2, \ldots, P$).

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

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

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

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

Step 7: Determine prioritised 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 Equation (4). These variables also are triangular fuzzy numbers.

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

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

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

Step 9: Determine prioritised 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 Equation (6).

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

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 Equation (7) where K is the number of alternatives ($k = 1, 2, \ldots, K$).

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

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. Equation (8) illustrates the formula.

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

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

$$DI_k = \frac{a + 2b + c}{4} \tag{9}$$

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 B (Table 12).

4.2.1 *Objective function*

Expected profit: The objective function, as expressed in Equation (10), maximises the expected profit. The first part of the objective function represents the 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 the over-stocking cost from sales revenue. In contrast, the second part represents the expected value of profit from product j and customer n when the realised demand of product j and customer n is more than the actual quantity produced. It is calculated by subtracting the 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 incurred 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.

$$\begin{aligned} Max\ z_1 \ & \sum_{n=1}^{N}\sum_{j=1}^{J}\int_{0}^{P_{jn}^{m}} [S_{jn}X_{jn} - v_{jn}(P_{jn}^{m} - X_{jn})] f_{jn}(x)\, \mathrm{d}X_{jn} + \sum_{n=1}^{N}\sum_{j=1}^{J}\int_{P_{jn}^{m}}^{\infty} [S_{jn}P_{jn}^{m} - u_{jn}(X_{jn} - P_{jn}^{m})] f_{jn}(x) \mathrm{d}X_{jn} \\ & - \sum_{j=1}^{J} C_j^{m} \sum_{n=1}^{N} P_{jn}^{m} - \sum_{i=1}^{I} C_i^{p} Q_i^{p} - \sum_{j=1}^{J} C_j^{r} P_j^{r} - \sum_{i=1}^{I} C_i^{re} Q_i^{re} - \sum_{i=1}^{I} C_i^{d} Q_i^{d} \\ & - \sum_{j=1}^{J} C_j^{sub} P_j^{sub} - \sum_{j=1}^{J} C_j^{coll} P_j^{coll} - \sum_{j=1}^{J} CS_j^{r} U_j^{r} - \sum_{i=1}^{I} CS_i^{re} U_i^{re} \end{aligned} \tag{10}$$

4.2.2 *Constraints*

The constraints of the problem are formulated as follows:

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

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

$$Q_i^{re} + Q_i^{d} = Q_i^{r} \quad \forall i \tag{12}$$

$$P_j^{sub} + P_j^{r} = P_j^{coll} \quad \forall j \tag{13}$$

$$P_j^{coll} \leq Z \sum_{n=1}^{N} P_{jn}^{m} \quad \forall j \tag{14}$$

$$Q_i^{re} \leq EQ_i^{r} \quad \forall i \tag{15}$$

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

$$Q_i^{r} = \sum_{j=1}^{J} q_{ij} P_j^{r} \quad \forall i \tag{16}$$

$$Q_i^{sub} = \sum_{j=1}^{J} q_{ij} P_j^{sub} \quad \forall i \tag{17}$$

Capacity constraints: The constraints in Equations (18) and (19) represent the maximum capacity of the manufacturer and disassembly sites.

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

$$e_J^{r} P_j^{r} \leq W_j^{r} \quad \forall j \tag{19}$$

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

$$P_j^{r} \leq BU_j^{r} \quad \forall j \tag{20}$$

$$Q_i^{re} \leq BU_i^{re} \quad \forall i \tag{21}$$

Binary and non-negativity constraints:

$$U_j^{r}, U_i^{re} \in \{0, 1\} \quad \forall i, j \tag{22}$$

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

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 end, a multi-objective mathematical model is proposed. Because of two reasons, we cannot combine Stage 2 and Stage 3 as one stage. Firstly, the demands of customers are stochastic variables and they are determined by minimising 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 the 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 minimisation of costs and defect rates, and maximisation 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, as shown in Equation (24), minimises 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.

