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Design and Optimization of Closed-Loop Supply Chain Management

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Design and Optimization of Closed-Loop Supply Chain Management

by

Saman Hassanzadeh Amin

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2012

Design and Optimization of Closed-Loop Supply Chain Management

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Declaration of Co-Authorship / Previous Publication

I. Co-Authorship Declaration

I hereby declare that this thesis does not incorporate material that is result of joint research. In all cases, the key ideas, primary contributions, experimental designs, data analysis and interpretation, were performed by the author and Dr. Guoqing Zhang as advisor.

I certify that, with the above qualification, this thesis, and the research to which it refers, is the product of my own work.

II. Declaration of Previous Publication

This thesis includes four original papers that have been previously published/submitted for publication in peer reviewed journals, as follows:

Thesis Chapter	Publication title/full citation	Publication status
Chapter 3	**Amin, S. H.,** Zhang, G., A multi-objective facility location model for closed-loop supply chain network under uncertain demand and return, ***Applied Mathematical Modelling***.	*Submitted*
Chapter 4	**Amin, S. H.,** Zhang, G. (2012). An integrated model for closed loop supply chain configuration and supplier selection: Multi-objective approach, ***Expert Systems with Applications***, 39 (8), 6782-6791.	*Published*
Chapter 5	**Amin, S. H.,** Zhang, G., A three-stage model for closed-loop supply chain configuration under uncertainty, ***International Journal of Production Research***.	*Accepted*
Chapter 6	**Amin, S. H.,** Zhang, G. (2012). A proposed mathematical model for closed loop network configuration based on product life cycle, ***The International Journal of Advanced Manufacturing Technology***, 58 (5), 791-801.	*Published*

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ABSTRACT

Because of cost and environmental concerns, reverse supply chain (RSC) has received a lot of attention. RSC is defined as the activities of the collection and recovery of product returns in supply chain management. The integration of forward supply chain (FSC) and RSC results in a closed-loop supply chain (CLSC). In this dissertation, FSC, RSC, and CLSC are introduced. Then, the research objectives are mentioned. The objective of this dissertation is to develop effective approaches to support closed-loop supply chain configurations and analyses, especially develop methodologies to examine impacts of multi-objectives, and uncertainty on CLSC.

In Chapter 2, literature of CLSC configuration is reviewed including deterministic and uncertain models. In addition, gaps in the literature are mentioned. In Chapter 3, a facility location model is examined. After problem definition, a mixed-integer linear programming model is proposed. Then, the model is developed to consider multi-objectives under uncertain demand and return. In Chapter 4, a CLSC network is examined. In this chapter, an integrated model for CLSC configuration and supplier selection is proposed and a solution approach is developed for the multi-objective model. A numerical example is used to validate the model. In Chapter 5, a three stage model for closed-loop supply chain configuration is proposed based on a general network. It is supposed that demand is an uncertain parameter. Besides, an illustrative example is applied to show the three-stage model. In addition, managerial insights are discussed in this chapter. In Chapter 6, a mixed-integer linear programming model is proposed to configure a CLSC network. The network has been designed based on product life cycle. The objective is to maximize profit by determining quantity of parts and products in the network. We also extend the model for the condition that the remanufactured products are sent to the secondary market. Finally in Chapter 7, conclusions and future works are provided.

DEDICATION

To my parents

ACKNOWLEDGEMENTS

I express my sincere gratitude to my advisor, Dr. Gouqing Zhang for his guidance, encouragement, and support during my Ph.D. study at the University of Windsor. I am indebted for his support and advice for my professional and personal development.

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CHAPTER 1. INTRODUCTION

Nowadays, supply chain management (SCM) has received a lot of attentions. In APICS Dictionary, SCM is defined as the design, planning, execution, control, and monitoring of supply chain activities with the objective of creating net value, building a competitive infrastructure, leveraging worldwide logistics, synchronizing supply with demand, and measuring performance globally. There are two types of supply chains: forward and reverse supply chains.

1.1. Forward supply chain

The forward supply chain (FSC) includes of series of activities in the process of converting raw materials to finished products. The managers try to improve forward supply chain performances in areas such as demand management, procurement, and order fulfillment (Cooper et al., 1997).

1.2. Reverse supply chain

Reverse supply chain (RSC) 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). Reverse logistics include the process of planning, implementing and controlling the inbound flow and storage of secondary goods and related information opposite to the traditional supply chain directions for the purpose of recovering value and proper disposal (Fleischmann, 2001). Figure 1.1 shows a framework of reverse logistics. Besides, the differences between forward and reverse logistics are written in Table 1.1. In addition, Table 1.2 shows the costs of reverse logistics and it provides a comparison between forward and reverse supply chains costs.

The design of reverse logistics network is a difficult problem because of economic aspects and the effects of it on other aspects of human life, such as the environment and sustainability of natural resources (Lee and Dong, 2009; Francas and Minner, 2009).

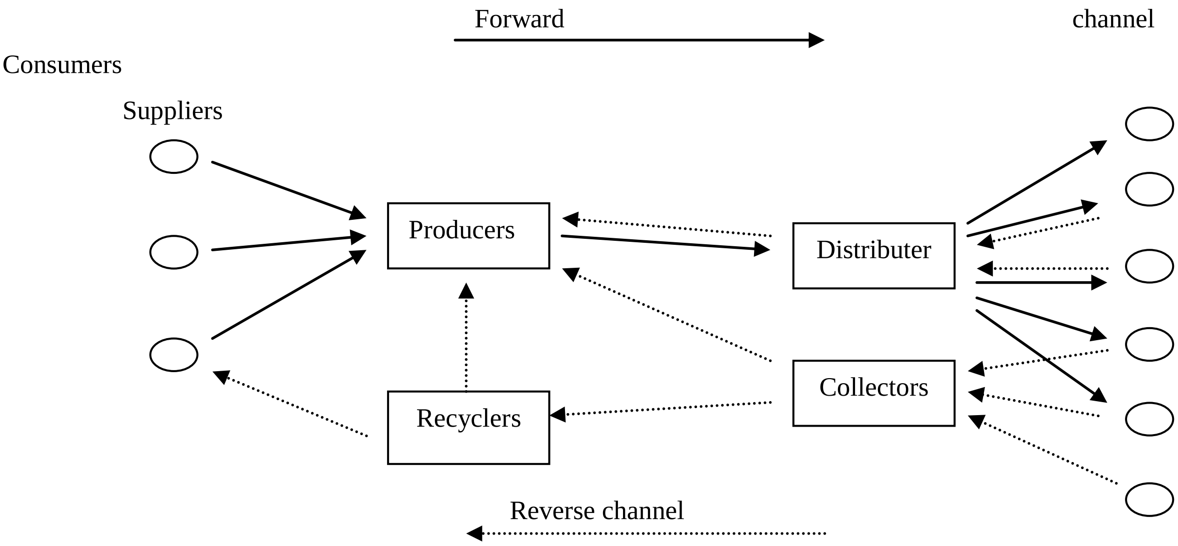


Figure 1.1. Framework of reverse distribution (Fleischmann et al., 1997)

Table 1.1
Differences in forward and reverse logistics (Tibben-Lembke and Rogers, 2002)

Forward	**Reverse**
Forecasting relatively straightforward	Forecasting more difficult
One to many transportation	Many to one transportation
Product quality uniform	Product quality not uniform
Destination/routing clear	Product packaging often damaged
Standardized channel	Destination/routing unclear
Disposition options	Exception driven
Pricing relatively uniform	Disposition not clear
Importance of speed recognized	Pricing dependent on many factors
Forward distribution costs closely monitored by accounting systems	Speed often not considered a priority
Inventory management consistent	Reverse costs less directly visible
Product lifecycle manageable	Inventory management not consistent
Negotiation between parties straightforward	Product lifecycle issues more complex
Marketing methods well-known	Negotiation complicated by additional considerations
Real-time information readily available to track product	Marketing complicated by several factors
	Visibility of process less transparent

Table 1.2
Reverse logistics costs (Tibben-Lembke and Rogers, 2002)

Cost	**Comparison with forward logistics**
Transportation	Greater
Inventory holding cost	Lower
Shrinkage (theft)	Much lower
Obsolescence	May be higher
Collection	Much higher – less standardized
Sorting, quality diagnosis	Much greater
Handling	Much higher
Refurbishing / repackaging	Significant for RL, non-existent for forward
Change from book value	Significant for RL, non-existent for forward

Reprocessing of used products can be efficient in (Pochampally et al., 2008):

1. Saving natural resources: We consider land and reduce the need to drill for oil and dig for minerals by making products using materials and components obtained from reprocessing instead of virgin materials.
2. Saving energy: It usually takes less energy to make products from reprocessed materials and components than from virgin materials.
3. Saving clean air and water: Making products from reprocessed materials and components create less air pollution and water pollution than from virgin materials.
4. Saving landfill space: When reprocessed materials and components are used to make a product, they do not go into landfills.
5. Saving money: It costs much less to make products from reprocessed materials and components than from virgin materials.

Product returns may occur for a variety of reasons over the product life cycle. Commercial returns are products returned to the reseller by consumers within 30, 60, or 90 days after purchase. End-of-use returns occur when a functional product is replaced by a technological upgrade. End-of-life returns are available when the product becomes technically obsolete or no longer contains any utility for the current user. As an example, consider the cell telephone industry. In the United States, consumers may return a mobile phone to the airtime provider for any reason during a 30-day period after purchase (a commercial return). Furthermore, 80% of mobile phone users upgrade their perfectly functional mobile phones annually, making their previous models available as an end-of-use return. Finally, some users of mobile phones relinquish their phone only when it is no longer supported by the airtime provider and it becomes available as an end-of-life return (e.g., the technology is obsolete). There are also repair and warranty returns that occur throughout, and even beyond, the product life cycle. It should be clear that, for consumer electronics alone, there are billions of returned products annually in the United States, and therefore enormous potential for value recovery (Guide and Van Wassenhove, 2009).

Reverse logistics options consist of reuse, resale, repair, refurbishing, remanufacturing, cannibalization, and recycling (Thierry et al., 1995). In the remanufacturing process, used products are disassembled in disassembly sites. Then they are divided to two kinds of parts. Usable parts are cleaned, refurbished, and they are transmitted into part inventory. Then the new products are manufactured from the old and new parts (Kim et al., 2006). The purpose of refurbishing is to increase the quality of products. Quality standards are less rigorous than those for new products. Military and commercial aircraft are examples of these products. Although the quality of products is improved by refurbishing, remaining service life is generally less than the average service life of new ones (Thierry et al., 1995). For each type of product return, there is a most attractive recovery option. Commercial returns have barely been used and are best reintroduced to the market as quickly as possible. The majority of these returns require only light repair operations (cleaning and cosmetic). End-of-use returns may have been used intensively over a period of time and may therefore require more extensive remanufacturing activities. The high variability in the use of these products may also result in very different product disposition and remanufacturing requirements. Ideally, one would like to acquire end-of-use products of sufficient quality to enable profitable remanufacturing. End-of-life products are predominantly technologically obsolete and often worn out. This makes parts recovery and recycling the only practical recovery alternatives (Guide and Van Wassenhove, 2009).

1.3. Closed-loop supply chain

The integration of forward supply chain and reverse supply chain constructs a closed-loop supply chain (CLSC) (Guide and Van Wassenhove, 2009). In other words, there are both forward and reverse channels in CLSC networks.

Reverse logistics (RL) and closed-loop supply chain (CLSC) are the subjects of several researches. Figure 1.2 shows the number of articles on RL and CLSC from 2000 until beginning of 2012 which is obtained by SCOPUS. In addition, some scientific journals have published special issues for the subject of RL. For more information, you can refer to Table 1.3. These evidences show that a lot of researchers are working on RL and CLSC subjects. Furthermore, these fields of study have a lot of opportunities for future research.

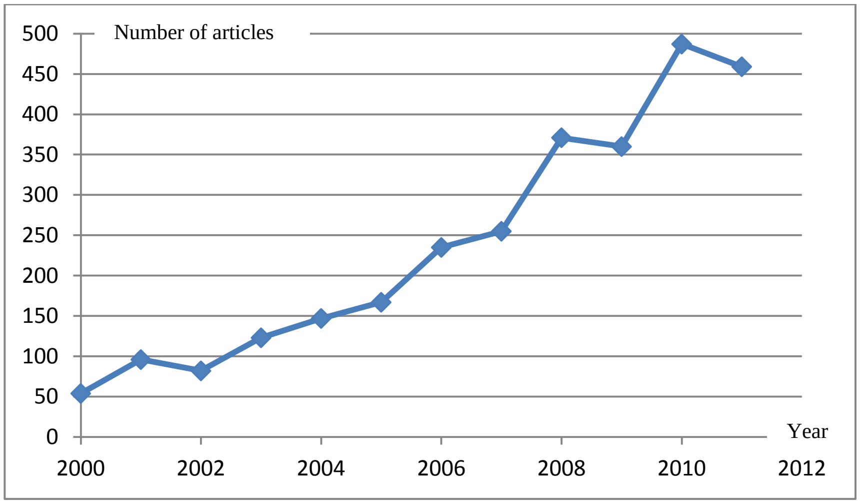


Figure. 1.2. The numbers of scientific articles are identified by a search of "reverse logistics" or "closed-loop supply chain" from 2000 to 2012. The search was performed on SCOPUS on 21 February 2012.

Table 1.3
Special issues in related to reverse logistics

Journal	**Subject**	**Year**	**Volume**	**Issue**
Interfaces	Closed-loop supply chain	2003	33	6
California Management Review	Closed-loop supply chain	2004	46	2
Production & Operations Management	Closed-loop supply chain	2006	15	3 & 4
Computers & Operations Research	Reverse logistics	2007	34	2
Journal of Operations Management	SCM in a sustainable environment	2007	25	6

1.4. Research objectives

The objective of this dissertation is to develop effective approaches to support closed-loop supply chain configurations and analyses especially develop methodologies to examine impacts of the following issues on CLSC:

Uncertainty: In the mathematical models, there are several parameters such as cost, demand, and return which are not deterministic. As a result, several sources of uncertainty should be considered.

Multi-objectives: In closed-loop network configuration, not only it is preferred to minimize the total cost (including operation, transportation, and holding costs), but also it is necessary to optimize other factors such as recycling materials and wastes because of environmental concerns. In addition, different criteria should be considered in selection of members of supply chain (such as suppliers). As a consequence, multi-objective models should be proposed and appropriate solution approaches should be developed.

1.5. Solution methodologies

In this section, some important approaches are mentioned. These tools are applied in this dissertation.

Mixed-integer linear programming: A mixed-integer linear program is the minimization or maximization of a linear function subject to linear constraints. There are two kinds of variables including nonnegative and integer variables in this problem. Binary variables are special case of integer variables that can be 0 or 1.

Multi-objective programming: Multi objective optimization allows a degree of freedom which is lacking in mono objective optimization. The flexibility is not without consequences for the method used to find an optimum for the problem when it is finally modelled. The search will give us not a unique solution but a set of solutions. These solutions are called Pareto solutions, and the set of solutions that we find at the end of search is called the tradeoff surface (Collette and Siarry, 2003).

Stochastic programming: The goal of stochastic optimization is to find a solution that will perform well under any possible realization of the random parameters. The objective functions of many of stochastic models are minimization of the expected cost or maximization of the expected profit of the system (Snyder, 2006).

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

Triangular fuzzy number (TFN) is one of the most important fuzzy numbers. TFNs can be denoted as $X = (a, n, b)$ and $Y = (c, m, d)$, where n and m are the central values, a and c are the left spreads, and b and d are the right spreads (see Figure 1.3). Then $C = (a+c, n+m, b+d)$ is the addition of these two numbers. Besides, $D = (a-c, n-m, b-d)$ is the subtraction of them. Moreover, $E = (a\times c, n\times m, b\times d)$ is the multiplication of them (Lai and Hwang, 1995; Zimmermann, 2001).

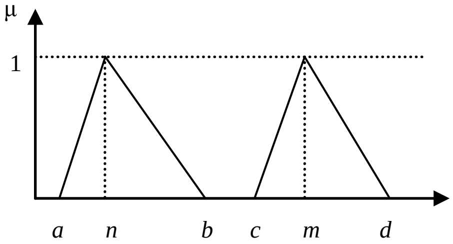


Figure 1.3. Triangular fuzzy numbers

$$\mu_X(x) = \begin{cases} 0, & x < a \\ \dfrac{x-a}{n-a}, & a \le x \le n \\ \dfrac{b-x}{b-n}, & n \le x \le b \\ 0, & x > b \end{cases}$$

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 1.4 displays a typical QFD. Besides, the first matrix of QFD which is called house of quality (HOQ) is illustrated in Figure 1.5. 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.

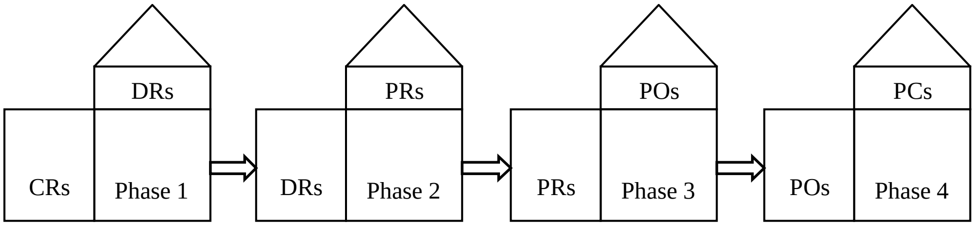
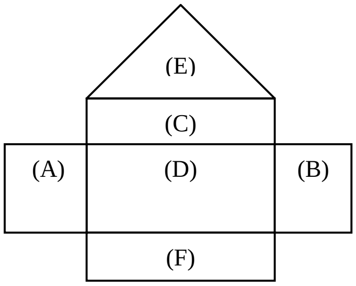


Figure. 1.4. Quality function deployment including customer requirements (CRs), design requirements (DRs), parts requirements (PRs), process operations (POs), and production characteristics (PCs)



(A) Customer requirements (CRs)
(B) Prioritized CRs
(C) Design requirements (DRs)
(D) Relationship between CRs and DRs
(E) Interrelationship between DRs
(F) Prioritized technical descriptors

Figure. 1.5. House of quality

1.6. Organization of the dissertation

The dissertation is arranged as follows: Chapter 2 presents review of literature. In Chapter 3, a facility location model for closed-loop supply chain network is discussed. Then, an integrated model for closed-loop supply chain configuration and supplier selection is proposed in Chapter 4. Chapter 5 presents a three-stage model for closed-loop supply chain configuration under uncertainty. A mathematical model is proposed based on product life cycle in Chapter 6. Finally, Chapter 7 presents conclusions and future works.

CHAPTER 2. REVIEW OF LITERATURE

Several papers have been published about reverse logistics 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. Pokharel and Mutha (2009) reviewed articles of reverse logistics. They stated that it is useful to develop pricing models for acquiring used products. It is also mentioned that a limited articles have taken into account stochastic demand of new products and supply of used-products. Akcali and Cetinkaya (2011) provided literature review and survey for the papers of RL and CLSC.

2.1. Deterministic models for closed-loop supply chains

Network configuration is one of the main research streams in RL. The majority of authors use facility location models to formulate CLSC networks. Jayaraman et al. (1999) proposed a mixed-integer programming model. The model can determine the location of remanufacturing /distribution facilities, the transhipment, production, and stocking of the optimal quantities of remanufactured products and used parts. Fleischmann et al. (2001) proposed a general model for closed-loop supply chain network. The model is designed based on forward facility location model. Copier remanufacturing and paper recycling are utilized to show the efficiency of the model. Kim et al. (2006) 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. Lu and Bostel (2007) presented a two-level location problem with three types of facility to be located in a specific reverse logistics system. They proposed a mixed-integer programming model, in which simultaneously consider “forward” and “reverse” flows and their mutual interactions. They developed an algorithm based on Lagrangian heuristics. Ko and Evans (2007) proposed a mixed-integer nonlinear programming model that is a multi period, two-echelon, multi commodity, and capacitated network design problem. They considered forward and reverse flows simultaneously. Srivastava (2008) proposed a framework for analysing a network. The model determines the disposition decision for various grades of different products concurrently with location-allocation and capacity decisions for facilities for a time horizon. Kannan et al. (2009) designed an integrated forward logistics multi-echelon distribution inventory supply chain model and closed-loop multi-echelon distribution inventory supply chain model for the built-to-order environment using genetic algorithm and particle swarm optimisation. Lee et al. (2009) formulated a mathematical model for a general CLSC network by proposing a heuristic approach (Genetic Algorithm). Although the model can determine the optimal numbers of disassembly and processing centers, the supplier selection is not taken into account. The authors supposed that there is only one supplier. Xanthopoulos and Iakovou (2009) developed two phases model for reverse logistics. In the first phase, appropriate components are identified by a decision making model. In the second one, a multi-period optimization model is applied to configure the network.

Lee and Chan (2009) proposed a Genetic Algorithm to determine such locations in order to maximize the coverage of customers. Besides, the use of RFID is suggested to count the quantities of collected items in collection points and send the signal to the central return center. Cruz-Rivera and Ertel (2009) modelled a reverse logistics network through an incapacitated facility Location Problem. The solution of this model is obtained using software. Furthermore, they presented a brief description of the current Mexican ELV management system and the future trends in ELV generation in Mexico. Wang and Hsu (2010) investigated the integration of forward and reverse logistics, and they proposed a generalized closed-loop model for the logistics planning by formulating a cyclic logistics network problem into an integer linear programming model. Moreover, the decisions for selecting the places of factories, distribution centers, and dismantlers with the respective operation units were supported with the minimum cost. They also developed a revised spanning-tree based genetic algorithm. Kannan et al. (2010) developed a multi echelon, multi period, multi product closed-loop supply chain network model for product returns and the decisions are made regarding material procurement, production, distribution, recycling and disposal. The proposed heuristics based Genetic Algorithm is applied as a solution methodology. Achillas et al. (2010) presented a decision support tool for policy-makers and regulators to optimise electronic products' reverse logistics network. To that effect, they formulated a mixed-integer linear programming mathematical model taking into account existing infrastructure of collection points and recycling facilities. Sasikumar et al. (2010) developed a mixed-integer nonlinear programming model for maximizing the profit of a multi-echelon reverse logistics network and also presented a real-life case study of truck tire remanufacturing for the secondary market segment. The proposed model is solved using LINGO.

2.2. Uncertain models for closed-loop supply chains

Several investigations have been conducted about CLSC configuration. In the majority of them, the parameters are deterministic (such as Kim et al., 2006). In addition, some of authors considered uncertainty (e.g. Listes, 2007). However, the minority of them are taken into account two or more sources of uncertainty (Snyder, 2006; Peidro et al., 2009).

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; Zhang and Ma, 2009;

Peidro et al., 2009). 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). Inderfurth (2005) examined a closed-loop supply chain network by stochastic programming. They considered uncertainty in demand and return. In addition, they defined a parameter to measure uncertainty in quality. 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. Selim and Ozkarahan (2008) developed a fuzzy goal programming approach for a reverse logistics network. The uncertainty in demand and decision makers' (DM) aspiration levels for the goals are taken into account. 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 deterministic optimization model for a reverse logistics network. Then, a scenario-based stochastic model is developed. Qin and Ji (2010) configured a reverse logistics network by three kinds of mathematical models. In the first and second ones, expected cost and α-cost are minimised, respectively. In addition, in the third one, credibility is maximized. The unique feature of this paper is that costs and return are triangular fuzzy numbers. The authors proposed fuzzy simulation and Genetic Algorithm to solve the model. El-Sayed et al. (2010) developed a stochastic model for a generic closed-loop network. It is supposed that demand is an uncertain parameter. In addition, the model is designed for multi-periods. They considered uncertainty in demand, return, and cost. 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. They considered uncertain demand and return. Shi et al. (2011)

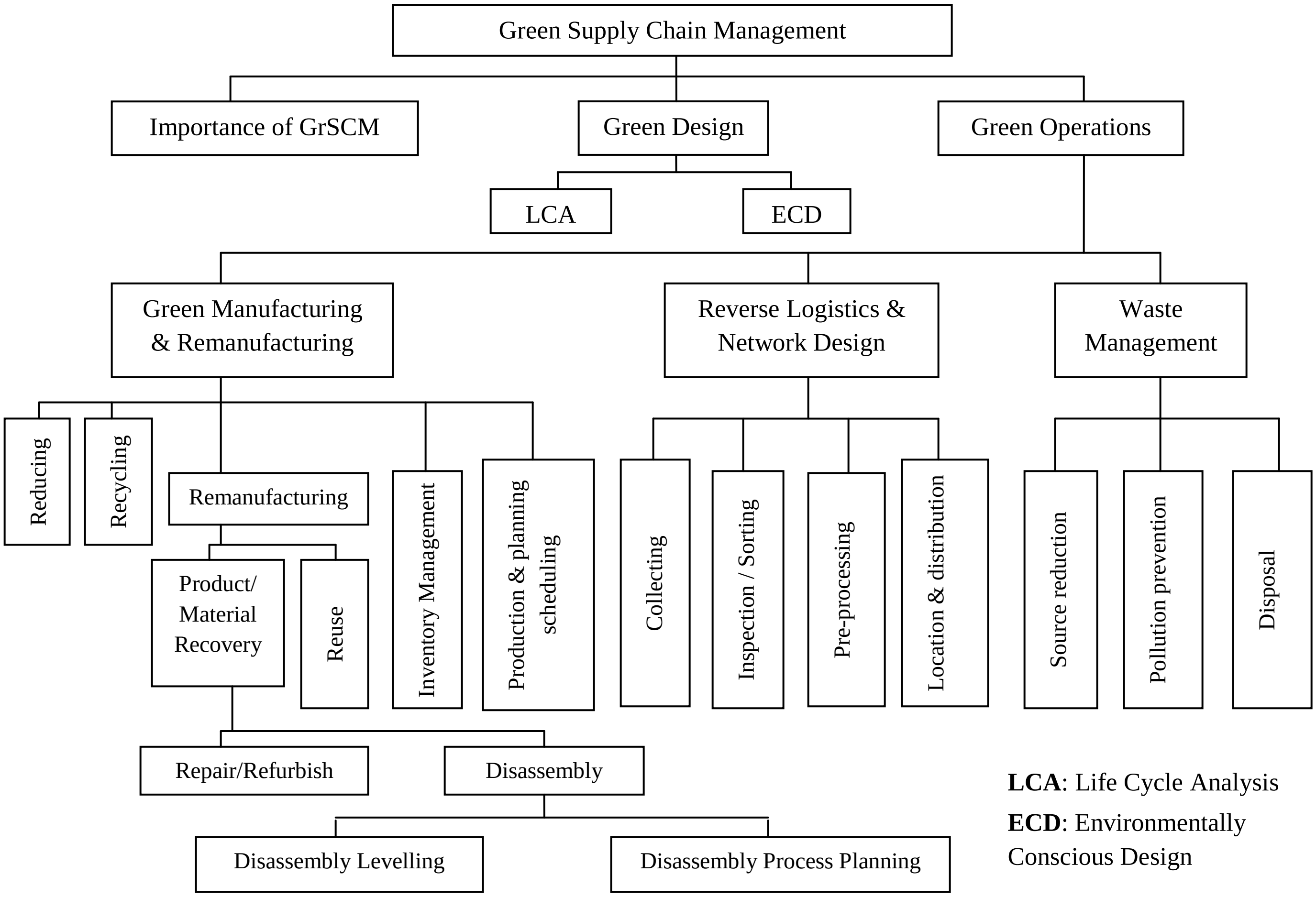
studied a production planning problem for a multi-product closed-loop system. The authors considered uncertain demand and return by stochastic programming. Pishvaee et al. (2011) proposed a deterministic mixed-integer linear programming model for a closed-loop supply chain network. Then, robust optimization has been applied for the model to consider uncertainty.

2.3. Multi-objective models for closed-loop supply chains

Some authors have used multi-objective and goal programming models to formulate closed-loop supply chain networks. One objective can be minimizing the total cost. Besides, because of importance of environmental issues, some objective functions may be added. Figure 2.1 shows a classification of green supply chain management and importance of green operations in reverse logistics. Krikke et al. (2003) developed quantitative modelling to support decision-making concerning both the design structure of a product, i.e. modularity, reparability and recyclability, and the design structure of the logistic network. Environmental impacts are measured by linear-energy and waste functions. They applied to a closed-loop supply chain design problem for refrigerators using real life R & D data of a Japanese consumer electronics company concerning its European operations. The objectives are minimization of the supply chain costs, energy use, and residual waste. Sheu et al. (2005) proposed a linear multi-objective programming model that systematically optimizes the operations of both integrated logistics and corresponding used-product reverse logistics in a given green-supply chain. Factors such as the used-product return ratio and corresponding subsidies from governmental organizations for reverse logistics are considered in the model formulation. The objectives are maximization of the manufacturing chain-based net profit, and the reverse chain-based net profit. Uster et al. (2007) considered a multi-product closed-loop supply chain network design problem where they located collection centers and remanufacturing facilities while coordinating the forward and reverse flows in the network so as to minimize the processing, transportation, and fixed location costs. They utilized Benders decomposition approach to solve the model. Demirel and Gokcen (2008) presented a mixed-integer mathematical model for a remanufacturing system, which includes both forward and reverse flows, and illustrated on a numerical example. Pati et al. (2008)

formulated a mixed-integer goal programming model to determine the facility location, route and flow of different varieties of recyclable wastepaper in the multi-item, multi-echelon and multi-facility decision making framework. In the paper of Du and Evans (2008), a bi-objective optimization model is proposed. The objectives consist of minimization of the total costs and minimization of the overall tardiness of cycle time. The solution approach includes a combination of dual simplex, Scatter Search, and the constraint method. Gupta and Evans (2009) proposed a non-preemptive goal programming approach to model a closed-loop supply chain network. Pishvaee et al. (2010) developed a bi-objective mixed-integer programming model. The first objective minimizes the total costs and the second one maximizes the responsiveness of a logistics network. Then, the problem has been solved by Memetic Algorithm.

Table 2.1 shows classification of closed-loop network configuration references based on operations research techniques.



LCA: Life Cycle Analysis

ECD: Environmentally Conscious Design

Figure 2.1. Green supply chain management framework (Srivastava, 2008)

Table 2.1

Classification of references based on operations research techniques

Category	Techniques	References
Single techniques	Linear multi-objective programming	Sheu et al. (2005)
	Mixed-integer goal programming	Pati et al. (2008)
	Mixed-integer linear programming	Jayaraman et al. (1999), Fleischmann et al. (2001), Krikke et al. (2003), Kim et al. (2006), Demirel and Gokcen (2008), Cruz-Rivera and Ertel (2009), Achillas et al. (2010)
	Stochastic programming	Inderfurth (2005), Francas and Minner (2009), El-Sayed et al. (2010), Pishvaee et al. (2009)
	Mixed-integer nonlinear programming	Sasikumar et al. (2010)
Hybrid techniques	Stochastic programming, decomposition approach	Listes (2007)
	Stochastic programming, Lagrangian heuristics	Shi et al. (2010), Shi et al. (2011)
	Mixed-integer linear programming, Branch & Bound technique	Salema et al. (2007)
	Mixed-integer nonlinear programming, Genetic Algorithm (GA)	Ko and Evans (2007)
	Mixed-integer linear programming, Benders decomposition	Uster et al. (2007)
	Mixed-integer linear programming, Lagrangian heuristics	Lu and Bostel (2007)
	Mixed-integer linear programming, Scatter Search (SS)	Du and Evans (2008)
	Fuzzy goal programming	Selim and Ozkarahan (2008)
	Mixed-integer linear programming, Stochastic programming, Simulated Annealing (SA)	Lee and Dong (2009)
	Fuzzy programming, fuzzy simulation, Genetic Algorithm (GA)	Qin and Ji (2010)
	Mixed-integer linear programming, mixed-integer nonlinear programming, Differential Evolution (DE)	Lieckens and Vandaele (2007)
	Mixed-integer linear programming, Genetic Algorithm (GA), Particle Swarm Optimization (PSO)	Kannan et al. (2009)
	Nonlinear programming, Genetic Algorithm (GA)	Lee and Chan (2009)
	Multi-criteria decision making, Mixed-integer linear programming	Xanthopoulos and Iakovou (2009)
	Mixed-integer linear programming, Genetic Algorithm (GA)	Lee et al. (2009), Kannan et al. (2010)
	Integer linear programming , Spanning Tree (ST), Genetic Algorithm (GA)	Wang and Hsu (2010)
	Multi-objective programming, Memetic Algorithm (MA)	Pishvaee et al. (2010)
	Mixed-integer linear programming, Robust optimization	Pishvaee et al. (2011)

2.4. Supplier selection

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

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

Ghodsypour and O’Brien (1998) proposed a new model to select the best supplier and determine the order allocation. They used analytical hierarchy process (AHP) to consider qualitative criteria. On the other hand, linear programming (single objective) was utilized to take into account quantitative metrics. After this paper, a lot of investigations have been performed using this idea. Table 2.2 shows some of them. All of these models are formulated as multi-objective programming, because it is desirable to maximize and minimize some objective functions, simultaneously. The main differences between these papers are related to the application of decision techniques. However, all of them are written for open loop supply chain networks. In addition, the majority of them only are examined constraints of demand and capacity of suppliers. On the other hand, one of the key elements of closed-loop supply networks is external supplier. To date, suppliers are selected based on single criterion (purchasing cost) in closed-loop supply chain networks. But, other factors such as quality and delivery and responsiveness of suppliers also are essential.

Table 2.2
Summary of some papers about supplier selection and order allocation

Authors	Supplier selection techniques	Order allocation techniques
Ghodsypour and O’Brien (1998)	Analytical hierarchy process (AHP)	Linear programming
Xia and Wu (2007)	AHP and rough sets theory	Mixed-integer programming
Ustun and Demirtas (2008)	ANP	Goal programming
Sanayei et al. (2008)	Utility theory	Linear programming
Lin (2009)	Fuzzy preference programming	Linear programming
Demirtas and Ustun (2009)	ANP	Goal programming
Wu et al. (2009)	ANP	Mixed-integer programming
Faez et al. (2009)	Fuzzy case-based reasoning	Mixed-integer programming
Razmi et al. (2009)	Fuzzy	Fuzzy linear programming
Amin et al. (2011)	Fuzzy SWOT analysis	Fuzzy linear programming

2.5. Potential future research

The potential future researches based on literature survey are as follows:

1- In closed-loop network configuration, not only it is preferred to minimize the total cost (including operation, transportation, and holding costs), but also it is necessary to optimize other factors such as recycling materials and wastes because of environmental concerns. In addition, different criteria should be considered in selection of members of supply chain (such as suppliers). As a consequence, multi-objective models should be developed and appropriate solution approaches should be utilized.

2- Another problem is related to the uncertainty. In the mathematical models, there are several parameters such as cost, demand, and return which are not deterministic. As a result, several sources of uncertainty should be considered. To this aim, some techniques such as fuzzy sets theory, stochastic programming, and robust optimization can be applied.

3- The minority of authors have taken into account multi-objective closed-loop supply chain models under uncertainty. It is valuable to examine integrated models including multi-objective and uncertainty.

4- There are several types of costs in reverse logistics such as transportation, inventory, shrinkage (theft), obsolescence, collection, sorting, quality diagnosis, handling, repackaging, and change from book value. In the majority of models, authors have considered only some of these costs. It is worthwhile to take into account a collection of them.

5- Another issue is the complexity of mathematical models. The complexity of network leads to large mathematical models that cannot be solved quickly by commercial software such as GAMS. Therefore, heuristic and meta-heuristics algorithms such as Scatter Search should be proposed.

6- The most of proposed closed-loop supply chain models have not considered multi-period inventory management parameters. In this situation, the inventory and related holding costs should be calculated.

7- The most of closed-loop supply chain models are mixed-integer linear programming models. There are some techniques such as Branch & Bound and Benders decomposition approach to calculate exact solutions. The application of these techniques and designing efficient solution algorithms can be subject of future research.

CHAPTER 3. A MULTI-OBJECTIVE FACILITY LOCATION MODEL FOR CLOSED-LOOP SUPPLY CHAIN NETWORK UNDER UNCERTAIN DEMAND AND RETURN

3.1. Introduction

Supply chain management (SCM) has received a lot of attentions. There are two types of supply chains: forward and reverse supply chains. The forward supply chain (FSC) contains of series of activities which result in the conversion of raw materials to finished products. Managers try to improve forward supply chain performances in areas such as demand management, procurement, and order fulfilment (Cooper et al., 1997). Reverse supply chain (RSC) is defined as the activities of the collection and recovery of product returns in SCM. Economic features, government directions, and customer pressure are three aspects of reverse logistics (Melo et al., 2009). The integration of a forward supply chain and a reverse supply chain results in a closed-loop supply chain (CLSC) (Guide and Van Wassenhove, 2009). In other words, there are both forward and reverse channels in CLSC networks.

Several investigations have been done about forward facility location models. Facility location models try to answer the following questions: How many facilities should be open? Where each facility should be located? What is the allocation? Which set of collection centres should be opened and operated? What products should be processed in these open facilities? Some authors have examined facility location models for closed-loop supply chain networks (such as Fleischmann et al., 2001). The objective of these models is to determine decision variables of both forward and reverse channels. Minimization of total cost is considered as main objective function. A minority of authors not only considered the total cost, but also they took into account other factors by multi-objective models. On the other hand, some researchers investigated uncertainty in CLSC configuration (for instance Salema et al., 2007). Uncertainties in supply and demand are two major sources of vagueness in SCM. Uncertainty in supply is appeared because of the mistakes or delays in the supplier’s deliveries. Demand uncertainty is defined as inexact forecasting demands or as volatility demands (Davis, 1993; Snyder, 2006; Zhang and Ma, 2009). Uncertain return is another important source of ambiguity in reverse logistics. To our knowledge, most of authors have not taken into account multi-objective closed-loop supply chain models under uncertainty. Thus, it is valuable to examine integrated models including multi-objective models with uncertain parameters.

In this chapter, a facility location model is proposed for a general closed-loop supply chain network. The model is designed for multiple plants (manufacturing and remanufacturing), demand markets, collection centres, and products. The goal is to know how many and which plants and collection centres should be open, and which products and in which quantities should be stock in them. The objective function minimizes the total cost. In this chapter, two test problems are examined. In addition, the model is developed to multi-objective by considering environmental factors. Then, it is solved by two methods including weighted sums and ε-constraint methods. Furthermore, trade-off surfaces of test problems are examined. The multi-objective model also is extended by stochastic programming (scenario-based) to examine the effects of uncertain demand and return on the network configuration. Finally, computational results are discussed and analysed. This research is among the first investigations that consider multi-objective mathematical models under uncertainty in CLSC network configuration.

The organization of this chapter is as follows. In Section 3.2, a general network is described. In Section 3.3, the mathematical model is provided. Then, two test problems are presented in Section 3.4. An extension to multi-objective programming is provided in Section 3.5. In addition, the model is developed by stochastic programming in Section 3.6. Finally, conclusions are discussed in Section 3.7.

3.2. Network description

In this section, a general closed-loop supply chain network is described. Figure 3.1 shows the network which includes plants, collection centres, and demand markets. The plants can manufacture new products and remanufacture returned products. The products are sent to demand markets by plants. Then, the returned products are sent to collection centres. Collection centres have the following responsibilities: collecting of used products from demand markets, determining the condition of the returns by inspection and/or separation to find out whether they are recoverable or not, sending recoverable returns to the plants, sending the unrecoverable returns (because of economic and/or technological reasons) to the disposal centre. The objective is to know how many and which plants and collection centres should be open, and which products and in which quantities should be stock in them.

The following assumptions are made in the network configuration:

- All of the returned products from demand markets are collected in collection centres.
- Locations of demand markets are fixed.
- Locations and capacities of plants and collection centres are known in advance.

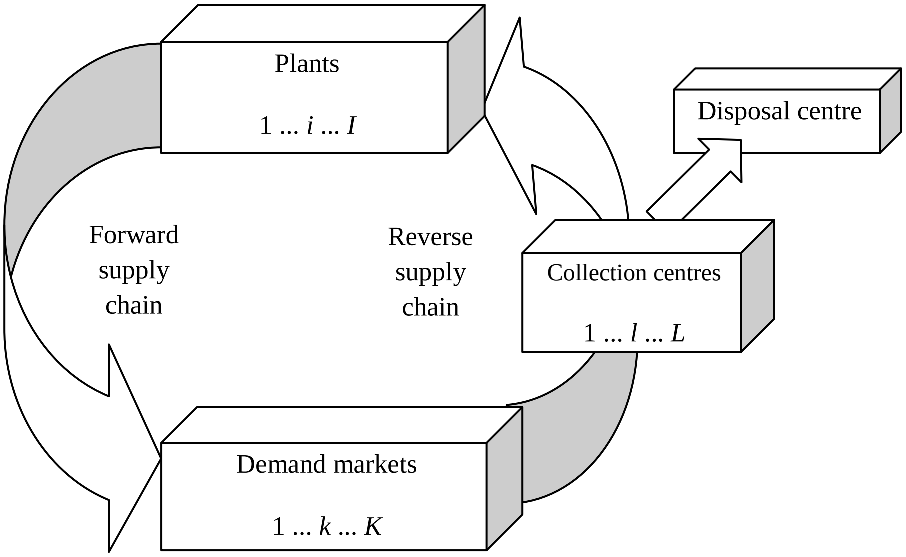


Figure 3.1. The closed-loop supply chain network

3.3. Mathematical model

The network can be formulated as a mixed-integer linear programming model. Sets, parameters, and decision variables are defined as follows:

Sets

I = set of potential manufacturing and remanufacturing plants locations (1 ... i ... I)

J = set of products (1 ... j ... J)

K = set of demand markets locations (1 ... k ... K)

L = set of potential collection centres locations (1 ... l ... L)

Parameters

A_j = production cost of product *j*

B_j = transportation cost of product *j* per km between plants and demand markets

C_j = transportation cost of product *j* per km between demand markets and collection centres

D_j = transportation cost of product *j* per km between collection centres and plants

O_j = transportation cost of product *j* per km between collection centres and disposal centre

E_i = fixed cost for opening plant *i*

F_l = fixed cost for opening collection centre *l*

G_j = cost saving of product *j* (because of product recovery)

H_j = disposal cost of product *j*

P_{ij} = capacity of plant *i* for product *j*

Q_{lj} = capacity of collection centre *l* for product *j*

t_{ik} = the distance between location *i* and *k* generated based on the Euclidean method (t_{kl} and t_{li} are defined in the same way). t_l is the distance between collection centre *l* and disposal centre

d_{kj} = demand of customer *k* for product *j*

r_{kj} = return of customer *k* for product *j*

α_j = minimum disposal fraction of product *j*

Variables

X_{ikj} = quantity of product *j* produced by plant *i* for demand market *k*

Y_{klj} = quantity of returned product *j* from demand market *k* to collection centre *l*

S_{lij} = quantity of returned product *j* from collection centre *l* to plant *i*

T_{lj} = quantity of returned product *j* from collection centre *l* to disposal centre

Z_i = 1, if a plant is located and set up at potential site *i*, 0, otherwise

W_l = 1, if a collection centre is located and set up at potential site *l*, 0, otherwise

$$Min\ z_1 = \sum_i E_i Z_i + \sum_l F_l W_l + \sum_i \sum_k \sum_j (A_j + B_j\, t_{ik}) X_{ikj} + \sum_k \sum_l \sum_j C_j\, t_{kl}\, Y_{klj}$$

$$+ \sum_l \sum_i \sum_j (-G_j + D_j\, t_{li}) S_{lij} + \sum_l \sum_j (H_j + O_j\, t_l) T_{lj}$$

s.t.

$$\sum_i X_{ikj} \geq d_{kj} \qquad \forall k, j, \qquad (3.1)$$

$$\sum_l \sum_j S_{lij} + \sum_k \sum_j X_{ikj} \leq Z_i \sum_j P_{ij} \qquad \forall i, \qquad (3.2)$$

$$\sum_l Y_{klj} \leq \sum_i X_{ikj} \qquad \forall k, j, \qquad (3.3)$$

$$\alpha_j \sum_k Y_{klj} \leq T_{lj} \qquad \forall l, j, \qquad (3.4)$$

$$\sum_k \sum_j Y_{klj} \leq W_l \sum_j Q_{lj} \qquad \forall l, \qquad (3.5)$$

$$\sum_k Y_{klj} = \sum_i S_{lij} + T_{lj} \qquad \forall l, j, \qquad (3.6)$$

$$\sum_l Y_{klj} = r_{kj} \qquad \forall k, j, \qquad (3.7)$$

$$Z_i, W_l \in \{0, 1\} \qquad \forall i, l, \qquad (3.8)$$

$$X_{ikj}, Y_{klj}, S_{lij}, T_{lj} \geq 0 \qquad \forall i, k, l, j, \qquad (3.9)$$

The objective function is minimization of the total cost. The first and second parts show the fixed costs of opening plants and collection centres, respectively. The third part represents the production and transportation costs of new products. The forth part is related to product recovery and transportation costs of returned products. Besides, the fifth part represents the total recovery and transportation costs of returned products from collection centres to plants. Besides, the sixth part calculates disposal and transportation costs.