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

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

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

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

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

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

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

4.3.2 *Constraints*

The constraints of the problem are formulated as follows:

$$\sum_{i=1}^{I} b_{ik}^{P} Q_{ik}^{p} \le W_k^s s_k \quad \forall k \tag{28}$$

$$\sum_{j=1}^{J} b_{jm}^{sub} P_{jm}^{sub} \le W_m^{sub} t_m \quad \forall m \tag{29}$$

$$\sum_{i=1}^{I} e_{il}^{re} O_{il}^{re} \le W_l^{re} w_l \quad \forall l \tag{30}$$

$$\sum_{k=1}^{K} Q_{ik}^{p} = Q_i^{p} \quad \forall i \tag{31}$$

$$\sum_{l=1}^{L} Q_{il}^{re} = Q_i^{re} \quad \forall i \tag{32}$$

$$\sum_{m=1}^{M} P_{jm}^{sub} = P_j^{sub} \quad \forall j \tag{33}$$

$$\sum_{k=1}^{K} s_k \leq G \tag{34}$$

$$\sum_{m=1}^{M} t_m \leq T \tag{35}$$

$$\sum_{l=1}^{L} w_l \leq F \tag{36}$$

$$s_k, t_m, w_l \in \{0, 1\} \quad \forall k, m, l \tag{37}$$

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

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

4.3.3 *Solution methodology*

Multi-objective problems can be solved using different methods. In this paper, a weighted sums method and a compromise method are applied. The goal is to transform our problem so that it turns into a mono-objective optimisation 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 utilised to approximate the efficient set. Equation (39) has to be solved for all $\lambda_c \in R^D$ with $0 \leq \lambda_c \leq 1$ 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 minimisations. Our problem is transformed to a single objective which is shown in Equation (40).

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

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

Compromise method

Compromise programming tries to find a solution that comes as close as possible to the ideal values. An 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 Equation (41) where $z_c{}^* = min\ (z_c)$. It should be noted that all objective functions are minimisations. Any point that minimises L_V for $1 \leq V \leq \infty$ and $0 \leq \lambda_c \leq 1$ 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 Equation (42).

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

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

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 three computer models. In addition, each product is produced with five parts. The manufacturer is interested to know how many products and parts exist in each part of the closed-loop network. There are five 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 utilised to solve the model. GAMS is a high-level modelling software for mathematical programming and optimisation. 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, a linguistic set is utilised to express experts' opinions. Each of the three decision makers establishes a weight for customer requirements. The results are shown in Table 3. The manager of the company has determined a weight for each decision maker. In this example, there are three decision makers, one of who 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.

The aggregated weights between CRs and DRs are calculated. In addition, prioritised technical descriptors are obtained. Figure 7 illustrates the first matrix. According to the model, the second matrix that is displayed in Figure 8

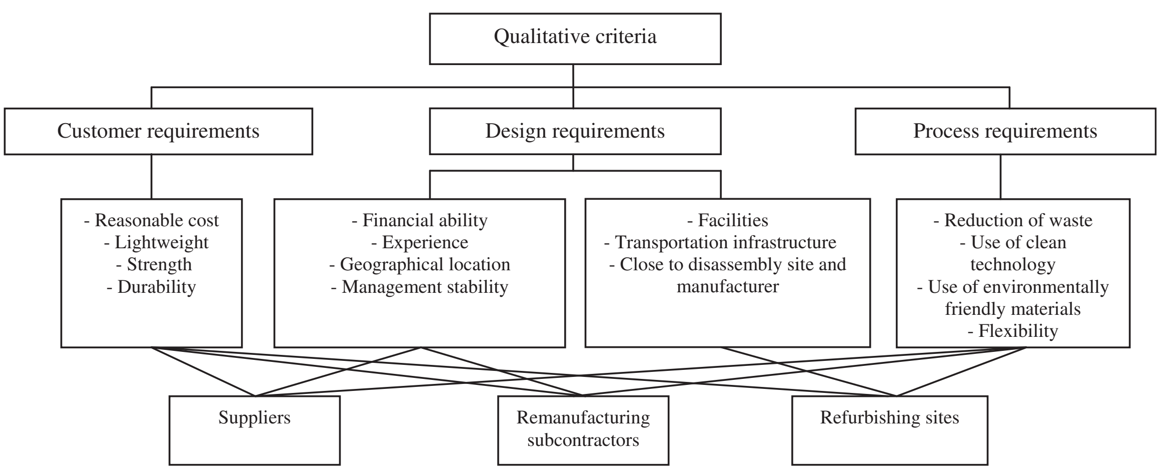

Figure 6. Qualitative criteria.

Table 3. The importance of CRs.

Customer requirements	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 0.4	DM_2 0.3	DM_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)

is also completed. 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 normalised numbers represent the importance (weight) of alternatives. According to this table, the fifth alternative (A_5) is the best.

5.2 *Stage 2*

In the second stage, the closed-loop supply chain is configured. In this stage, it is supposed that there is a 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 the mathematical

Table 5. The impact of customer requirements on design requirements.