The constraint (3.1) ensures that the total number of each product for each demand market is equal or greater than the demand. Constraint (3.2) is a capacity constraint of plants. Constraint (3.3) represents that forward flow is greater than reverse flow. Constraint (3.4) enforces a minimum disposal fraction for each product. Constraint (3.5) is capacity constraint of collection centres. Constraint (3.6) shows that the quantity of returned products from demand market is equal to the quantity of returned products to plants and quantity of products in disposal centre for each collection centre and each product. Constraint (3.7) shows the returned products. Constraint (3.8) ensures the binary nature of decision variables while Constraint (3.9) preserves the non-negativity restriction on the decision variables.

3.4. Application of the proposed model

Copier remanufacturing has been investigated in some papers such as Fleischmann et al. (2001). Major manufacturers such as Canon are reselling and remanufacturing used copy machines collected from their customers. During an initial inspection at a collection site, quality standards of used machines are checked to make sure the returned products have certain quality standards. Remanufacturing is often carried out in the original manufacturing plants using the same equipment. Machines that cannot be reused as a whole may still provide a source for reusable spare parts. The remainder is typically sent to a disposal centre.

The goal of this section is to show the application of the mathematical model by numerical examples. To this aim, two test problems are examined. In the test problem 1, a deterministic example is considered. Data of costs and minimum disposal fraction are adopted from Fleischmann et al. (2001). Table 3.1 shows the data in detail. The potential locations for manufacturers, demand markets, collection centres, and disposal centre were generated from uniform distribution between 0 and 100 units of distance on the x and y coordinates. Test problem 1 consists of deterministic parameters. However, it is hard to estimate the values of parameters in real world. In the test problem 2, it is supposed that parameters (except demand and return) follow uniform distribution. Table 3.1 shows the values. The objective is to consider a realistic model by using uniform distribution.

Table 3.1

Data for copier remanufacturing example

Test problem 1		
$I = 4$ (number of plants)	$C_j = 0.005$	$H_j = 2.5$
$J = 3$ (number of products)	$D_j = 0.003$	$P_{ij} = 84{,}000$
$K = 5$ (number of demand markets)	$O_j = 0.00155$	$Q_{lj} = 34{,}000$
$L = 4$ (number of collection centres)	$E_i = 5{,}000{,}000$	$d_{kj} = 30{,}000$
$A_j = 15$	$F_l = 500{,}000$	$r_{kj} = 10{,}000$
$B_j = 0.01455$	$G_j = 7$	$\alpha_j = 0.4$
Test problem 2		
$I = 4$ (number of plants)	$C_j =$ uniform (0.0045, 0.0055)	$H_j =$ uniform (2.25, 2.75)
$J = 3$ (number of products)	$D_j =$ uniform (0.0027, 0.0033)	$P_{ij} =$ uniform (75,600, 92,400)
$K = 5$ (number of demand markets)	$O_j =$ uniform (0.0014, 0.0017)	$Q_{lj} =$ uniform (30,600, 37,400)
$L = 4$ (number of collection centres)	$E_i =$ uniform (4,500,000, 5,500,000)	$d_{kj} = 30{,}000$
$A_j =$ uniform (13.5, 16.5)	$F_l =$ uniform (450,000, 550,000)	$r_{kj} = 10{,}000$
$B_j =$ uniform (0.0131, 0.0160)	$G_j =$ uniform (6.3, 7.7)	$\alpha_j =$ uniform (0.27, 0.33)

Test problems have been solved by CPLEX 9.1.0. CPLEX is an optimization software package which is suitable for solving mixed-integer linear programming problems. All computational work was performed on a personal computer (32-bit operating system, 2.33 GHz CPU, and 4.00 GB). The model statistics are 797 non-zero elements, 78 single equations, 189 single variables, and 8 discrete variables. The objective value (total cost), in the test problem 1 is 17,878,724 and in the test problem 2 is 17,406,850. Figures 3.2 and 3.3 show the optimal networks for test problems 1 and 2, respectively (product 2). It can be seen that in the test problem 1, plants 1 and 3 are open. However, plants 2 and 3 work in the test problem 2. In addition, different collection centres are open in the test problems 1 and 2. As a result, considering uniform distribution not only changes the total cost of network configuration, but also it alters the open facilities.

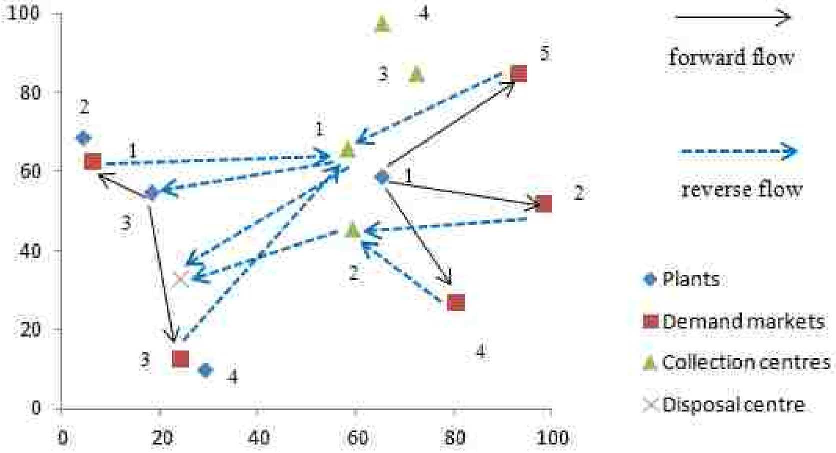


Figure 3.2. Optimal closed-loop supply chain network (test problem 1, product 2)

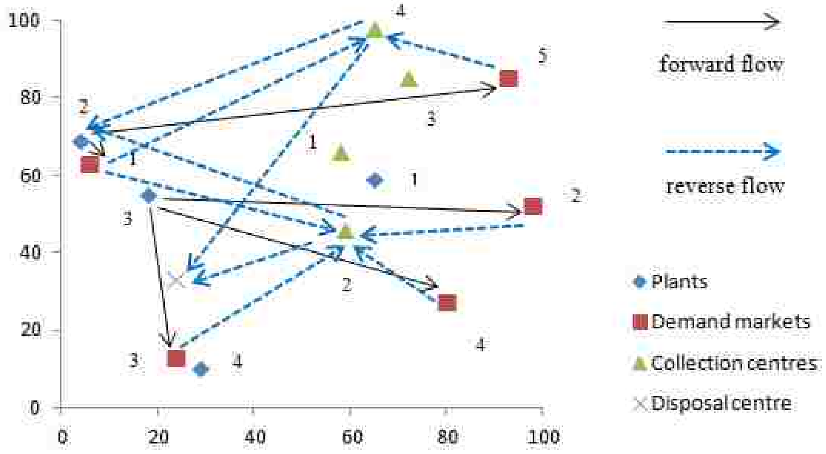


Figure 3.3. Optimal closed-loop supply chain network (test problem 2, product 2)

3.5. An extension to multi-objectives

In the mentioned mathematical model, the total cost is minimized. However, environmental issues also should be considered. To this aim, new parameters are defined. M_{ij} is parameter of using environmental friendly materials by plant i to produce product j. Recyclable materials is an example of this parameter (Ruan and Xu, 2011). Another parameter is N_{lj} which is defined as parameter of using clean technology by collection centre l to process product j. Clean technology consists of renewable and recycling energy such as solar power (Kemp and Volpi, 2008). Both of two parameters are qualitative and should be determined by decision makers. Some decision making techniques such as analytic hierarchy process (AHP), and analytic network process

(ANP) can be helpful to convert qualitative assessments to quantitative results. These two parameters are between 0 and 1. The second objective function can be written as Eq. (3.10).

$$Max\ z_2 = \sum_i \sum_j M_{ij} (\sum_k X_{ikj} + \sum_l S_{lij}) + \sum_l \sum_j N_{lj} (\sum_k Y_{klj} + \sum_i S_{lij} + T_{lj}) \tag{3.10}$$

3.5.1. Solution approach

To solve the multi-objective problem, two methods are utilized including weighted sums method, and *ε*-constraint method. These methods can transform our problem to a mono-objective optimization problem. For more information you can refer to Collette and Siarry (2003).

3.5.1.1. Weighted sums method

In this method, objective functions are combined by assigning appropriate weights. The weights (w_1 and w_2 in this case) are determined by decision makers. Some methods such as AHP and ANP also can be applied in determining the weights of objectives. It is noticeable that w_1, $w_2 \geq 0$ and $w_1 + w_2 = 1$. Eq. (3.11) shows the formula for our problem.

$$\begin{aligned} & Min\ z = w_1 z_1 - w_2 z_2 \\ & s.t. \\ & Eq.\,(3.1) - (3.9) \end{aligned} \tag{3.11}$$

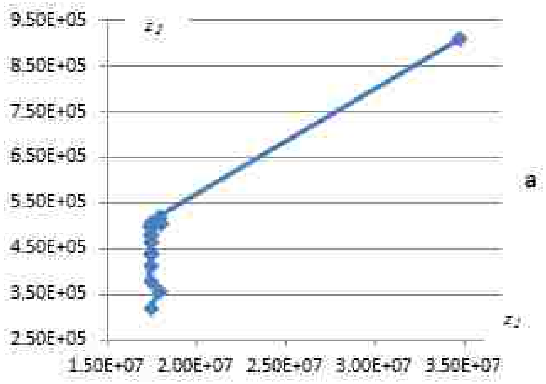
3.5.1.2. ε-constraint method

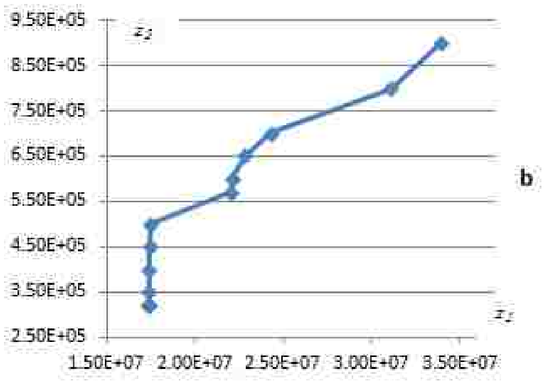
In this method, the multi-objective optimization problem is transformed to a mono-objective optimization problem with additional constraints. The objective function with a high priority is considered as objective function. Other objectives are written as constraints by using a constraint vector *ε*. The transformed problem is written in Eq. (3.12).

$$\begin{aligned} & Min\ z = z_1 \\ & s.t. \\ & z_2 \geq \varepsilon \\ & Eq.\,(3.1) - (3.9) \end{aligned} \tag{3.12}$$

3.5.2. Trade-off surfaces

The goal of multi-objective programming models is to find efficient solutions. An efficient solution has the property that it is impossible to improve any one objective values without sacrificing on at least one other objective. The small number of efficient solutions produces the trade-off surface or Pareto front (Collette and Siarry, 2003; Wadhwa and Ravindran, 2007). In this section, the test problem 2 is solved by two mentioned methods and trade-off surfaces are depicted in the Figure 3.4. To this aim, different weights are assigned and the values of objective functions are calculated. In addition, the trade-off surface of the problem is obtained by changing the value of ε. As mentioned before, CPLEX 9.1.0 is utilized to solve the problem. It is supposed that M_{ij} and N_{li} have uniform distribution between 0 and 1.





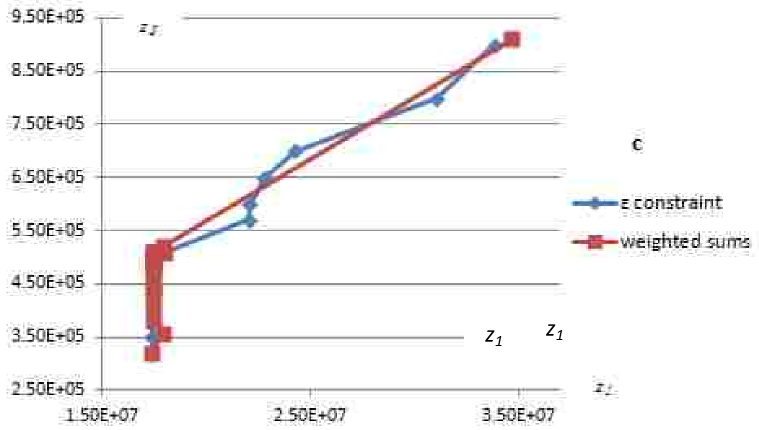


Figure 3.4. Trade-off surfaces for the test problem 2: (a) weighted sums method, (b) ε-constraint method, (c) weighted sums and ε-constraint methods

It is easy to use weighted sums method, but it can be applied only to the convex sets. This is a weakness of this method that makes it difficult to identify the trade-off surface of the problem. The ε-constraint method can be applied for non convex problems. However, it is very sensitive to the selection of parameter ε. A good choice can provide a good spread of solutions on the trade-off surface. This issue can be considered as a weakness of this method.

It can be seen in the Figure 3.4 that weighted sums method cannot identify some solutions between 17,891,000 and 34,684,000 values of the first objective function. However, ε-constraint method can obtain more solutions. As a result, for the test problem 2, ε-constraint method is more efficient rather than weighted sums method. The values of objective functions of ε-constraint method have been written in the Table 3.2. The numbers of open facilities (plants and collection centres) also have been written.

Table 3.2
Results of ε-constraint method

ε	Value of the first objective	Value of the second objective	Open plants	Open collection centres
50,000	17,407,000	319,120	2, 3	2, 4
100,000	17,407,000	319,120	2, 3	2, 4
200,000	17,407,000	319,120	2, 3	2, 4
300,000	17,407,000	319,120	2, 3	2, 4
350,000	17,407,000	350,000	2, 3	2, 4
400,000	17,413,000	400,000	2, 3	2, 4
450,000	17,440,000	450,000	2, 3	2, 3
500,000	17,473,000	500,000	2, 3	2, 3
600,000	22,094,000	600,000	2, 3, 4	2, 3
650,000	22,794,000	650,000	2, 3, 4	2, 3
700,000	24,298,000	700,000	2, 3, 4	1, 2, 3
800,000	31,091,000	800,000	1, 2, 3, 4	2, 3
900,000	33,870,000	900,000	1, 2, 3, 4	1, 2, 3

3.6. An extension to consider uncertainty

Several parameters have uncertain values in practice. Uncertainty in demand is major source of uncertainty in supply chain management. Uncertain return is another important source of vagueness in reverse logistics. It is useful to take into account this issue in the optimization model.

3.6.1. Stochastic programming

The uncertainty in parameters can be modelled by stochastic programming. The goal of stochastic programming is to discover a solution that will perform well under any possible realization of the random parameters. The random parameters can be stated as continuous values or discrete scenarios (Snyder, 2006). In this chapter, a scenario-based analysis is utilized to consider uncertainty. For more information, you can refer to Birge and Louveaux (1997) and Al-Othman et al. (2008). Suppose that vector y includes all binary variables. Besides, vector x has all non-negative variables. Moreover, q and C are vectors related to fix and variable costs, respectively. It is also assumed that a, b, e, and f are matrices. Minimization problem can be written as follow:

$$\begin{aligned} & Min\ z = q\,y + C\ x && (3.13) \\ & s.t. \\ & a\ x\ \le b \\ & e\ x\ \le f\ y \\ & y \in \{0,1\} \quad x \ge 0 \end{aligned}$$

Assume that there are U scenarios and scenario u can happen with probability p_u. The expected value of the objective function can be calculated by (3.14).

$$\begin{aligned} & Min\ z = q\,y + \sum_u p_u C_u x_u && (3.14) \\ & s.t. \\ & a_u x_u \le b_u \qquad \forall u, \\ & e_u x_u \le f\ y \qquad \forall u, \\ & y \in \{0,1\} \quad x_u \ge 0 \quad \forall u \end{aligned}$$

To formulate the closed-loop supply chain network under uncertainty, new sets, parameters, and variables should be added to the previous definitions.

Sets

U = set of scenarios (1 ... u ... U)

Parameters

d_{kju} = demand of customer k for product j for scenario u

r_{kju} = return of customer k for product j for scenario u

p_u = probability of scenario u

Variables

X_{ikju} = quantity of product j produced by plant i for demand market k in scenario u

Y_{klju} = quantity of returned product j from demand market k to collection centre l in scenario u

S_{liju} = quantity of returned product j from collection centre l to plant i in scenario u

T_{lju} = quantity of returned product *j* from collection centre *l* to disposal centre in scenario *u*

The multi-objective stochastic model (scenario-based) can be written as:

$$Min\ z\ =\ \sum_i E_i Z_i + \sum_l F_l W_l + \sum_u \sum_i \sum_k \sum_j p_u (A_j + B_j\, t_{ik}) X_{ikju} + \sum_u \sum_k \sum_l \sum_j p_u C_j\, t_{kl}\ Y_{klju}$$

$$+ \sum_u \sum_l \sum_i \sum_j p_u (-G_j + D_j\, t_{li}) S_{liju} + \sum_u \sum_l \sum_j p_u (H_j + O_j\, t_l) T_{lju}$$

s.t.

$$\sum_i \sum_j M_{ij} (\sum_k X_{ikju} + \sum_l S_{liju}) + \sum_l \sum_j N_{lj} (\sum_k Y_{klju} + \sum_i S_{liju} + T_{lju}) \geq \varepsilon \qquad \forall u, \qquad (3.15)$$

$$\sum_i X_{ikju} \geq d_{kju} \qquad \forall k, j, u, \qquad (3.16)$$

$$\sum_l \sum_j S_{liju} + \sum_k \sum_j X_{ikju} \leq Z_i \sum_j P_{ij} \qquad \forall i, u, \qquad (3.17)$$

$$\sum_l Y_{klju} \leq \sum_i X_{ikju} \qquad \forall k, j, u, \qquad (3.18)$$

$$\alpha_j \sum_k Y_{klju} \leq T_{lju} \qquad \forall l, j, u, \qquad (3.19)$$

$$\sum_k \sum_j Y_{klju} \leq W_l \sum_j Q_{lj} \qquad \forall l, u, \qquad (3.20)$$

$$\sum_k Y_{klju} = \sum_i S_{liju} + T_{lju} \qquad \forall l, j, u, \qquad (3.21)$$

$$\sum_l Y_{klju} = r_{kju} \qquad \forall k, j, u, \qquad (3.22)$$

$$Z_i, W_l \in \{0, 1\} \qquad \forall i, l, \qquad (3.23)$$

$$X_{ikju}, Y_{klju}, S_{liju}, T_{lju} \geq 0 \qquad \forall i, k, l, j, u, \qquad (3.24)$$

3.6.2. Computational results

To consider the effects of uncertainty, scenario analysis is performed. The selected scenarios for analysis and discussion are listed in Table 3.3. Parameters of scenario 5 (base-case) are similar to the test problem 2. Each of the scenarios (1-9) represents different scenario reflecting variations in demand and return. Actually, different combinations of 10% increase and decrease in demand and return have been considered. In addition, the scenarios are compared in terms of changes in the value of objective function with respect to the base-case (scenario 5), as illustrated in Table 3.3. Besides, stochastic model has been solved and change in the value of objective function has been written in Table 3.3. Figure 3.5 shows the value of objective functions in deterministic and stochastic models.

Sensitivity analysis of results shows that the optimum closed-loop supply chain network is very sensitive to changes in demand and return. As shown in Table 3.3, planning for a 10% increase in demand (scenario 6) would result to a network that has about 6.67% more cost than the base-case, while assuming 10% decrease in demand (scenario 7) reduces the cost about 6.49%. Deviations in cost also can be observed for return (scenarios 3 and 4). However, it can be seen that the effect of uncertainty in demand is higher than return because the demand has more significant contribution than return in the objective function. Such deviations in cost reveal that planning under uncertain situation (demand and return) is risky, and forecasts of vague parameters can be helpful. Results of the stochastic scenario (scenario 10) show that the stochastic programming model can obtain flexible optimum closed-loop supply chain configuration with the objective function near to the base-case (0.05% change). This observation shows that the proposed stochastic programming model takes into account the risks related to different sources of uncertainty including demand and return.

Minimum disposal fraction of product *j* (α_j) is an important parameter which is related to reverse supply chain. To show the effect of this parameter on the objective function, sensitivity analysis is performed. Figure 3.6 shows the results for both of deterministic (base-case) and stochastic models.

Table 3.3

Scenario analysis

Deterministic models	797 non-zero elements, 78 single equations, 189 single variables, and 8 discrete variables.			
Scenario	Demand	Return	Probability	Change %
1	33,000	9,000	0.075	6.43
2	27,000	11,000	0.075	-3.53
3	30,000	11,000	0.1	0.23
4	30,000	9,000	0.1	-0.22
5 (base-case)	30,000	10,000	0.3	0.00
6	33,000	10,000	0.1	6.67
7	27,000	10,000	0.1	-6.49
8	33,000	11,000	0.075	6.91
9	27,000	9,000	0.075	-6.75
10 Stochastic model	Combination of nine scenarios 8723 non-zero elements, 704 single equations, 1630 single variables, and 8 discrete variables.			0.05

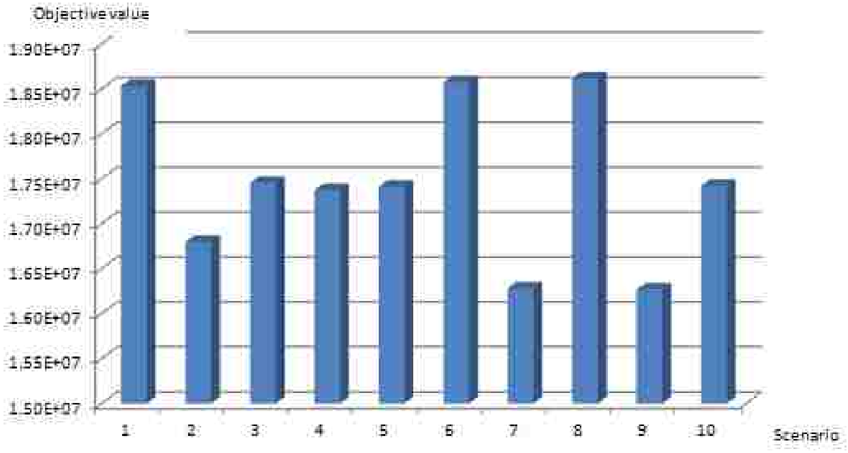


Figure 3.5. Objective values of deterministic scenarios (1-9) and stochastic case (scenario 10)

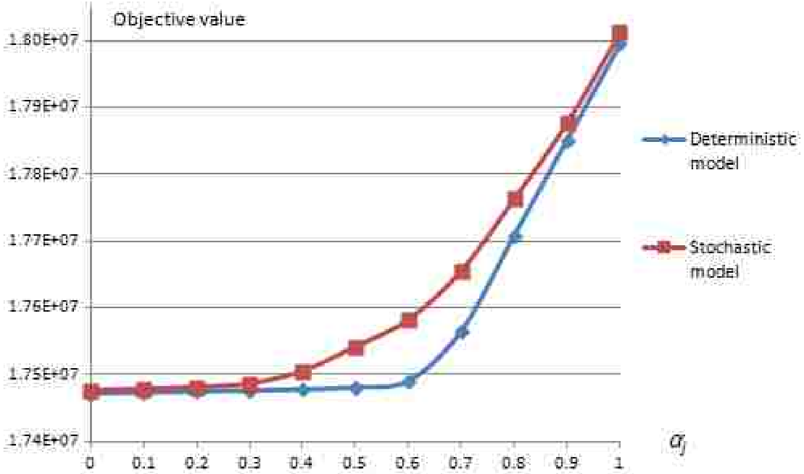


Figure 3.6. Sensitivity analysis of α_j in deterministic (base-case) and stochastic scenarios

3.7. Conclusions

In this research, a facility location model is proposed for a closed-loop supply chain network. The model is designed for multiple plants, demand markets, collection centres, and products. To show the application of the mathematical model, two test problems are examined for a copier remanufacturing example. Besides, the model is extended to consider environmental objective. Two methods are utilized to solve the multi-objective programming model including weighted sums and ε-constraint methods. The results of test problem 2 show that ε-constraint method can obtain more efficient solutions than weighted sums method. Therefore, ε-constraint method is selected for this example. The model also is developed by stochastic programming (scenario-based) to examine the effects of uncertain demand and return on the network configuration. The computational results demonstrate that the stochastic programming model can gain flexible optimal closed-loop supply chain configuration with the objective function near to the base-case.

There are some potential future works. One of the weaknesses of scenario-based analysis is the small number of scenarios because of computational reasons. It is useful to examine the effects of uncertainty on the model by other methods such as robust optimization and compare the results. In this research, two qualitative factors (environmental friendly materials and using clean technology) have been considered. It is helpful to propose a new method based on some environmental standards such as Ecoindicator 99. Another future research is to develop heuristic approaches such as Genetic Algorithm and Scatter Search because it is hard to solve large problems in a reasonable time.

CHAPTER 4. AN INTEGRATED MODEL FOR CLOSED-LOOP SUPPLY CHAIN CONFIGURATION AND SUPPLIER SELECTION: MULTI-OBJECTIVE APPROACH

4.1. Introduction

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

Although several investigations have been performed for supplier selection in open loops, supplier selection in CLSC network is a novel subject. There are some differences between supplier selection in open loops and closed-loops networks. The importance of some criteria is higher in closed-loops supply chains rather than open ones. Generally, several factors such as quality, delivery, capacity, and price are considered in supplier selection (Weber et al.,1991). Kahraman et al. (2003) categorized supplier selection criteria into four groups including supplier criteria, product performance criteria, service performance criteria, and cost criteria. In closed-loops, product performance criteria would have more importance rather than open loops because the products should have some characteristics such as durability, strength, and lightweight to be reusable and recoverable. In addition, the number of disposed products depends on product performance criteria and has influence on the total cost. Environmental criteria are another group of characteristics that should be emphasized in closed-loop configuration. Recycling, clean technology, pollution reduction capacity, and environmental costs are examples of environmental factors. It is noticeable that conservation of environment is one of the goals of CLSC configuration. Recently, a few papers have considered green supplier selection; however, they have not focused on RL. In addition, order allocation and CLSC network configuration are not taken into account in them. Another difference between supplier selection in closed-loops and open loops referred to the sources of uncertainty. Demand and supply usually are the sources of uncertainty in open loops. Supplier selection helps the researchers and practitioner to overcome the uncertainty in supply. However, in CLSC the return is added to the sources of uncertainty. Thus, the manufacturer should set a balance between supply, demand, and return and he/she should buy new parts according to the uncertain return. In other words, supplier selection and order allocation should be performed concurrently with CLSC configuration to prevent over-stocking and under-stocking costs in purchasing process.

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

The chapter is organized as follows. In Section 4.2, the problem is defined. Section 4.3 is devoted to the proposed model and the solution approach. In Section 4.4, we present a numerical example to validate the model. Finally, in Section 4.5 conclusions are presented.

4.2. Problem definition

In this study, a CLSC network is investigated that consists of disassembly, refurbishing and disposal sites. Figure 4.1 shows the network. The network is managed by manufacturer. The manufacturer produces products according to the demand. After using the products by customers, some of them are returned. The returned products are taken to disassembly site. Then, they are separated to reusable parts and wastes. The wastes go to the disposal site. On the other hand, reusable parts are taken to refurbishing site to be cleaned and refurbished. These parts are added to part inventory as new parts. It is noticeable that capacities of disassembly, disposal, and refurbishing sites are limited. According to the demand and refurbished parts, the manufacturer purchases new parts from external suppliers. Not only the cost of parts is important for manufacturer, but also he should consider other criteria such as delivery, and quality. The manufacturer encounters two types of decisions. First, he is interested to know the number of optimal products and parts in each section of the network. For instance, the number of returned parts is one of the variables. These factors are called tactical decisions. Network configuration provides information for tactical decisions. On the other hand, some strategic decisions should be considered. Supplier selection is one of them. Supplier selection is helpful to assess suppliers based on several factors. In CLSC networks, the parts are supplied from returned and new parts. The coordination and cooperation of these two sources can affect the rate of production, and ultimately change the cost of finished products. Besides, the lack of supply in new or returned parts can increase the holding costs of part inventory. Refurbishing site selection is another strategic decision.

When there are some alternatives for refurbishing parts, the manufacturer prefers to select the site which has the lowest cost.

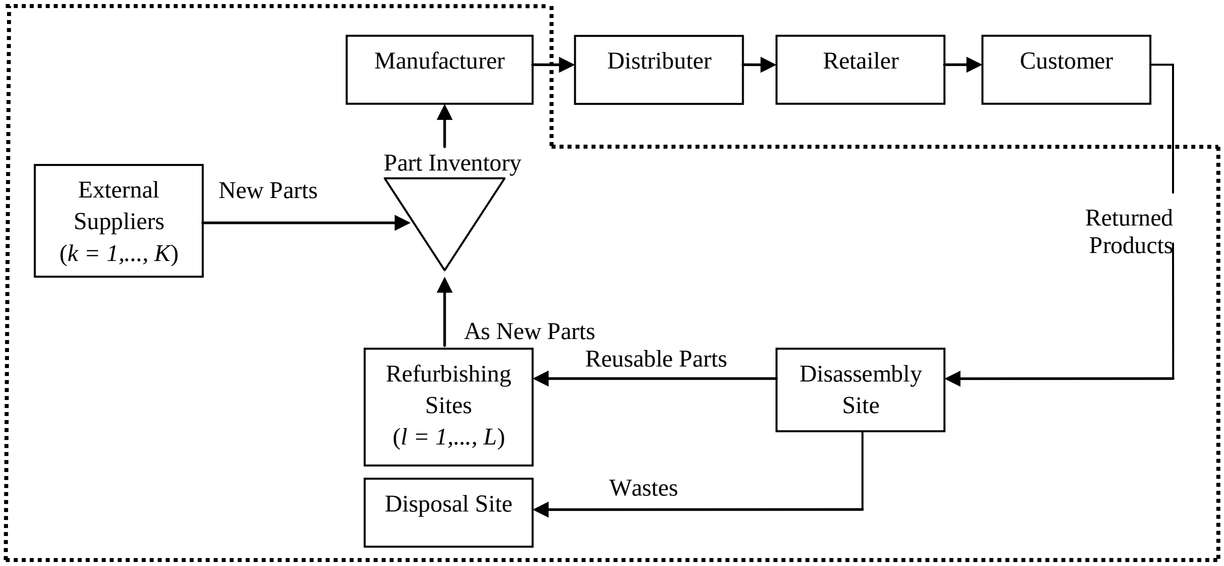


Figure 4.1. A closes-loop supply chain (dashed area)

4.3. Proposed model

In this section, the proposed model is described. Figure 4.2 shows the framework of our approach. First, the manufacturer identifies potential suppliers and defines appropriate criteria. Then, decision makers evaluate suppliers by the proposed fuzzy model. The results of this phase are the weights (importance) of suppliers based on qualitative metrics. In the next phase, the closed-loop supply chain network is formulated as multi objective mixed-integer linear programming model. In this stage, the related variables (strategic and tactical decision variables) are calculated.

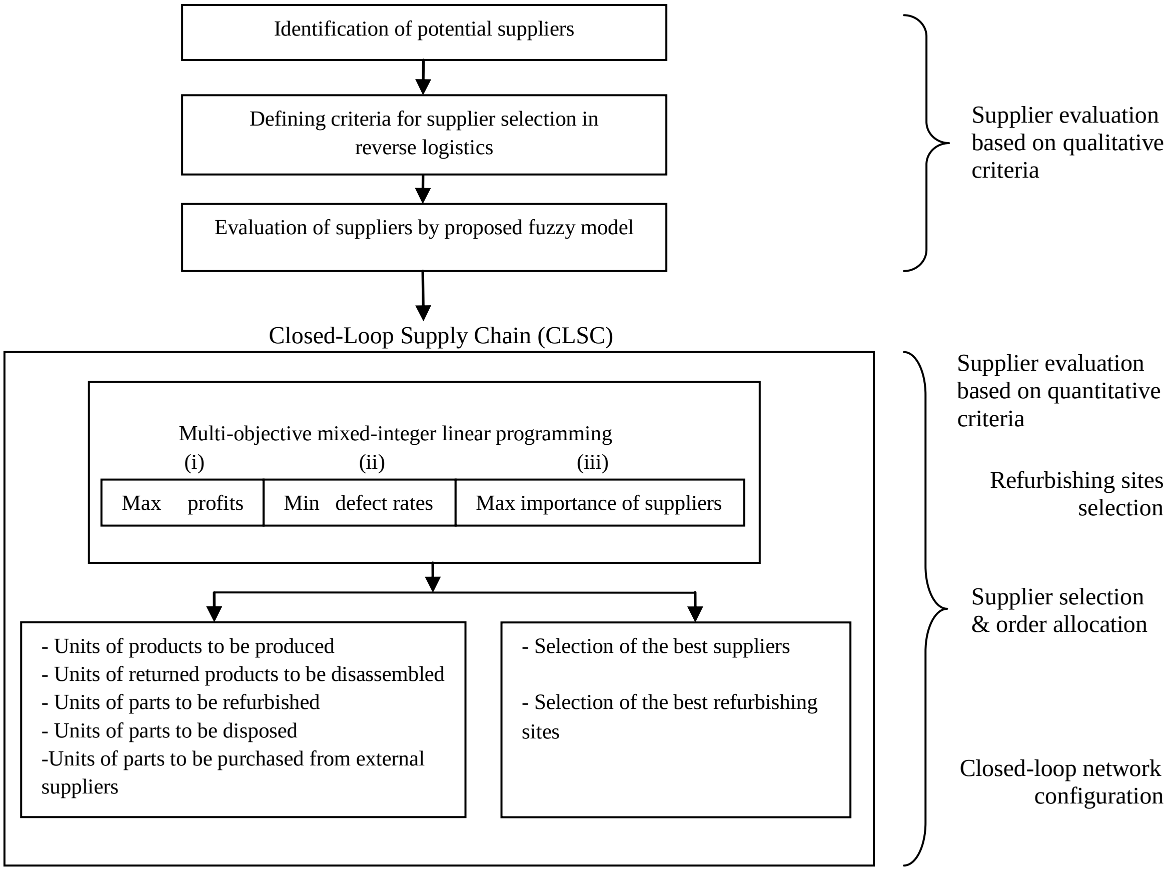


Figure 4.2. Framework of the proposed model

4.3.1. Evaluation of suppliers

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

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

Step 1: Define suitable criteria: In this research, we propose a new framework for defining supplier selection criteria, especially in the field of reverse logistics. The framework is designed based on supplier-related (Ca_1), part-related (Ca_2), and process-related (Ca_3) categories. Figure 4.3 illustrates the framework. The majority of supplier selection studies have focused on supplier related criteria such as delivery, cost, financial ability and experience. These metrics are enough when the suppliers are assessed without considering specific parts and processes. Between part-related criteria, price and quality (defect rates) are frequently used. For instance, Dickson (1966) identified 23 different criteria based on a questionnaire sent to 273 purchasing agent and managers from North America. The most important ones were quality, delivery, performance history, warrant and claim policy, production facilities and capacity, net price, and technical capabilities.

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

Step 2: Let U = {VL, L, ML, M, MH, H, VH} be the linguistic set used to express opinions on the group of criteria. This scale is adopted from Amin and Razmi (2009). The linguistic variables of U can be quantified using triangular fuzzy numbers (please refer to Figure 4.4). Each decision maker establishes a level of importance for each category by using linguistic variables and TFNs (Ca_x represents importance of category x, $x = 1, 2, 3$). Then, they are combined by Eq. (4.1) and the weights of categories are calculated.

$$Ca_x = \frac{Ca_{x1} + Ca_{x2} + ... + Ca_{xN}}{N} \tag{4.1}$$

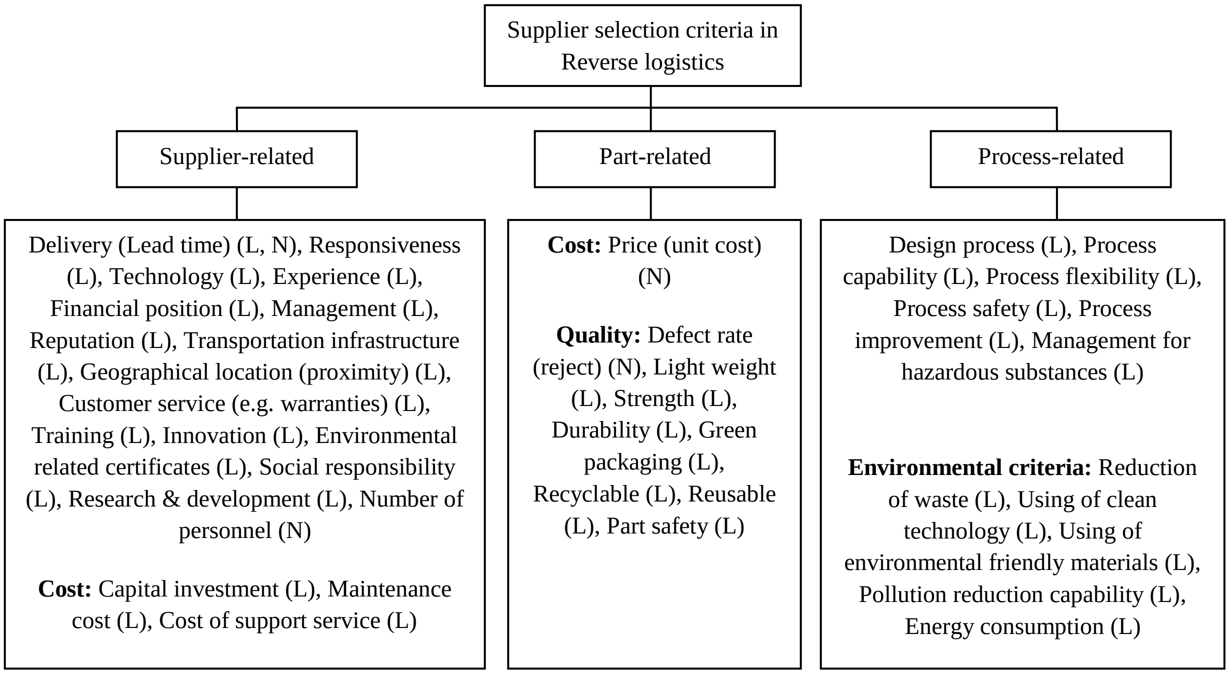


Figure 4.3. Proposed supplier selection criteria in reverse logistics
(L): Qualitative criteria; (N): Quantitative criteria

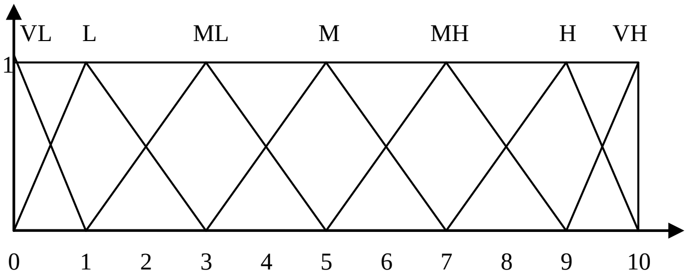


Figure 4.4. A linguistic scale (Amin and Razmi, 2009)

Step 3: Let w_{xmN} represents the importance of criterion *m* in category *x* by decision maker *N*. Decision makers establish a level of importance by Eq. (4.2).

$$w_{xm} = \frac{w_{xm1} + w_{xm2} + \ldots + w_{xmN}}{N} \tag{4.2}$$

Step 4: Let Su_{xmikN} represents the assessment of supplier *k* that manufactures part *i* based on criterion *m* in category *x* which is performed by decision maker *N*. Each decision maker establishes a level of importance. The aggregated weight of supplier *k* based on criterion *m* and part *i* in category *x* (Su_{xmik}) is calculated by Eq. (4.3).

$$Su_{xmik} = \frac{Su_{xmik1} + Su_{xmik2} + \ldots + Sux_{xmikN}}{N} \tag{4.3}$$

Step 5: In this step, weights of categories are multiplied by weights of criteria and aggregated weights. Eq. (4.4) shows the formula. In this equation, a_{ik} is a TFN. Now, the numbers should be defuzzified. In this research, a simple method is applied to defuzzify the numbers. A deffuzzified number of $a_{ik} = (a, n, b)$ is calculated by Eq. (4.5).

$$a_{ik} = \sum_{x=1}^{3}\sum_{m=1}^{M} Ca_x \times w_{xm} \times Su_{xmik} \tag{4.4}$$

$$be_{ik} = \frac{a+n+b}{3} \tag{4.5}$$

Step 6: The normalized weights (importance) of suppliers based on each criterion is calculated by Eq. (4.6). Now, the suppliers can be ranked.

$$t_{ik} = \frac{be_{ik}}{\sum_{k=1}^{K} be_{ik}} \tag{4.6}$$

4.3.2. Mathematical model for CLSC

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

- If the quantity of provided parts from refurbishing site is not enough for requirement of manufacturer, manufacturer should purchase parts from external suppliers.
- The Maximum capacity of disassembly and refurbishing sites and suppliers are known.
- The sum of disassembling and refurbishing costs is less than purchasing cost of a new part.
- The proposed model is a single period one.