DRs / CRs	Financial ability			Experience			Geographical location			Management stability		
	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

	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 environmentally 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 Alternatives	Reduction of waste			Use of clean technology			Use of environmentally friendly materials			Flexibility		
	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 normalisation.

	a	*b*	*c*	Score	Normalisation	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

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 the 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 Part 1, 950 units are refurbished and 950 units are disposed of. In addition, Table 8 shows how many parts should be purchased from an external supplier.

5.3 *Stage 3*

The mathematical programming model is solved using techniques including the single-objective (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 a minimum of $12. However, the results of the second objective show that Part 1 is bought from Supplier 1 due to the maximum weight (0.21).

The values of objective functions for the single-objective, 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 depending on other factors.

6. Managerial implications and discussions

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

Table 8. Results of Stage 2.

P^m_{jn} (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^{coll}_j	809	603	700		
P^r_j	500	200	700		
P^{sub}_j	309	403	–		
Part-related variables					
i	1	2	3	4	5
Q^{sub}_i	1021	1518	1734	1021	1518
Q^r_i	1900	1800	4702	3301	2501
Q^{re}_i	950	900	2351	1651	1250
Q^d_i	950	900	2351	1651	1250
Q^P_i	3872	4218	8786	5973	5269

Table 9. Results of multi-objective techniques.

First objective			Second objective			Third objective			Fourth objective			Equal weights			Compromise method		
j	m	P^{sub}_{jm}	j	m	P^{sub}_{jm}	j	m	P^{sub}_{jm}	j	m	P^{sub}_{jm}	j	m	P^{sub}_{jm}	j	m	P^{sub}_{jm}
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^p_{ik}	i	k	Q^p_{ik}	i	k	Q^p_{ik}	i	k	Q^p_{ik}	i	k	Q^p_{ik}	i	k	Q^p_{ik}
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^{re}_{il}	i	l	Q^{re}_{il}	i	l	Q^{re}_{il}	i	l	Q^{re}_{il}	i	l	Q^{re}_{il}	i	l	Q^{re}_{il}
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

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	478,649	7047	2905	31,891
Second objective	572,883	8006	1957	31,891
Third objective	597,675	7821	1747	31,683
Fourth objective	558,849	7222	2923	32,823
Equal weights	478,649	7283	3098	32,265
Compromise method	521,470	7288	1755	31,832

Table 11. Comparison between the first stage and HOQ.

	HOQ			The proposed model		
	Score	Normalisation	Rank	Score	Normalisation	Rank
A_1	212	0.178	4	1678	0.188	4
A_2	250	0.210	3	1897	0.212	3
A_3	172	0.144	5	1422	0.159	5
A_4	275	0.231	2	1941	0.217	2
A_5	283	0.238	1	2010	0.225	1

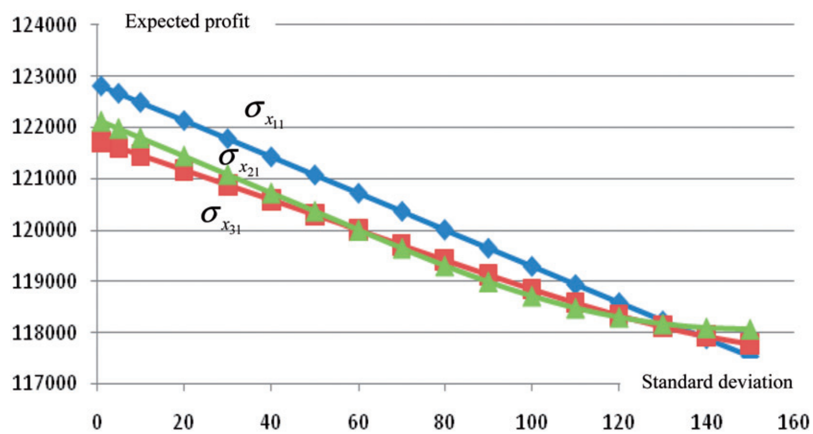

Figure 9. Expected profit as a function of standard deviation.

6.1 *Comparison between the proposed model and HOQ*

In the first stage, the new QFD method is utilised to evaluate the alternatives. The proposed model includes two QFD matrices. We also solve the problem through the HOQ method that has one QFD matrix. The results are illustrated in Table 11. According to the table, the ranks of suppliers are the same. However, the weights of them have changed. For example, the weight (importance) of Supplier 5 increased in the HOQ method. It is noticeable that not only is the ranking important but that the weights also have significant effects on the results because they are inputs of Stage 3.

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 a 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.

6.3 *Comparison of single and multiple-sourcing policies*

In a 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) than with the 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 satisfied.