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

Indices

i Set of parts, $i = 1,...,I$

j Set of products, $j = 1,...,J$

k Set of suppliers, $k = 1,...,K$

l	Set of refurbishing sites, $l = 1,...,L$

Decision variables

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

Parameters

S_j	Unit selling price for the product j
a_j	Resource usage to produce one unit of product j
c_j	Unit direct manufacturing cost of product j
D_j	Demand for product j
d_j	Set-up cost of disassembly site for product j
E_i	Max capacity of disassembly site to dissemble part i
f_i	Unit disassembly cost for part i
h_i	Unit disposing cost for part i
e_i	Resource usage to disassemble one unit of part i
o_{il}	Unit refurbishing cost for part i in refurbishing site l
p_{il}	Set-up cost of refurbishing site l for part i
g_{il}	Resource usage to refurbish one unit of part i in refurbishing site l
G_{il}	Max capacity of refurbishing site l to refurbish part i
q_{ij}	Unit requirements for part i to produce one unit of product j

r_{ik}	The cost of purchasing part *i* from external supplier *k*
b_{ik}	Internal resource usage of supplier *k* to produce one unit of part *i*
B_k	Max capacity reserved of external supplier *k*
v_k	Minimum purchase quantity from supplier *k*
H_j	Max percent of product *j* returns
O_i	Max percent of reusable part *i*
A	Max capacity of the manufacturer plant
C	Max number of refurbishing sites
s_{ik}	Defect rate for part *i* that is produced by supplier *k*
t_{ik}	Weight (importance) of supplier *k* for part *i*

Model formulation

$$Max\ Z_1 \quad \sum_{j=1}^{J}(S_j - C_j)P_j - \sum_{i=1}^{I}\sum_{k=1}^{K} r_{ik}Q_{ik} - \sum_{i=1}^{I} f_i\, T_i - \sum_{l=1}^{L}\sum_{i=1}^{I} o_{il}X_{il} - \sum_{i=1}^{I} h_i V_i \tag{4.7}$$

$$- \sum_{l=1}^{L}\sum_{i=1}^{I} p_{il}U_{il} - \sum_{j=1}^{J} d_j F_j$$

$$Min\ Z_2 \quad \sum_{i=1}^{I}\sum_{k=1}^{K} s_{ik}Q_{ik} \tag{4.8}$$

$$Max\ Z_3 \quad \sum_{i=1}^{I}\sum_{k=1}^{K} t_{ik}Q_{ik} \tag{4.9}$$

Subject to

$$\sum_{j=1}^{J} q_{ij}P_j = \sum_{l=1}^{L} X_{il} + \sum_{k=1}^{K} Q_{ik} \qquad \forall i \tag{4.10}$$

$$\sum_{l=1}^{L} X_{il} + V_i = T_i \qquad \forall i \tag{4.11}$$

$$T_i = \sum_{j=1}^{J} q_{ij}R_j \qquad \forall i \tag{4.12}$$

$$\sum_{j=1}^{J} a_j P_j \leq A \tag{4.13}$$

$$u_k v_k \leq \sum_{i=1}^{I} b_{ik} Q_{ik} \leq u_k B_k \qquad \forall k \tag{4.14}$$

$$e_i T_i \leq E_i \qquad \forall i \tag{4.15}$$

$$g_{il} X_{il} \leq G_{il} U_{il} \qquad \forall i, l \tag{4.16}$$

$$P_j = D_j \qquad \forall j \tag{4.17}$$

$$\sum_{l=1}^{L} X_{il} \leq O_i T_i \qquad \forall i \tag{4.18}$$

$$V_i \leq (1 - O_i) T_i \qquad \forall i \tag{4.19}$$

$$R_j = H_j P_j \qquad \forall j \tag{4.20}$$

$$\sum_{l=1}^{L} \sum_{i=1}^{I} U_{il} \leq C \tag{4.21}$$

$$R_j \leq M F_j \qquad \forall j \tag{4.22}$$

$$U_{il}, F_j, u_k \in \{0,1\} \qquad \forall i, j, k, l \tag{4.23}$$

$$P_j, R_j, Q_{ik}, T_i, X_{il}, V_i \geq 0 \qquad \forall i, j, k, l \tag{4.24}$$

The objective function (4.7) maximizes the total profit. The first part of this objective function represents profit of selling products. The second part represents the costs of parts purchasing from external suppliers. The third part represents the disassembly cost incurs from disassembly site, and consists of unit disassembly cost multiplied by the amount of parts to be disassembled. The costs of refurbishing and disposal sites are calculated in the fourth and fifth parts. In addition, the sixth and seventh parts represent the set-up costs of refurbishing and disassembly sites. It is noticeable that refurbishing sites are selected based on maximum profit. The objective function (4.8) minimizes defect rates. Furthermore, the objective function (4.9) maximizes importance of external suppliers, which is calculated from the proposed fuzzy method including weights of external suppliers multiplied by the amount of parts purchased from them.

Constraint (4.10) ensures that the numbers of manufactured parts are equal to the number of refurbished and purchased parts. Constraint (4.11) represents that the number of disassembled parts are equal to the number of reusable parts and wastes. Constraint (4.12) ensures the relationship between parts and products. Constraints (4.13)-(4.16) represent minimum purchasing quantity from suppliers, and maximum capacity of manufacturer, external suppliers, disassembly, and refurbishing sites. Constraint (4.17) shows that the number of manufactured products is equal to demand. Constraints (4.18) and (4.19) reflect the maximum percent of reusable parts and wastes. Moreover, Constraint (4.20) shows the limitation of max percent of returns. Besides, Constraint (4.21) represents the limitation of the number of refurbishing sites.

4.3.3. Solution approach

For solving the proposed multi objective model, the compromise programming method is adopted (Hwang and Yoon, 1981). The aim is to minimize a function which is a measure to how close the decision maker can get to the ideal vector. A possible measure of closeness to the ideal solution is a family of L_p-metrics. Eq. (4.25) shows the formula where Y is the number of objectives. The steps of this method are as follows:

$$L_p = [\sum_{y=1}^{Y} W_y^{p} \left| \frac{Z_y - Z_y^-}{Z_y^+ - Z_y^-} \right|^{p}]^{\frac{1}{p}} \tag{4.25}$$

1- Decision makers determine the importance of objective functions. Eq. (4.26) shows the formula for three objective functions.

$$\sum_{y=1}^{3} W_y = 1 \qquad W_y \geq 0 \quad (y = 1,2,3) \tag{4.26}$$

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

I) Utilize pairwise comparison matrices: two objective functions are compared at each time to find out which one is more important. Figure 4.4 can be utilized as a fuzzy scale.

II) Synthesization is used to calculate weight of each objective function.

III) Perform consistency test to check whether judgment of decision makers is consistent.

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

2- The new objective function is constructed which is shown in Eq. (4.27) where Z_y^+ and Z_y^- (y = 1, 2, 3) denote the upper bound and lower bound of single objective functions subject to constraints (4.10) - (4.24). Obviously, the results differ depending on the value of *p*. Generally, *p* is 1 or 2. But, other values of *p* also can be used.

$$Min\ Z \quad [W_1^p \times (\frac{Z_1^+ - Z_1}{Z_1^+ - Z_1^-})^p + W_2^p \times (\frac{Z_2 - Z_2^-}{Z_2^+ - Z_2^-})^p + W_3^p \times (\frac{Z_3^+ - Z_3}{Z_3^+ - Z_3^-})^p \ ]^{\frac{1}{p}} \qquad (4.27)$$

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

4.4. Numerical example

In this section, a numerical example is presented to show the proposed model. Suppose that a computer manufacturer assembles and sells 5 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. Furthermore, it is important that which suppliers are eligible to supply required parts. In the first phase, manager of company forms a decision making group which is composed of 3 decision makers. They evaluate potential suppliers (5) based on each purchased part. Thus, the group selects appropriate criteria that are illustrated in Figure 4.5. Then the members of group determine the importance of categories and criteria which are obtained by linguistic variables and triangular fuzzy numbers. The results are written in Tables 4.1.a & 4.1.b. In the next step, each supplier is assessed according to the criteria. Table 4.1.c shows the process of assessment for supplier 1 who sells part 1. The process is repeated for other suppliers and parts. Then, the weights of categories are multiplied by weights of criteria and aggregated weights. Therefore, final scores can be calculated. Table 4.1.d shows the results for supplier 1 and part 1. This process is repeated and scores are calculated for other alternatives. Now the weights (importance) of suppliers can be obtained by normalization. The results are illustrated in Table 4.1.e.

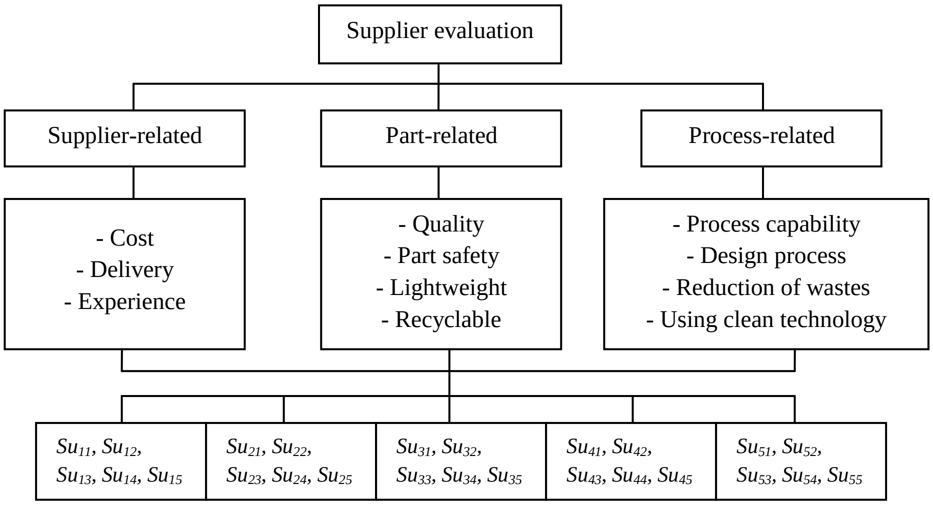


Figure 4.5. Supplier evaluation based on qualitative criteria

In the second phase, the CLSC network is examined by using multi objective MILP. The required parameters are written in Appendix A. In this research, GAMS (General Algebraic Modelling System) is utilized to solve the model. This software is designed for modeling linear, nonlinear and mixed-integer optimization problems. The decision-making group determines the importance of objective functions as $W_1 = 0.7$, $W_2 = 0.1$, and $W_3 = 0.2$. The problem is solved for $p = 1$. The results of solving multi objective functions problem are written in Tables 4.2. Table 4.2.d shows that the units of purchased parts from suppliers are different for each objective function. Aggregated objective function enables us to consider all of objective functions, simultaneously.

Table 4.1

Evaluation of suppliers based on qualitative criteria

Table 4.1.a

Importance of categories

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

Table 4.1.b

Importance of criteria

Criteria	DM$_1$	DM$_2$	DM$_3$	Weights of criteria
Cost	VH	VH	H	(8.3, 9.7, 10.0)
Delivery	MH	M	M	(3.7, 5.7, 7.7)
Experience	MH	M	MH	(4.3, 6.3, 8.3)
Quality	H	MH	VH	(7.0, 8.7, 9.7)
Part safety	VH	H	MH	(7.0, 8.7, 9.7)
Lightweight	MH	M	M	(3.7, 5.7, 7.7)
Recyclable	M	MH	MH	(4.3, 6.3, 8.3)
Process capability	M	MH	M	(3.7, 5.7, 7.7)
Design process	MH	H	VH	(7.0, 8.7, 9.7)
Reduction of wastes	H	MH	VH	(7.0, 8.7, 9.7)
Using clean technology	M	ML	MH	(3.0, 5.0, 7.0)

Table 4.1.c

Assessment supplier 1 based on part 1

	DM$_1$	DM$_2$	DM$_3$	Aggregated weights
Cost	H	MH	M	(5.0, 7.0, 8.7)
Delivery	M	MH	M	(3.7, 5.7, 7.7)
Experience	M	MH	MH	(4.3, 6.3, 8.3)
Quality	ML	L	M	(1.3, 3.0, 5.0)
Part safety	VH	MH	H	(7.0, 8.7, 9.7)
Lightweight	MH	MH	M	(4.3, 6.3, 8.3)
Recyclable	MH	M	M	(3.7, 5.7, 7.7)
Process capability	MH	MH	H	(5.6, 7.7, 9.3)
Design process	MH	M	MH	(4.3, 6.3, 8.3)
Reduction of wastes	M	MH	MH	(4.3, 6.3, 8.3)
Using clean technology	ML	MH	ML	(2.3, 4.3, 6.3)

Table 4.1.d

Final score for supplier 1 based on part 1(be_{11})

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

Table 4.1.e

t_{ik} (Weight of supplier *k* for part *i*)

i / k	1	2	3	4	5
1	0.21	0.19	0.20	0.20	0.20
2	0.18	0.21	0.20	0.20	0.21
3	0.20	0.24	0.19	0.17	0.20
4	0.21	0.20	0.20	0.21	0.18
5	0.18	0.18	0.23	0.20	0.21

Table 4.2
Results of CLSC configuration

Table 4.2.a
Product-related variables (multi objective problem)

j	**1**	**2**	**3**	**4**	**5**
P_j	1400	1500	1400	1400	1500
R_j	700	750	700	700	750

Table 4.2.b
Part-related variables (multi objective problem)

i	**1**	**2**	**3**	**4**	**5**
T_i	7200	6550	7850	8650	8000
V_i	3600	3275	3925	4325	4000

Table 4.2.c
X_{il} (Units of part *i* to be refurbished in refurbishing site *l*)

i / l	**1**	**2**	**3**	**4**	**5**
1	-	3600	-	-	-
2	-	-	-	3275	-
3	-	3925	-	-	-
4	-	4325	-	-	-
5	4000	-	-	-	-

Table 4.2.d
Q_{ik} (Units of part *i* to be purchased from external supplier *k*)

First objective (*Z₁*)			**Second objective (*Z₂*)**			**Third objective (*Z₃*)**			**Multi objective (*Z*)**		
i	*k*	Q_{ik}	*i*	*k*	Q_{ik}	*i*	*k*	Q_{ik}	*i*	*k*	Q_{ik}
1	4	10800	1	2	10800	1	1	6667	1	4	10800
2	3	9825	2	2	9825	1	5	4133	2	5	9825
3	1	5000	3	2	11775	2	5	9825	3	1	5000
3	5	6775	4	1	6667	3	2	11775	3	5	6775
4	2	12975	4	5	6308	4	4	12975	4	2	12975
5	4	12000	5	3	12000	5	3	12000	5	3	12000

4.5. Conclusions

In this chapter, we presented an integrated mathematical model for supplier selection, order allocation, and closed-loop network configuration, as a novel innovation. The network consists of manufacturer, disassembly, refurbishing, and disposal sites. In the first phase, fuzzy sets theory is used to overcome the uncertainty in assessment of eligible suppliers. Therefore, the importance of suppliers can be calculated. Then, we designed multi objective mixed-integer linear programming model to optimize the supply chain network. The model not only determines the amount of parts and products in the nodes of

CLSC network (tactical decisions), but also it selects the best suppliers and refurbishing sites (strategic decisions). GAMS is utilized to solve the proposed model. In addition, a numerical example is performed to analyze and validate the model. Computational results demonstrated the efficiency and effectiveness of the proposed model.

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

CHAPTER 5. A THREE-STAGE MODEL FOR CLOSED-LOOP SUPPLY CHAIN CONFIGURATION UNDER UNCERTAINTY

5.1. Introduction

Several investigations have been performed about closed-loop supply chain (CLSC) configuration. In the majority of them, the parameters are deterministic (such as Kim et al., 2006). However, the minority of authors considered uncertainty (such as Listes, 2007). 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. 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 an 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 chapter, 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 chapter, 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 an uncertain environment.

The chapter is arranged as follows: In Section 5.2, the problem is defined. Then, a new model is proposed in Section 5.3. Section 5.4 presents an illustrative example. Besides, discussions are presented in Section 5.5. Finally, Section 5.6 presents conclusions.

5.2. Problem definition

Figure 5.1 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 chapter, 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.

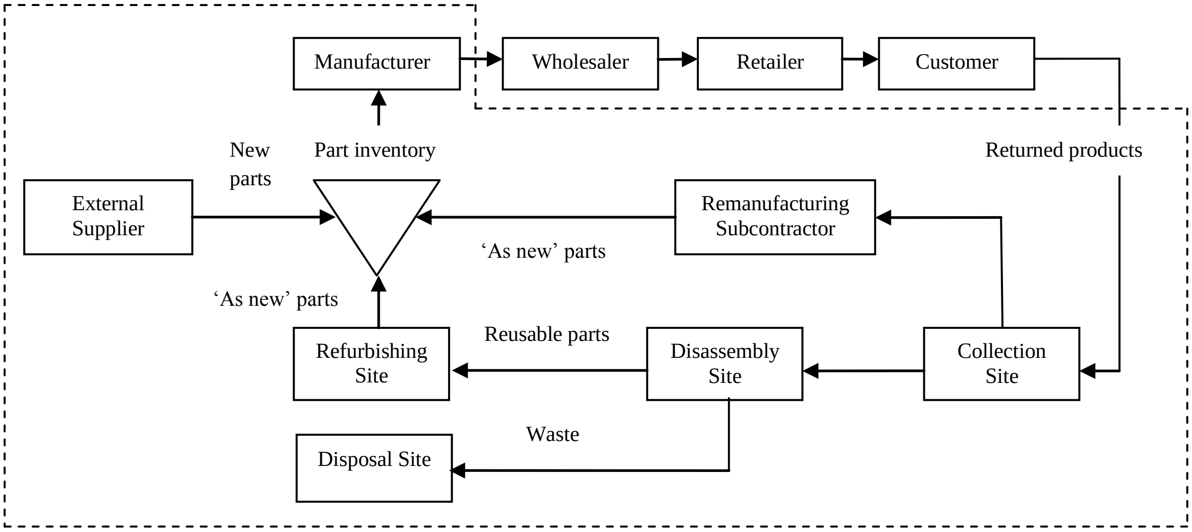


Figure 5.1. Framework for remanufacturing system – the dashed area (Kim et al., 2006)

5.3. 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 5.2 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.

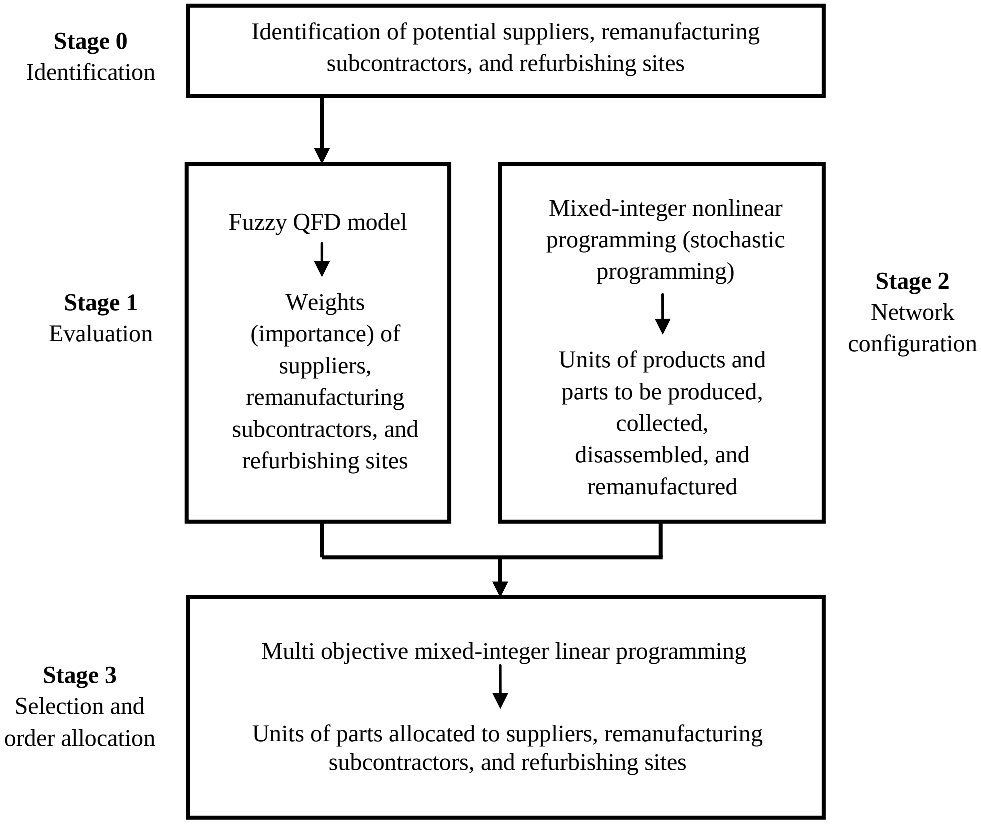
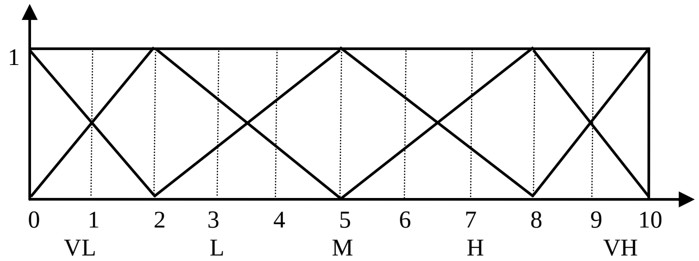


Figure 5.2. Framework of the proposed model

5.3.1. 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 5.3 displays the scale.