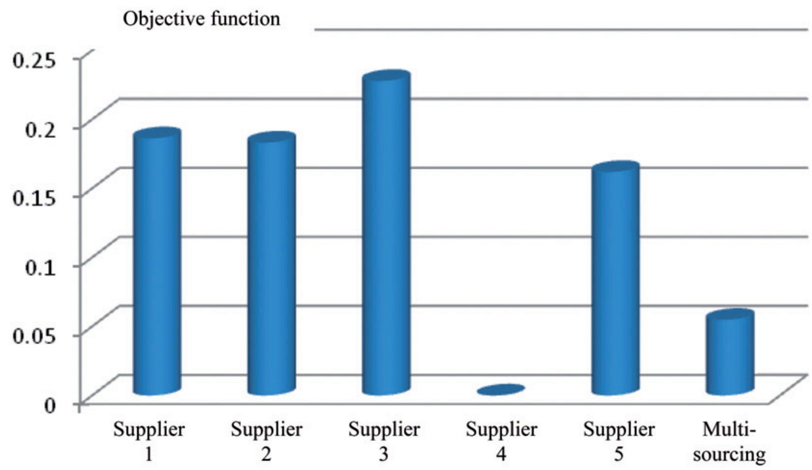

Figure 10. Value of objective function of single and multiple-sourcing policies (compromise method).

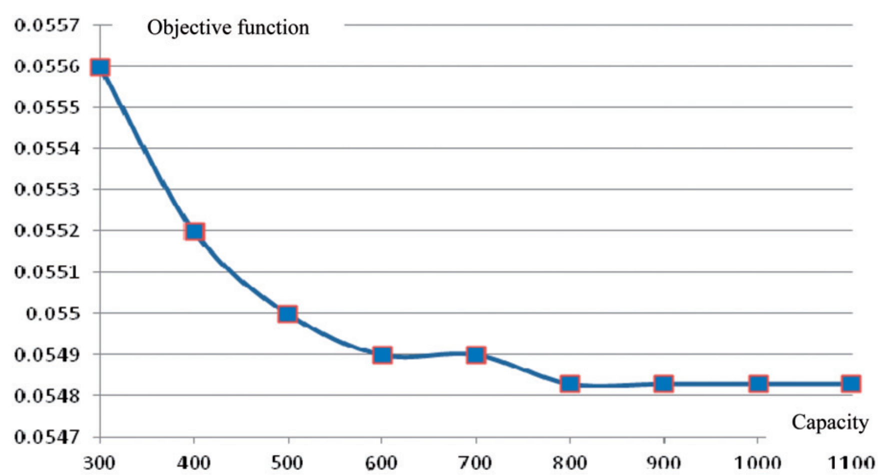

Figure 11. Sensitivity analysis for capacity of remanufacturing subcontractors.

6.4 *Sensitivity analysis of capacity*

We observed the changes of the objective function by varying the capacity of remanufacturing subcontractors while the other factors remain 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.

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 the 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 a 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, which is unknown. But, the production level of each product is essential to determine the quantity of purchased parts. Another direction for future research is to investigate 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, 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 is denoted by x. A fuzzy set A is a function $A: X \rightarrow [0,\ 1]$.

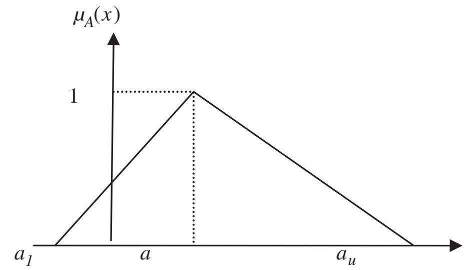

Figure 12. A triangular fuzzy number $A = (a_1, a, a_u)$.

There are several types of fuzzy numbers. Triangular fuzzy number (TFN) is one of them. A TFN A is denoted by the 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 in Equation (43).

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

Let $A = (a_1, a, a_u)$ and $B = (b_1, b, b_u)$ be two TFNs then addition, multiplication, and subtraction can be defined as follows. For more information, readers can refer to Bector and Chandra (2005).

(a) Addition of two fuzzy numbers $A \oplus B = (a_1 + b_1, a + b, a_u + b_u)$
(b) Multiplication of two fuzzy numbers $A \otimes B = (a_1 \times b_1, a \times b, a_u \times b_u)$
(c) 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, $i = 1, \ldots, I$
j Set of products, $j = 1, \ldots, J$
k Set of suppliers, $k = 1, \ldots, K$
l Set of refurbishing sites, $l = 1, \ldots, L$
m Set of remanufacturing subcontractors, $m = 1, \ldots, M$
n Set of customers, $n = 1, \ldots, N$

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 of
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_{il}^{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