VL	(0, 0, 2)
L	(0, 2, 5)
M	(2, 5, 8)
H	(5, 8, 10)
VH	(8, 10, 10)

Figure 5.3. 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 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. (5.1) should be satisfied where E is the number of decision makers (e = 1, 2,..., E).

$$\sum_{e=1}^{E} r_e = 1 \tag{5.1}$$

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. (5.2) where P is the number of CRs (p = 1, 2,..., P).

$$w_p = (r_1 \otimes w_{p1}) \oplus ... \oplus (r_E \otimes w_{pE}) \tag{5.2}$$

Step 5: Determine the relationship between CRs and DRs. Each decision maker is asked to express opinion using the linguistic variables 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. (5.3) 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).

$$a_{ph} = (r_1 \otimes a_{ph1}) \oplus ... \oplus (r_E \otimes a_{phE}) \tag{5.3}$$

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. (5.4). These variables also are triangular fuzzy numbers.

$$f_h = \frac{1}{P} \otimes [(w_1 \otimes a_{1h}) \oplus ... \oplus (w_P \otimes a_{Ph})] \tag{5.4}$$

Step 8: Calculate aggregated weights between DRs and PRs. Aggregated weight (b_{hu}) is calculated by Eq. (5.5) 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).

$$b_{hu} = (r_1 \otimes b_{hu1}) \oplus ... \oplus (r_E \otimes b_{huE}) \tag{5.5}$$

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. (5.6).

$$g_u = \frac{1}{H} \otimes [(f_1 \otimes b_{1u}) \oplus ... \oplus (f_H \otimes b_{Hu})] \tag{5.6}$$

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. (5.7) where K is the number of alternatives (*k = 1, 2, ...,* K).

$$AR_{ku} = (r_1 \otimes ar_{ku1}) \oplus ... \oplus (r_E \otimes ar_{kuE}) \tag{5.7}$$

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. (5.8) illustrates the formula.

$$FI_k = \frac{1}{U} \otimes [(AR_{k1} \otimes g_1) \oplus \ldots \oplus (AR_{kU} \otimes g_U)] \tag{5.8}$$

Step 12: Defuzzifiy the numbers and rank the alternatives. A deffuzzified number of $FI_k = (a, b, c)$ is calculated by Eq. (5.9). Now, the alternatives can be ranked. Besides, the numbers are normalized. The normalized numbers can be interpreted as the weights (importance) of alternatives.

$$DI_k = \frac{a + 2b + c}{4} \tag{5.9}$$

5.3.2. 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 Table 5.1.

Objective function

Expected profit: The objective function (5.10) 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.

Table 5.1
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*

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

$$-\sum_{j=1}^{J}C_{j}^{m}\sum_{n=1}^{N}P_{jn}^{m}-\sum_{i=1}^{I}C_{i}^{p}Q_{i}^{p}-\sum_{j=1}^{J}C_{j}^{r}P_{j}^{r}-\sum_{i=1}^{I}C_{i}^{re}Q_{i}^{re}-\sum_{i=1}^{I}C_{i}^{d}Q_{i}^{d} \qquad (5.10)$$

$$-\sum_{j=1}^{J}C_{j}^{sub}P_{j}^{sub}-\sum_{j=1}^{J}C_{j}^{coll}P_{j}^{coll}-\sum_{j=1}^{J}CS_{j}^{r}U_{j}^{r}-\sum_{i=1}^{I}CS_{i}^{re}U_{i}^{re}$$

Constraints

The constraints of the problem are formulated as follows:

Network constraints: Constraint (5.11) ensures that the numbers of manufactured parts are equal to the number of refurbished and purchased and remanufactured parts. Constraint (5.12) represents that the number of disassembled parts are equal to the number of refurbished parts and wastes. Constraint (5.13) shows that collected products are sent to the remanufacturing subcontractor and disassembly site. Constraint (5.14) reflects the maximum percent of return. Moreover, Constraint (5.15) shows the limitation of max percent of reusable parts.

$$\sum_{j=1}^{J}q_{ij}\sum_{n=1}^{N}P_{jn}^{m}=Q_{i}^{re}+Q_{i}^{p}+Q_{i}^{sub} \qquad \forall i \qquad (5.11)$$

$$Q_{i}^{re}+Q_{i}^{d}=Q_{i}^{r} \qquad \forall i \qquad (5.12)$$

$$P_{j}^{sub}+P_{j}^{r}=P_{j}^{coll} \qquad \forall j \qquad (5.13)$$

$$P_{j}^{coll}\le Z\sum_{n=1}^{N}P_{jn}^{m} \qquad \forall j \qquad (5.14)$$

$$Q_{i}^{re}\le E\ Q_{i}^{r} \qquad \forall i \qquad (5.15)$$

Product and part constraints: Constraints (5.16) and (5.17) ensure the relationship between parts and products in disassembly and remanufacturing sites.

$$Q_{i}^{r}=\sum_{j=1}^{J}q_{ij}P_{j}^{r} \qquad \forall i \qquad (5.16)$$

$$Q_i^{sub} = \sum_{j=1}^{J} q_{ij} P_j^{sub} \qquad \forall i \qquad (5.17)$$

Capacity constraints: Constraints (5.18) and (5.19) represent maximum capacity of manufacturer and disassembly sites.

$$\sum_{j=1}^{J} a_j \sum_{n=1}^{N} P_{jn}^{m} \leq W^{m} \qquad (5.18)$$

$$e_J^r P_j^r \leq W_j^r \qquad \forall j \qquad (5.19)$$

Set-up constraints: Constraints (5.20) and (5.21) are set-up constraints for set-up at the disassembly and refurbishing sites.

$$P_j^r \leq B\, U_j^r \qquad \forall j \qquad (5.20)$$

$$Q_i^{re} \leq B\, U_i^{re} \qquad \forall i \qquad (5.21)$$

Binary and non-negativity constraints:

$$U_j^r, U_i^{re} \in \{0,1\} \qquad \forall i, j \qquad (5.22)$$

$$P_{jn}^m, P_j^r, P_j^{coll}, P_j^{sub}, Q_i^P, Q_i^{sub}, Q_i^r, Q_i^{re}, Q_i^d \geq 0 \qquad \forall i, j, n \qquad (5.23)$$

5.3.3. 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.

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 (5.24) 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.

$$Min\ z_1 \quad \sum_{i=1}^{I}\sum_{k=1}^{K} C_{ik}^{P} Q_{ik}^{P} + \sum_{l=1}^{L}\sum_{i=1}^{I} C_{il}^{re} Q_{il}^{re} + \sum_{m=1}^{M}\sum_{j=1}^{J} C_{jm}^{sub} P_{jm}^{sub} + \sum_{k=1}^{K} g_k s_k + \sum_{m=1}^{M} y_m t_m + \sum_{l=1}^{L} h_l w_l \tag{5.24}$$

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

$$Max\ z_2 \quad \sum_{i=1}^{I}\sum_{k=1}^{K} WE_{ik}^{P} Q_{ik}^{P} + \sum_{l=1}^{L}\sum_{i=1}^{I} WE_{il}^{re} Q_{il}^{re} + \sum_{m=1}^{M}\sum_{j=1}^{J} WE_{jm}^{sub} P_{jm}^{sub} \tag{5.25}$$

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.

$$Min\ z_3 \quad \sum_{i=1}^{I}\sum_{k=1}^{K} DE_{ik}^{P} Q_{ik}^{P} + \sum_{l=1}^{L}\sum_{i=1}^{I} DE_{il}^{re} Q_{il}^{re} \tag{5.26}$$

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.

$$Max\ z_4 \quad \sum_{i=1}^{I}\sum_{k=1}^{K} OE_{ik}^{P} Q_{ik}^{P} + \sum_{l=1}^{L}\sum_{i=1}^{I} OE_{il}^{re} Q_{il}^{re} \tag{5.27}$$

Constraints

The constraints of the problem are formulated as follows:

$$\sum_{i=1}^{I} b_{ik}^{P} Q_{ik}^{p} \leq W_{k}^{s} s_{k} \qquad \forall k \tag{5.28}$$

$$\sum_{j=1}^{J} b_{jm}^{sub} P_{jm}^{sub} \leq W_{m}^{sub} t_{m} \qquad \forall m \tag{5.29}$$

$$\sum_{i=1}^{I} e_{il}^{re} O_{il}^{re} \leq W_{l}^{re} \ w_{l} \qquad \forall l \tag{5.30}$$

$$\sum_{k=1}^{K} Q_{ik}^{p} = Q_{i}^{p} \qquad \forall i \tag{5.31}$$

$$\sum_{l=1}^{L} Q_{il}^{re} = Q_{i}^{re} \qquad \forall i \tag{5.32}$$

$$\sum_{m=1}^{M} P_{jm}^{sub} = P_{j}^{sub} \qquad \forall j \tag{5.33}$$

$$\sum_{k=1}^{K} s_{k} \leq G \tag{5.34}$$

$$\sum_{m=1}^{M} t_{m} \leq T \tag{5.35}$$

$$\sum_{l=1}^{L} w_{l} \leq F \tag{5.36}$$

$$s_{k}, t_{m}, w_{l} \in \{0,1\} \qquad \forall k, m, l \tag{5.37}$$

$$Q_{ik}^{P}, Q_{il}^{re}, P_{jm}^{sub} \geq 0 \qquad \forall i, j, k, l, m \tag{5.38}$$

Constraints (5.28)-(5.30) represent the capacity of suppliers, remanufacturing subcontractors, and refurbishing sites, respectively. Constraints (5.31)-(5.33) show the total numbers of purchased and refurbished parts, and remanufactured products. Constraints (5.34)-(5.36) represent that the number of suppliers, remanufacturing subcontractors, and refurbishing sites must be less than or equal to the certain numbers.

Solution methodology

Multi objective problems can be solved using different methods. In this chapter, weighted sums method and compromise method are applied.

Weighted sums method

The most popular but not really appropriate method for solving multi objective problems is the weighted sums method. The Eq. (5.39) 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 minimization. Our problem is transformed to a single objective which is shown by Eq. (5.40).

$$Min \ \{\sum_{c=1}^{D} \lambda_c z_c(x) : x \in X\} \tag{5.39}$$

$$Min \quad \lambda_1 z_1 - \lambda_2 z_2 + \lambda_3 z_3 - \lambda_4 z_4 \tag{5.40}$$

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. (5.41) where $z_c^* = min\ (z_c)$. It should be noted that all objective functions are minimization. Any point that minimizes L_V for $1 \leq V \leq \infty$ and $0 \leq \lambda_c \leq 1$ and $\sum_c \lambda_c = 1$ is called a compromise solution (Wadhwa & Ravindran, 2007). Therefore, the objective function of the problem can be written in the form of Eq. (5.42).

$$L_V = \left[\sum_{c=1}^{D} \lambda_c^{\ V} [\frac{z_c - z_c^*}{z_c^*}]^V \right]^{\frac{1}{V}} \quad \forall V = 1,2,...,\infty \tag{5.41}$$

$$Min \quad [\lambda_1^{\ V} (\frac{z_1 - z_1^*}{z_1^*})^V - \lambda_2^{\ V} (\frac{z_2 - z_2^*}{z_2^*})^V + \lambda_3^{\ V} (\frac{z_3 - z_3^*}{z_3^*})^V - \lambda_4^{\ V} (\frac{z_4 - z_4^*}{z_4^*})^V]^{\frac{1}{V}} \quad \forall V = 1,2,...,\infty \tag{5.42}$$

5.4. 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 in Appendix B. The General Algebraic Modeling System (GAMS) is utilized to solve the model. GAMS is a high-level modeling software for mathematical programming and optimization. It has been run by default in this research.

5.4.1. Stage 1

In the first stage, the suppliers, remanufacturing subcontractors, and refurbishing sites are evaluated by the proposed fuzzy QFD method. Figure 5.4 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 5.2. 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 5.3. 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 5.4.

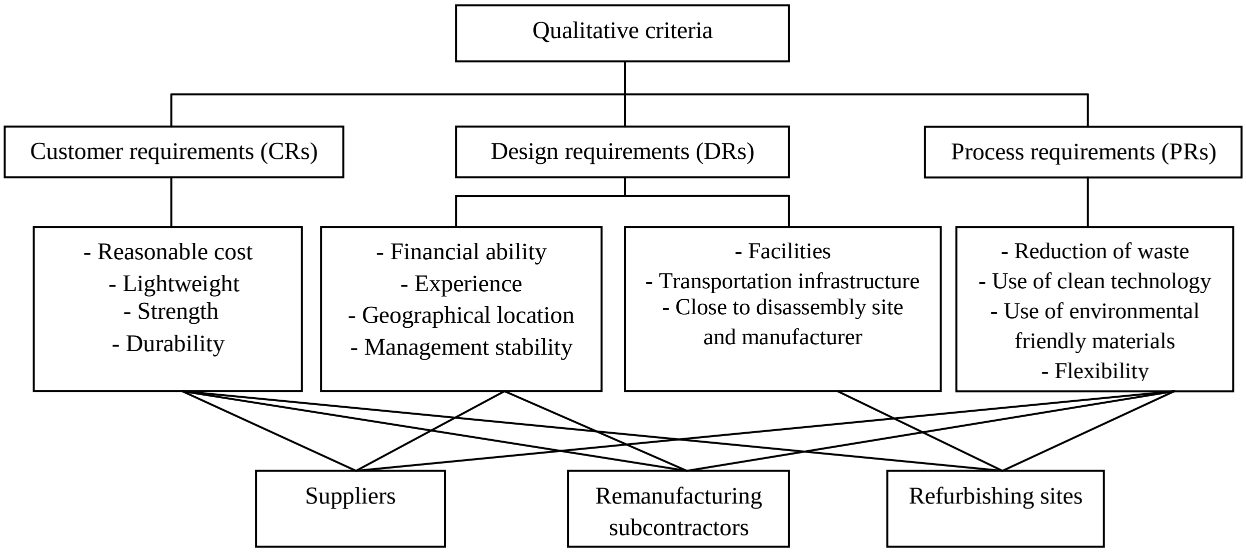


Figure 5.4. Qualitative criteria

Table 5.2

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 5.3

Aggregated weights

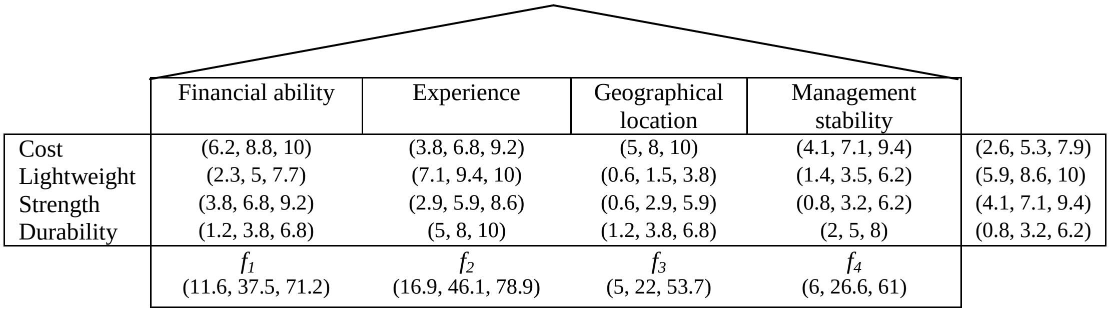
	DM_1	**DM_2**	**DM_3**	
	0.4	0.3	0.3	Aggregated weights
Reasonable cost	(5, 8, 10)	(0, 2, 5)	(2, 5, 8)	(2.6, 5.3, 7.9)
Lightweight	(5, 8, 10)	(8, 10, 10)	(5, 8, 10)	(5.9, 8.6, 10)
Strength	(5, 8, 10)	(2, 5, 8)	(5, 8, 10)	(4.1, 7.1, 9.4)
Durability	(2, 5, 8)	(0, 2, 5)	(0, 2, 5)	(0.8, 3.2, 6.2)

Table 5.4

Impact of customer requirements (CRs) on design requirements (DRs)

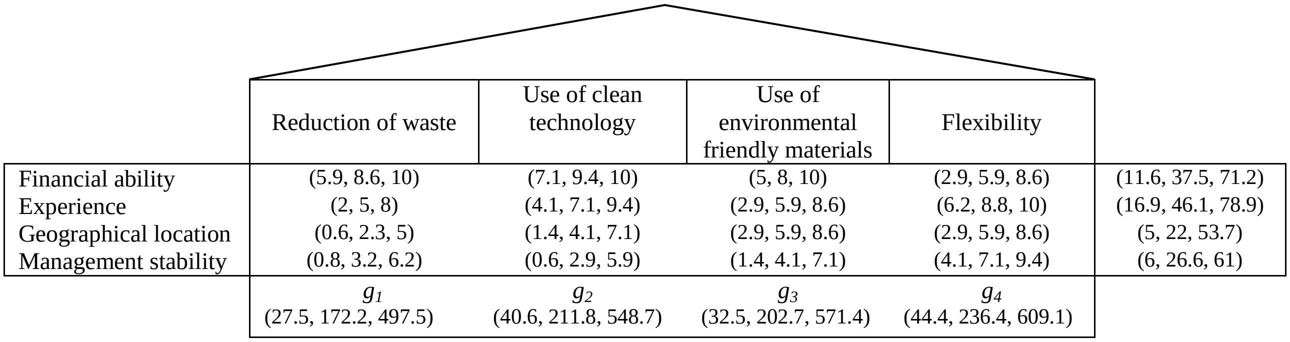
DRs	Financial ability			Experience			Geographical location			Management stability		
CRs	**DM_1**	**DM_2**	**DM_3**	**DM_1**	**DM_2**	**DM_3**	**DM_1**	**DM_2**	**DM_3**	**DM_1**	**DM_2**	**DM_3**
Reasonable cost	VH	H	H	M	H	H	H	H	H	H	M	H
Lightweight	M	H	L	VH	VH	H	VL	VL	M	M	VL	M
Strength	M	H	H	M	M	H	L	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 5.5 illustrates the first matrix. According to the model, the second matrix also is completed that is displayed in Figure 5.6. Moreover, the impact of each alternative on the PRs is considered in Table 5.5. Then, alternative ranking and *FI* are calculated. The final results are written in Table 5.6. 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 (11.6, 37.5, 71.2)	f_2 (16.9, 46.1, 78.9)	f_3 (5, 22, 53.7)	f_4 (6, 26.6, 61)	

Figure 5.5. 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 (27.5, 172.2, 497.5)	g_2 (40.6, 211.8, 548.7)	g_3 (32.5, 202.7, 571.4)	g_4 (44.4, 236.4, 609.1)	

Figure 5.6. The second matrix of QFD

Table 5.5
The impact of alternatives on process requirements (PRs)

PRs	Reduction of waste			Use of clean technology			Use of environmental friendly materials			Flexibility		
Alternatives	**DM₁**	**DM₂**	**DM₃**	**DM₁**	**DM₂**	**DM₃**	**DM₁**	**DM₂**	**DM₃**	**DM₁**	**DM₂**	**DM₃**
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 5.6
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

5.4.2. Stage 2

In the second stage, the closed-loop supply chain is configured. 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 5.7. 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 5.7 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 5.7 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 5.7 shows how many parts should be purchased from external supplier.

Table 5.7
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

5.4.3. Stage 3

The mathematical programming model is solved by some techniques including single objectives, equal weights, and compromise method. 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 5.8. 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 5.8
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 5.9. Each of the cases represents a unique situation. Table

5.9 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 5.9
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

5.5. Managerial insights and discussions

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

5.5.1. 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 5.10. 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 5.10
Comparison between the first stage and HOQ

	HOQ			The proposed model		
	Score	Normalization	Rank	Score	Normalization	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

5.5.2. 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 5.7 shows the sensitivity analysis for the demand of customer 1. It is observable that expected profit decreases by 5 percent as the uncertainty of demand (standard deviation) increases from 0 to 150.

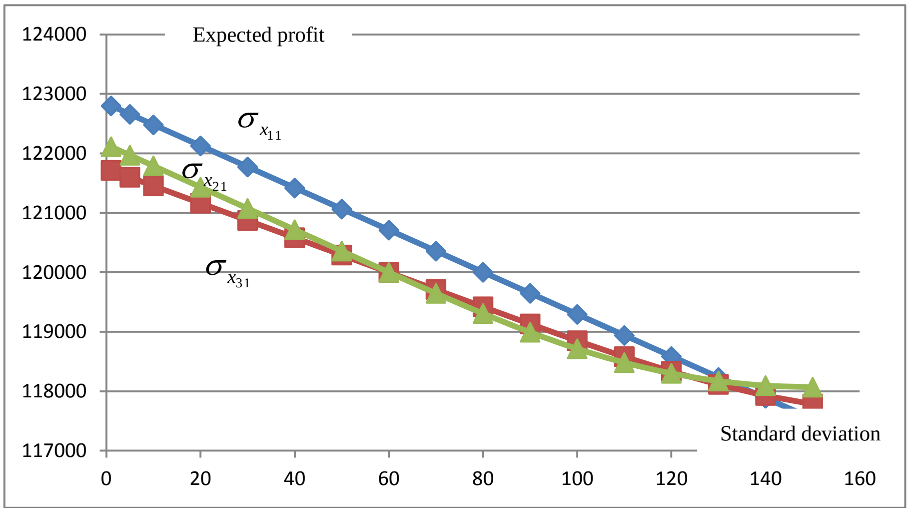


Figure 5.7. Expected profit as a function of standard deviations

5.5.3. Comparison of single and multiple sourcing policies

In single sourcing policy, the parts are purchased from one supplier. Figure 5.8 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.

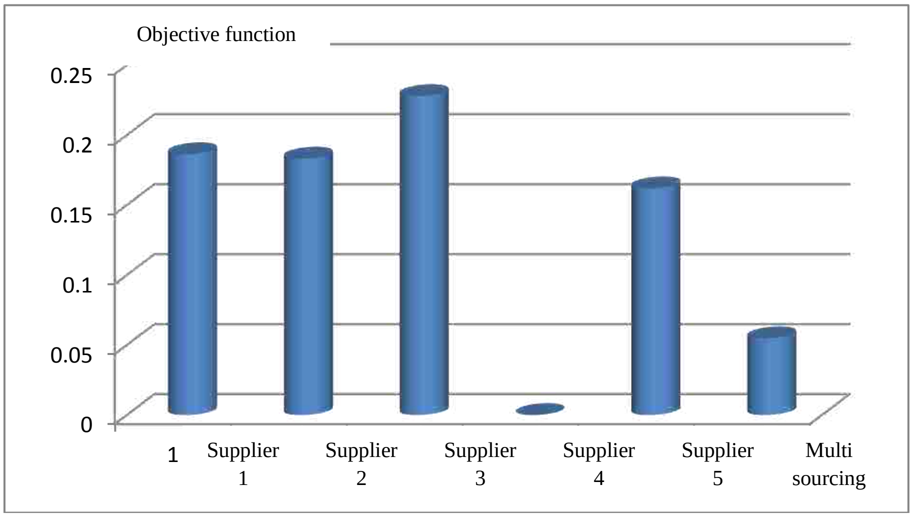


Figure 5.8. Value of objective function of single and multiple sourcing policies (compromise method)

5.5.4. 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 5.9. 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.

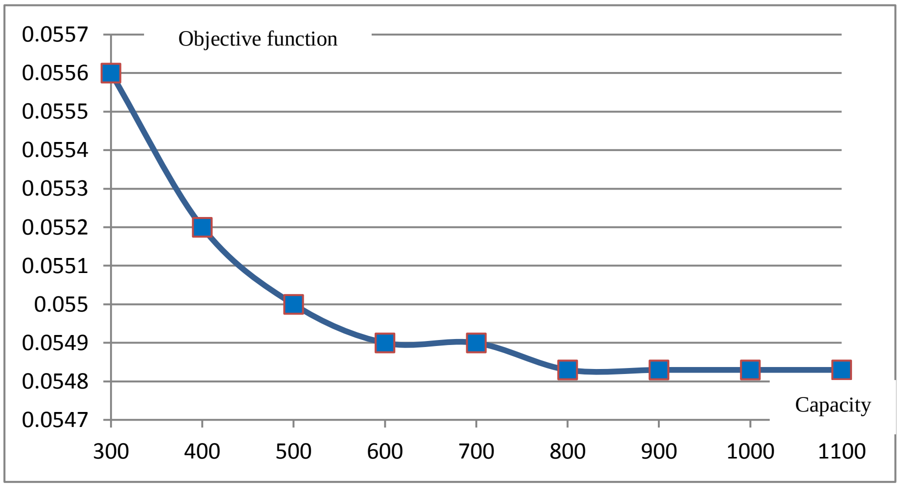


Figure 5.9. Sensitivity analysis for capacity of remanufacturing subcontractors

5.6. Conclusions

In this chapter, 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. To this aim, fuzzy sets theory and stochastic programming technique are utilized. 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.

CHAPTER 6. A PROPOSED MATHEMATICAL MODEL FOR CLOSED-LOOP NETWORK CONFIGURATION BASED ON PRODUCT LIFE CYCLE

6.1. Introduction

Nowadays, the majority of companies try to reuse and remanufacture products because of economic incentives and a growing environmental concern (Francas and Minner, 2009). There are three main requirements for sustainable development: resource conservation, environmental protection, and social development. Reverse logistics is an important concept that emphasizes on decreasing and reusing disposal (Petek and Glavic, 1996).

Recovery options for returned products consist of reuse, resale, repair, refurbishing, remanufacturing, cannibalization, and recycling (Thierry et al., 1995). In the remanufacturing process, used products are disassembled in disassembly sites. Usable parts are cleaned, refurbished, and they are transmitted into part inventory. Then the new products are manufactured from the old and new parts (Kim et al., 2006; Melo et al., 2009).

In reality, three main return-recovery pairs exist. Commercial returns are repaired. End of use returns often are remanufactured. In addition, end of life returns are recycled (Tibben-Lembke, 2004; Guide and Van Wassenhove, 2009). However, to the best of our knowledge no quantitative model is proposed based on three return-recovery pairs. It is noticeable that not only the quantity of manufactured products depends on the market demand, but also it is related to commercial returns because they can be used as new products after light repairs. Another challenge appears when some external suppliers and recycling sites exist. In this condition, the manufacturer prefers to minimize the costs. Although the majority of remanufactured products can compete with newly manufacturing products, markets tend to be separated for new and remanufactured products (Atasu et al., 2008). In other words, the new products may be sold in the same market, and the remanufacturing products may be sent to the secondary market.

In this chapter, we propose a general network based on product life cycle and return-recovery pairs. The closed-loop supply chain network consists of manufacturer, collection, repair, disassembly, recycling, and disposal sites. Demand can be either satisfied by commercial returns (after light repair) or new products. The manufacturer uses recycled parts, end of use returns and new parts to produce new products. New parts are purchased from external suppliers. To our knowledge, no investigation has examined a general network for return-recovery pairs including commercial, end of life, and end of use returns. We propose a mixed-integer linear programming model to maximize the profit and determine the number of products and parts in each part of the network. The model is designed for multi products, parts, suppliers, and recycling sites. Not only manufacturing, purchasing, collecting, disposing, disassembly, and repairing costs are taken into account, but also set up costs of disassembly, and repair sites are considered. Besides, the model determines the number of recycling sites. We also extend the model for a secondary market. In this condition, demands of same and secondary markets should be satisfied separately. The MILP models are solved, and they are validated through computational testing and sensitivity analysis.

The remainder of the chapter is organized as follows. In Section 6.2, the problem is defined. Section 6.3 is devoted to the proposed mathematical model. In Section 6.4, we present computational testing to validate the model. In Section 6.5, a sensitivity analysis is examined. Section 6.6 consists of the extended model. Finally, in Section 6.7 we present conclusions.

6.2. Problem definition

Supply chain networks are divided to open and closed loop networks. The degree of complexity in closed loop networks usually is higher than open ones. There are several types of closed loop supply chain networks. Unlike the previous investigations that suppose one or two returns, the proposed network is designed based on product life cycle and three types of returns (as a novel innovation). In this study, the reverse logistics consists of a manufacturer, collection, repair, disassembly, recycling, and disposal sites. Figure 6.1 shows the proposed network. The purchasing decision is a challenge for manufacturer because he must take into account the amount of end of use and end of life returns. Besides, some of the returned parts are not usable and should be disposed. The number of commercial returns is another challenge for manufacturer. The commercial returns can supply a portion of market demand. The objective of the proposed model is to maximize the profit by simultaneously determining quantity of products and parts in each part of the network. After using the products by customers, some of them are returned. The returned products are taken to the collection site. Then, they are separated to commercial returns, end of use returns, and end of life returns. Commercial returns are repaired in the repair site. These products can be used as new ones. On the other hand, end of use and end of life returns are disassembles. In this stage, the wastes are separated. End of life returns are recycled in recycling sites. The parts are added to part inventory as new parts. It is noticeable that capacities of manufacturer, repair, disassembly, and recycling sites are limited. According to the number of returned parts, the manufacturer purchases new parts from external suppliers. There are several suppliers who can supply required parts. The capacities of suppliers are known. Besides, it is supposed that suppliers reserve certain key resources for the manufacturer. A cell phone industry is a good example of this general network.

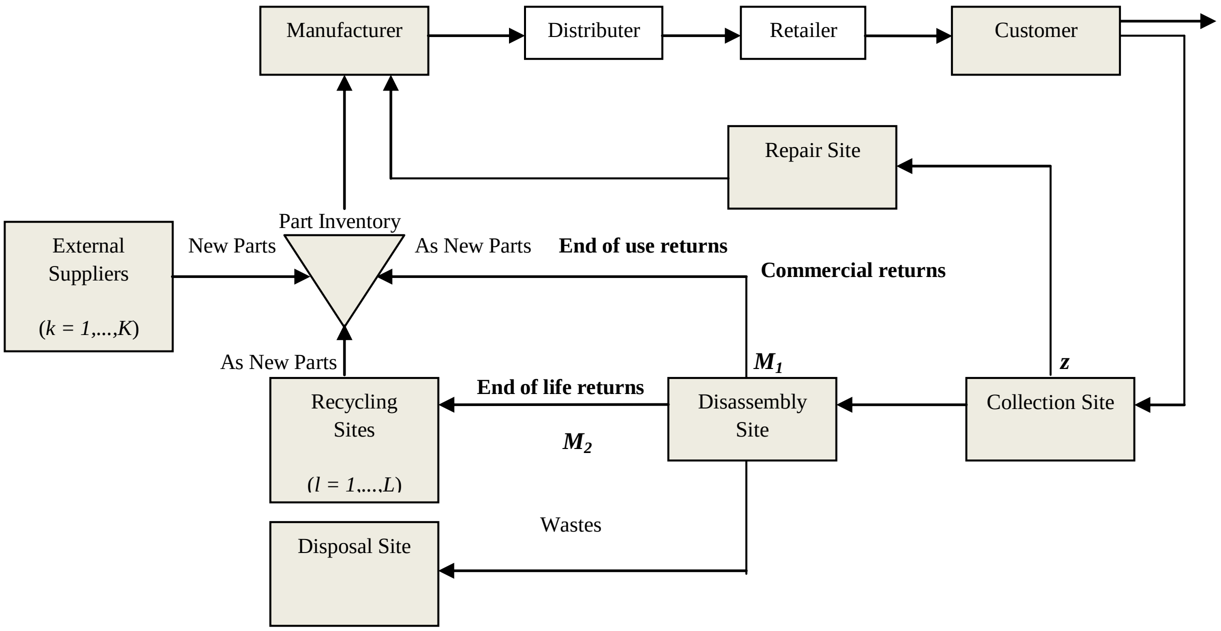


Figure 6.1. A closed loop supply chain network based on product life cycle (highlighted area)

6.3. Proposed mathematical model

The closed loop supply chain network can be formulated as a mathematical model. Indices, decision variables, and parameters of the proposed mathematical model are written in Table 6.1. The following assumptions are made in the designing the model:

- If the quantity of end of life and end of use returns is not enough for requirement of manufacturer, manufacturer should buy parts from suppliers.
- The demands of products are known.
- Maximum capacity of manufacturer, disassembly, repair, and recycling sites are known.
- The capacity of collection site is unlimited.
- The sum of disassembly and recycling costs of parts is less than purchasing cost of new ones.
- The proposed model is a single period one. Therefore, the beginning inventory is zero.

Table 6.1
Indices, decision variables, and parameters of the proposed mathematical model

Indices		**Parameters**	
i	Set of parts, $i=1,\dots,I$	S_j	Unit selling price for the product *j*
j	Set of products, $j=1,\dots,J$	a_j	Resource usage to produce one unit of product *j*
k	Set of suppliers, $k=1,\dots,K$	H_j	Unit inventory holding cost for collecting product *j*
l	Set of recycling sites, $l=1,\dots,L$	y_j	Unit direct manufacturing cost of product *j*
Decision variables		e_j	Resource usage to repair one unit of product *j*
X_j	Units of product *j* to be repaired	C_j	Max capacity of repair site for product *j*
P_j	Units of product *j* to be produced	D_j	Demand for product *j*
Y_j	Units of product *j* in collection site	c_j	Unit collection cost of product *j*
Z_j	Units of returned product *j* to be disassembled	d_j	Unit repair cost of product *j*
Q_{ik}	Units of part *i* to be purchased from external supplier *k*	f_j	Set-up cost of disassembly site for product *j*
E_i	Units of part *i* that are obtained in disassembly site	g_j	Set-up cost of repair site for product *j*
F_{il}	Units of part *i* to be recycled in recycling site *l*	B_i	Max capacity of disassembly site to dissemble part *i*
G_i	Units of part *i* to be disposed	h_i	Unit disassembly cost for part *i*
R_i	Units of end of use return of part *i*	m_i	Unit disposing cost for part *i*
U_{il}	Binary variable for set-up of recycling site *l* for part *i*	r_i	Resource usage to disassemble one unit of part *i*
V_j	Binary variable for set-up of disassembly site	n_{il}	Unit recycling cost for part *i* in recycling site *l*
W_j	Binary variable for set-up of repair site	o_{il}	Set-up cost of recycling site *l* for part *i*

Parameters		s_{il}	Resource usage to recycle one unit of part *i* in recycling site *l*
M_1	Max percent of end of use returns	O_{il}	Max capacity of recycling site *l* to recycle part *i*
M_2	Max percent of end of life returns	q_{ij}	Unit requirements for part *i* to produce one unit of product *j*
N	Max percent of total returns	p_{ik}	The cost of purchasing part *i* from external supplier *k*
z	Max percent of commercial returns	b_{ik}	Internal resource usage of supplier *k* to produce one unit of part *i*
A	Max capacity of the manufacturer plant	T_k	Max capacity reserved of external supplier *k*
t	Max number of recycling sites	M	A big number

$$Max\ z \quad \sum_{j=1}^{J} S_j(X_j + P_j) - \sum_{i=1}^{I}\sum_{k=1}^{K} p_{ik}Q_{ik} - \sum_{i=1}^{I} h_i E_i - \sum_{l=1}^{L}\sum_{i=1}^{I} n_{il}F_{il} - \sum_{i=1}^{I} m_i G_i \qquad (6.1)$$

$$-\sum_{j=1}^{J} y_j P_j - \sum_{j=1}^{J}(c_j + H_j)Y_j - \sum_{j=1}^{J} d_j X_j - \sum_{l=1}^{L}\sum_{i=1}^{I} o_{il}U_{il} - \sum_{j=1}^{J} f_j V_j - \sum_{j=1}^{J} g_j W_j$$

Subject to

$$\sum_{j=1}^{J} q_{ij}P_j = \sum_{l=1}^{L} F_{il} + \sum_{k=1}^{K} Q_{ik} + R_i \qquad \forall i \qquad (6.2)$$

$$R_i + \sum_{l=1}^{L} F_{il} + G_i = E_i \qquad \forall i \qquad (6.3)$$

$$E_i = \sum_{j=1}^{J} q_{ij} Z_j \qquad \forall i \qquad (6.4)$$

$$X_j + Z_j = Y_j \qquad \forall j \qquad (6.5)$$

$$\sum_{j=1}^{J} a_j P_j \le A \qquad (6.6)$$

$$\sum_{i=1}^{I} b_{ik}Q_{ik} \le T_k \qquad \forall k \qquad (6.7)$$

$$r_i\, E_i \le B_i \qquad \forall i \qquad (6.8)$$

$$s_{il}F_{il} \le O_{il}\, U_{il} \qquad \forall i, l \qquad (6.9)$$

$$e_j X_j \le C_j \qquad \forall j \qquad (6.10)$$

$$P_j + X_j = D_j \qquad \forall j \tag{6.11}$$

$$X_j \le z\, Y_j \qquad \forall j \tag{6.12}$$

$$Z_j \le (1-z)\, Y_j \qquad \forall j \tag{6.13}$$

$$R_i \le M_1\, E_i \qquad \forall i \tag{6.14}$$

$$\sum_{l=1}^{L} F_{il} \le M_2\, E_i \qquad \forall i \tag{6.15}$$

$$G_i \le (1 - M_1 - M_2)\, E_i \qquad \forall i \tag{6.16}$$

$$Y_j \le N(X_j + P_j) \qquad \forall j \tag{6.17}$$

$$\sum_{l=1}^{L} \sum_{i=1}^{I} U_{il} \le t \tag{6.18}$$

$$Z_j \le M\, V_j \qquad \forall j \tag{6.19}$$

$$X_j \le M\, W_j \qquad \forall j \tag{6.20}$$

$$U_{il}, V_j, W_j \in \{0,1\} \qquad \forall i, j, l \tag{6.21}$$

$$P_j, Z_j, Q_{ik}, E_i, F_{il}, G_i, R_i, Y_j, X_j \ge 0 \qquad \forall i, j, k, l \tag{6.22}$$

The objective function (6.1) maximizes the total profit. The first term of the objective function represents the selling profits of new and repaired products. The second part represents total cost of purchasing parts from external suppliers. Total cost of disassembly site is calculated by the third part, consists of unit disassembly cost multiplied by the amount of disassembled parts. Besides, the forth part represents total recycling costs. The fifth part represents total disposing costs. The sixth part represents total cost of manufacturer happens from the internal production cost, consists of unit manufacturing cost multiplied by the amount of finished product produced by him. Total cost of operation and holding costs of collection site is calculated in the seventh part. The eights part represents total cost of repair site. In addition, the ninth and tenth and eleventh parts include set up costs for recycling, disassembly, and repair sites respectively.

Constraints (6.2) ensure that the number of manufactured parts is equal to the number of recycled parts and the number of purchased parts from external suppliers, and the number of end of use parts. Constraints (6.3) show that the number of disassembly parts is equal to the summation of end of use and recycled and disposed parts. Constraints (6.4) ensure the relationship between parts and products in disassembly site. Besides, the constraints (6.5) represent that collected products are sent to repair or disassembly sites. Constraints (6.6)-(6.10) represent maximum capacity of manufacturer, external suppliers, disassembly, and recycling and repair sites. Constraints (6.11) show that the demand should be satisfied by manufactured products and repaired returns. Constraints (6.12) and (6.13) reflect the maximum percent of commercial returns. Furthermore, Constraints (6.14)-(6.16) show the limitation of end of use and end of life returns. The maximum percent of total returned products is considered in constraints (6.17). In addition, Constraint (6.18) represents the limitation of the number of recycling sites. Constraints (6.19) and (6.20) are related to the units of returned products to be disassembled and repaired. Finally, decision variables are defined in constraints (6.21) and (6.22).

6.4. Computational testing

In this section, a numerical example is presented. Suppose that a computer manufacturer assembles and sells 5 models of computer. Each product is produced by 5 parts. The manufacturer is interested to know how many should be manufactured according to demand. In addition, it is important to know how many should be purchased from each supplier. The required parameters are written in Appendix C. In this research, GAMS (Generalised Algebraic Modeling System) is used to obtain optimal solutions. The GAMS is specifically designed for modeling linear, nonlinear and mixed-integer optimization problems. The system is especially useful for large and complex problems.

The results are written in Table 6.2. According to the results of MILP, the manufacturer should produce 1050 units of product 1. These products are sent to the customers. Then, 700 units are returned. 350 units of them go to repair site, and they are used to satisfy demand. Another 350 units are disassembled. Part related variables also are illustrated in

Table 6.2. For example, 3600 units of part 1 are divided to 1199 units of end of use parts, 1202 units of wastes, and 1199 units of end of life parts. The shortage of required parts is purchased from external suppliers. For instance, the manufacturer buys part 1 from supplier 4 because he has suggested the least purchasing cost ($6). The units of recycled parts also are written in Table 6.2. The part 1 is recycled in recycling site 2 because cost of recycling in this site ($2) is less than the others.

Table 6.2
The computational results

Product-related variables					
j	**1**	**2**	**3**	**4**	**5**
X_j	350	375	350	350	375
P_j	1050	1125	1050	1050	1125
Y_j	700	750	700	700	750
Z_j	350	375	350	350	375
Part-related variables					
i	**1**	**2**	**3**	**4**	**5**
E_i	3600	3275	3925	4325	4000
G_i	1202	1095	1311	1445	1336
R_i	1199	1090	1307	1440	1332
Q_{ik} (Units of part *i* to be purchased from external supplier *k*)					
i / k	**1**	**2**	**3**	**4**	**5**
1	-	-	-	3607	-
2	-	-	-	-	3281
3	3932	-	-	-	-
4	-	4333	-	-	-
5	-	-	4008	-	-
F_{il} (Units of part *i* to be recycled in recycling site *l*)					
i / l	**1**	**2**	**3**	**4**	**5**
1	-	1199	-	-	-
2	-	-	-	1090	-
3	-	1307	-	-	-
4	-	1440	-	-	-
5	1332	-	-	-	-

6.5. Sensitivity analysis

In order to validate the proposed model, sensitivity analysis is performed. We observed the changes of objective function by varying the capacity of disassembly site for part 1, while the other factors are fixed. Figure 6.2 shows the result. This analysis illustrates that the maximum objective function can be obtained with a certain capacity of disassembly site (in this example, 4000). Therefore, in reality the capacity of disassembly site should be expanded to a specific level. Therefore, the costs of investment will decrease. On the other hand, the effects of change in max percent of total returns (N) are illustrated in Figure 6.3. It is undeniable that by increasing the amount of returns, the profit will increase. However, it is noticeable that the value of objective function for $N > 0.67$ is fixed. In this situation, the major portion of demand is satisfied by commercial returns. Besides, the rest of demand can be supplied by the parts that are obtained by the end of use and end of life returns. As a result, the manufacturer does not purchase new parts from external suppliers, and there is no any purchasing cost. Figure 6.4 shows the effects of max percent of commercial returns on the objective function. It is obvious that by increasing z, the value of objective function increases because the commercial returns only need some light repairs. In other words, the costs of light repairs are less than the costs of disassembly, recycling, and manufacturing new products. Therefore, the manufacturer prefers to have commercial returns as much as possible. Similar effects have been observed in Figure 6.5 for M_1 (max percent of end of use returns), and M_2 (max percent of end of life returns).

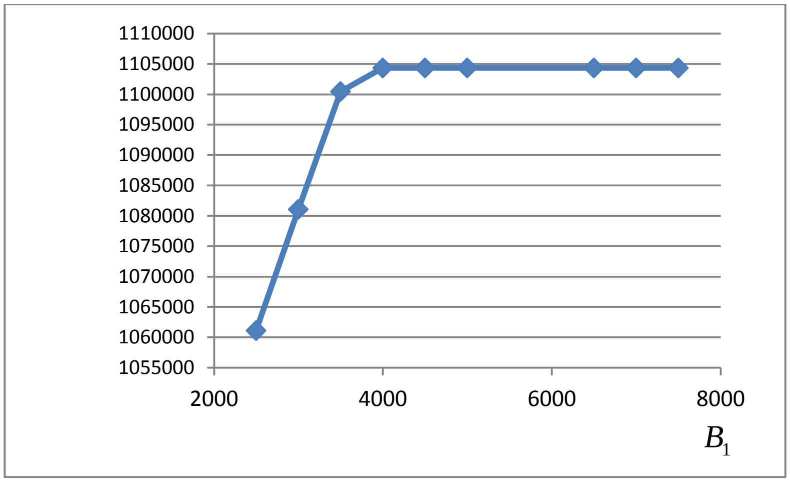


Figure 6.2. Sensitivity analysis of the max capacity of disassembly site to dissemble part 1

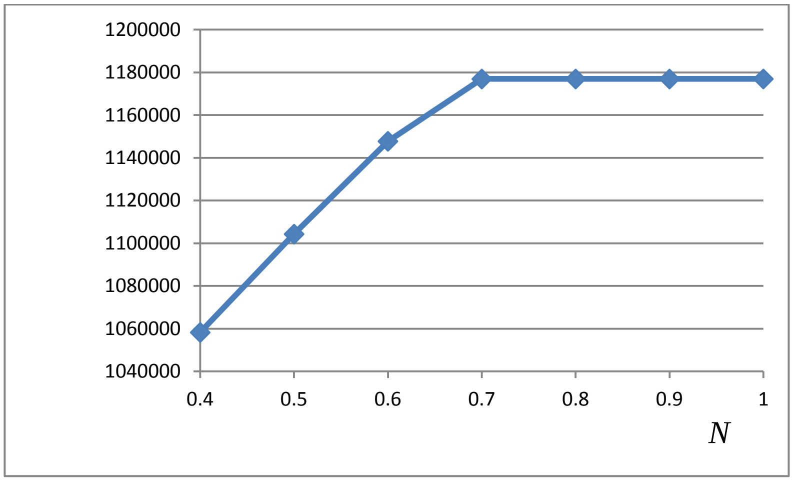


Figure 6.3. Sensitivity analysis of *N* (max percent of total returns)

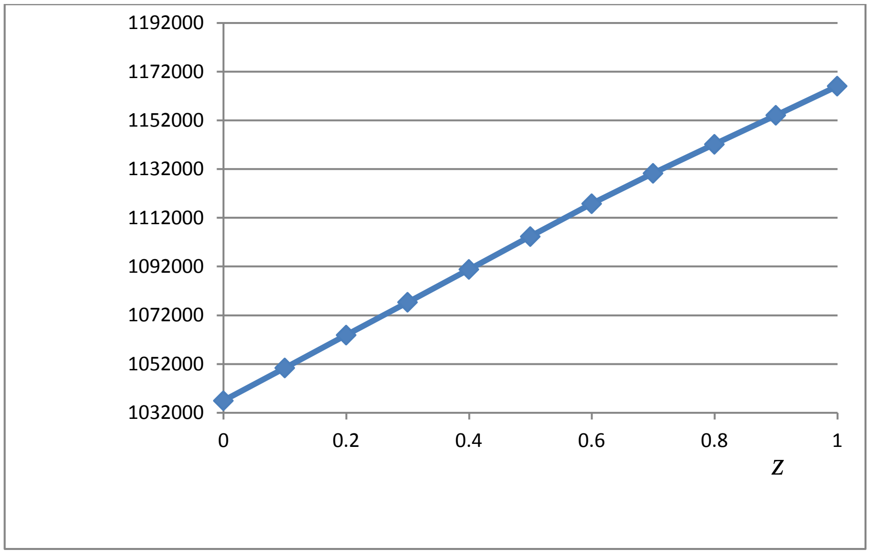


Figure 6.4. Sensitivity analysis of *z* (max percent of commercial returns)

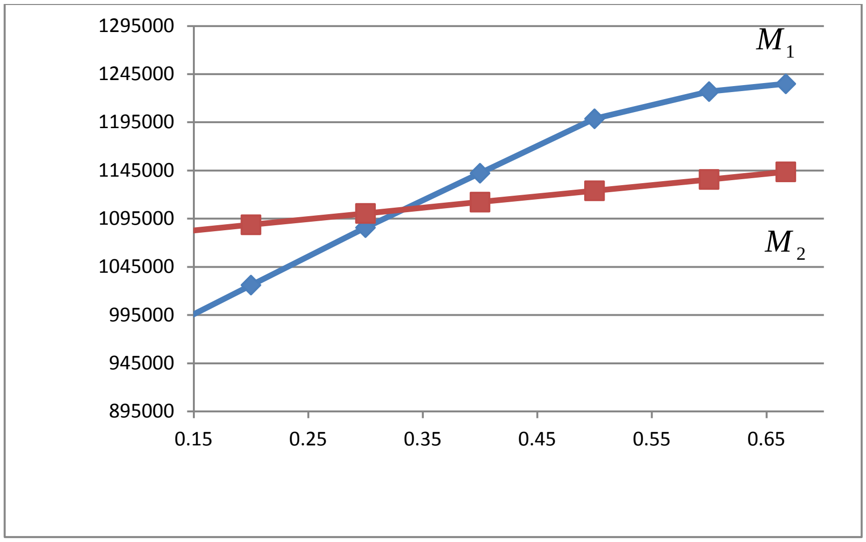


Figure 6.5. Sensitivity analysis of M_1 (max percent of end of use returns), M_2 (max percent of end of life returns)

6.6. Extended model

In this section, it is supposed that remanufactured products are sent to the secondary market. This process may happen because of the lower quality of remanufactured products. The secondary market may be another country. The manufacturer has to satisfy the demand of same and secondary markets. The shortage of products in the secondary market should be supplied by new products. The manufacturer is interested to know how much should be produced to satisfy the demands of same and secondary markets. The new variables and parameters are written in Table 6.3. Other parameters are as same as Table 6.1.

The objective function and some constraints are similar to the proposed model. Constraints (6.23) ensure that the number of manufactured parts for the secondary market is equal to the number of recycled parts and the number of purchased parts from external suppliers (for the secondary market), and the number of end of use parts. Constraints (6.24) represent that the number of manufactured parts for the same market is equal to the number of purchased parts from external suppliers for the same market. Furthermore, Constraints (6.25) and (6.26) are related to the demand. Constraints (6.27) show the maximum percent of total returned products. Constraints (6.28) ensure that the summation of parts of same and secondary markets is equal to the total parts. In the same order, Constraints (6.29) are designed for products. Constraints (6.30) and (6.31) are related to decision variables. The extended model is solved by GAMS. The results of sensitivity analyses are illustrated in Figures 6.6-6.9. Sensitivity analysis for the max capacity of disassembly site to dissemble part 1 (Figure 6.6) shows that there is a certain maximum capacity of disassembly site. These results are useful for managers because they can prevent additional costs in remanufacturing network configuration.

Table 6.3
Additional variables and parameters for the secondary market

Variables		**Parameters**	
PA_j	Units of product *j* to be produced for the same market	DA_j	Demand for product *j* in the same market
PE_j	Units of product *j* to be produced for the secondary market	DE_j	Demand for product *j* in the secondary market
QA_{ik}	Units of part *i* to be purchased from external supplier *k* for the same market		
QE_{ik}	Units of part *i* to be purchased from external supplier *k* for the secondary market		

(6.1)

Subject to

(6.3), (6.4), (6.5), (6.6), (6.7), (6.8), (6.9), (6.10), (6.12), (6.13), (6.14), (6.15), (6.16), (6.18), (6.19), (6.20)

$$\sum_{j=1}^{J} q_{ij} PE_j = \sum_{l=1}^{L} F_{il} + \sum_{k=1}^{K} QE_{ik} + R_i \qquad \forall i \tag{6.23}$$

$$\sum_{j=1}^{J} q_{ij} PA_j = \sum_{k=1}^{K} QA_{ik} \qquad \forall i \tag{6.24}$$

$$PA_j = DA_j \qquad \forall j \tag{6.25}$$

$$PE_j + X_j = DE_j \qquad \forall j \tag{6.26}$$

$$Y_j \leq N \; PA_j \qquad \forall j \tag{6.27}$$

$$QA_{ik} + QE_{ik} = Q_{ik} \qquad \forall i, k \tag{6.28}$$

$$PA_j + PE_j = P_j \qquad \forall j \tag{6.29}$$

$$U_{il}, V_j, W_j \in \{0,1\} \qquad \forall i, j, l \tag{6.30}$$

$$P_j, Z_j, Q_{ik}, E_i, F_{il}, G_i, R_i, Y_j, X_j, QA_{ik}, QE_{ik}, PA_j, PE_j \geq 0 \qquad \forall i, j, k, l \tag{6.31}$$

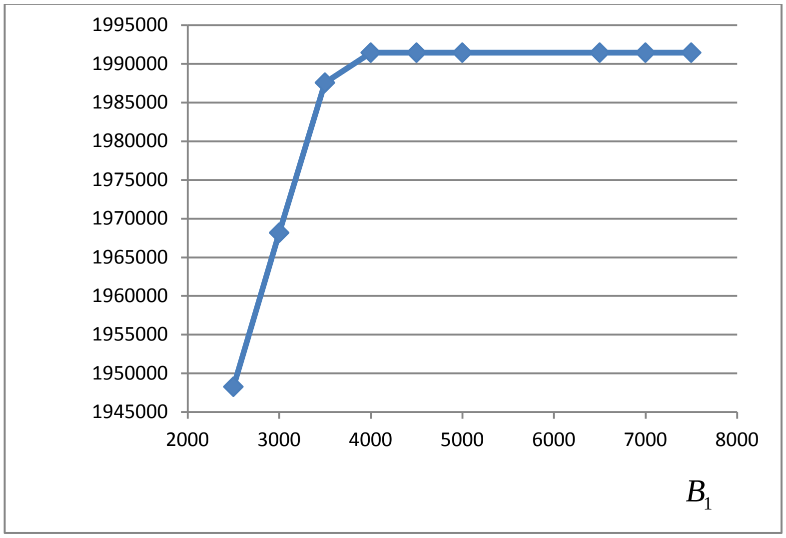


Figure 6.6. Sensitivity analysis of the max capacity of disassembly site to dissemble part 1 (secondary market)

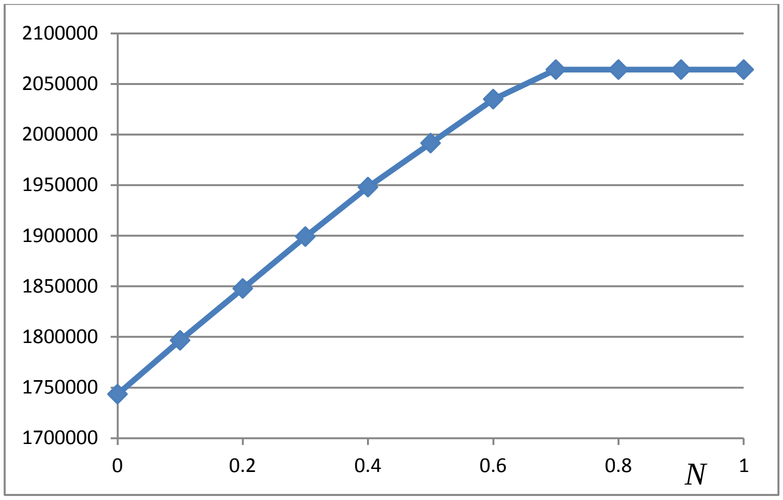


Figure 6.7. Sensitivity analysis of *N* (max percent of total returns), (secondary market)

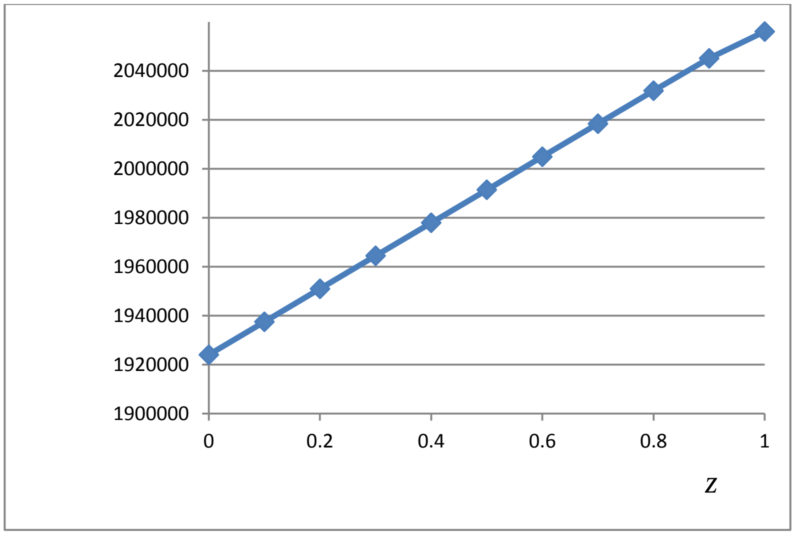


Figure 6.8. Sensitivity analysis of *z* (max percent of commercial returns), (secondary market)

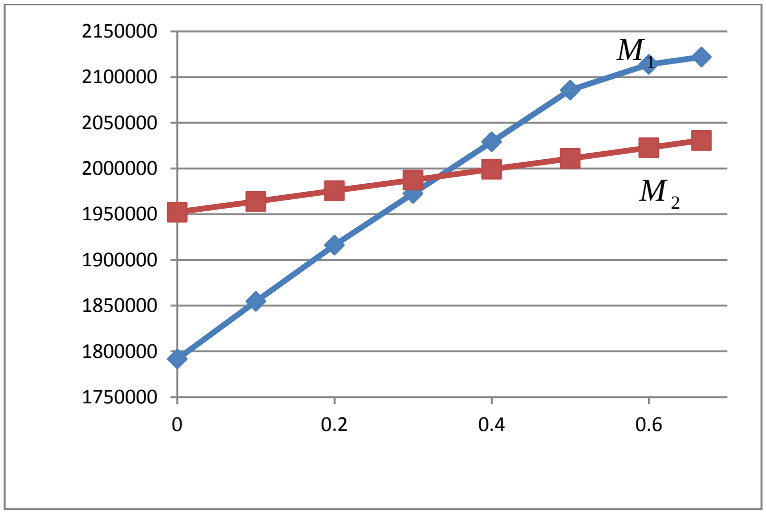


Figure 6.9. Sensitivity analysis of M_1 (max percent of end of use returns), M_2 (max percent of end of life returns), (secondary market)

6.7. Conclusions

We proposed a closed-loop supply chain that consists of manufacturer, collection, repair, disassembly, recycling, and disposal sites. The major contribution of this research lies in designing and solving a general network based on return-recovery pairs and product life cycle. We proposed a novel mathematical model to optimize the closed-loop network. The mixed-integer linear programming model determines the units of products to be produced, disassembled, and repaired. In addition, it determines units of parts to be purchased from external suppliers, units of parts to be disassembled, recycled, and disposed while maximizing the profit. The model is solved by GAMS. We also developed the model for situation that remanufactured products are sent to a secondary market. A numerical example is performed to analyze the results. Furthermore, sensitivity analysis is utilized to validate the models. The results of our paper indicate that the manufacturer should take into account key factors such as production capacity, demand, supplier's capacity, end of life, end of use, and commercial returns. One of the insights from our study is that the maximum objective function can be obtained with a certain capacity of disassembly site. Therefore, managers can decrease the costs of investment. We also observed that the value of objective function for primary market is more than the extended model which is formed of primary and secondary markets because the manufacturer needs to purchase fewer parts from external suppliers. This result is obtained when total demands are equal.

Many research directions still require intensive research. Uncertainty is one of the important problems in supply chain management. It is worthwhile to take into account uncertainty of parameters such as demand, and return. Besides, the proposed model is designed for a single period. The model can be extended to consider multiple periods. In this condition, the inventory level of t is different from t - 1. In addition, beginning inventory should be taken into account. In the proposed model, recycling and end of use returns and new parts were used to manufacture new products. The price of reused products is a function of other factors such as demand, manufacturing process, and environmentally concerns particularly for products that have short life cycle. Determining the price of remanufactured parts based on the market demand can be a subject of future research. Moreover, it is hard to solve the model, when the numbers of variables and constraints increase. In this situation, heuristics algorithms such as Genetic Algorithm and Scatter Search can be useful.

CHAPTER 7. CONCLUSIONS AND FUTURE RESEARCH

7.1. Conclusions

The objective of this dissertation is to develop effective approaches to support closed-loop supply chain configurations and analyses, especially develop methodologies to examine impacts of uncertainty, and multi-objectives issues on closed-loop supply chain networks. To this aim, some networks have been investigated and appropriate mathematical models and solution approaches have been extended.

In the Chapter 3, a capacitated facility location model has been proposed for a closed-loop supply chain network. The model has been designed for multiple plants, demand markets, collection centers, and products. In addition, two test problems have been examined. Besides, the model has been extended to consider environmental objective. Two methods have been utilized to solve the multi-objective programming model including weighted sums and ε-constraint methods. The results of test problem 2 show that ε-constraint method can obtain more efficient solutions than weighted sums method. Therefore, ε-constraint method is selected for this example. The model also has been developed by stochastic programming (scenario-based) to examine the effects of uncertain demand and return on the network configuration. The computational results demonstrate that the stochastic programming model can gain flexible optimal closed-loop supply chain configuration with the objective function near to the base-case. This research is among the first investigations that consider multi-objective mathematical models under uncertainty in CLSC network configuration.

In the Chapter 4, an integrated mathematical model for supplier selection, order allocation, and closed-loop network configuration has been proposed. The network consists of manufacturer, disassembly, refurbishing, and disposal sites. In the first phase, fuzzy sets theory has been used to overcome the uncertainty in assessment of eligible suppliers. Therefore, the importance of suppliers can be calculated. Then, we designed multi-objective mixed-integer linear programming model to optimize the supply chain network. The model not only determines the amount of parts and products in the nodes of CLSC network (tactical decisions), but also it selects the best suppliers and refurbishing sites (strategic decisions). GAMS has been utilized to solve the proposed model. In addition, a numerical example has been performed to analyze and validate the model. Computational results demonstrated the efficiency and effectiveness of the proposed model. To our knowledge, the proposed model is the first one that takes into account supplier selection, order allocation, and CLSC network configuration at the same time.

In the Chapter 5, a three-stage model has been 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 has been configured. In the proposed model, the uncertainty in selection process and demand has been considered. To this aim, fuzzy sets theory and stochastic programming technique have been utilized. 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. 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.

In the Chapter 6, we proposed a novel mathematical model to optimize the closed-loop network. The mixed-integer linear programming model determines the units of products to be produced, disassembled, and repaired. In addition, it determines units of parts to be purchased from external suppliers, units of parts to be disassembled, recycled, and disposed while maximizing the profit. The model has been solved by GAMS. We also developed the model for situation that remanufactured products are sent to a secondary market. A numerical example has been performed to analyze the results. Furthermore, sensitivity analysis is utilized to validate the models. The results of the research indicate that the manufacturer should take into account key factors such as production capacity, demand, supplier’s capacity, end of life, end of use, and commercial returns. One of the insights from our study is that the maximum objective function can be obtained with a certain capacity of disassembly site. Therefore, managers can decrease the costs of investment. To our knowledge, before this research no investigation has examined a general network for return-recovery pairs including commercial, end of life, and end of use returns.

7.2. Future research

The future works for this dissertation are as follows:

a) Developing solution approaches to obtain exact solutions: Mathematical models of this dissertation have been solved by commercial software (GAMS and CPLEX). It is worthwhile to propose exact solution approaches particularly for large size problems. To this aim, some techniques such as branch and cut can be helpful.

b) Developing mathematical models to consider environmental factors: In Chapter 3, we developed a mathematical model based on two environmental objectives (qualitative factors). It is valuable to extend multi-objective optimization models to consider environmental objectives such as reduction of waste (quantitative factors) in addition to the total cost. Besides, appropriate solution approaches should be developed.

c) Developing multiple period models: The proposed models are designed for a single period. The models can be extended to consider multiple periods. In this condition, the inventory level of t is different from t - 1. In addition, beginning inventory should be taken into account.

d) Determining the price of reused products: The price of reused products in CLSC is a function of other factors such as demand, manufacturing process, and environmentally concerns particularly for products that have short life cycle. Determining the price of remanufactured parts based on the market demand can be a subject of future research.

e) Developing solution approaches to consider uncertainty: In this dissertation, some techniques including fuzzy sets theory and stochastic programming have been utilized to consider uncertainty. It is useful to examine the effects of uncertainty on the model by other methods such as robust optimization and compare the results. In addition, not only uncertain demand and return should be considered, but also uncertainty in other factors such as costs should be taken into account.

f) Developing appropriate models to consider quality of returned products: The returned products have different qualities. It is necessary to develop models and solution approached to consider this issue for different kinds of returns (end of life, end of use, and commercial returns).

APPENDICES

APENDIX A. Data for the numerical example (Chapter 4)

Table A.1
Product-related parameters

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

Table A.2
Part-related parameters

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

Table A.3
Refurbishing site-related parameters

o_{il} (Unit refurbishing cost for part *i* in refurbishing site *l*)

i / l	**1**	**2**	**3**	**4**	**5**
1	3	2	3	3	4
2	4	4	3	2	4
3	4	3	4	3	4
4	4	3	3	4	3
5	3	3	4	4	4

p_{il} (Set-up cost of refurbishing site *l* for part *i*)

i / l	**1**	**2**	**3**	**4**	**5**
1	4	5	4	4	4
2	4	4	4	4	5
3	5	5	4	5	5
4	4	5	5	5	5
5	4	4	4	5	4

g_{il} (Resource usage to refurbish one unit of part *i* in refurbishing site *l*)

i* / *l	**1**	**2**	**3**	**4**	**5**
1	1	1	1	1	1
2	1	1	1	1	1
3	1	1	1	1	1
4	1	1	1	1	1
5	1	1	1	1	1

G_{il} (Max capacity of refurbishing site *l* to refurbish part *i*)

i* / *l	**1**	**2**	**3**	**4**	**5**
1	9000	10000	8500	10000	9500
2	10000	9000	8500	10000	9500
3	9000	10000	8000	9500	10000
4	8500	9000	10000	9500	8500
5	9000	9500	10000	9000	8500

Table A.4

q_{ij} (The usage of part *i* per unit of product *j*)

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

Table A.5

Supplier-related parameters

r_{ik} (The cost of purchasing part *i* from external supplier *k*)

i* / *k	**1**	**2**	**3**	**4**	**5**
1	14	14	18	12	19
2	16	21	14	16	14
3	13	23	20	15	14
4	15	14	18	19	14
5	18	15	14	13	15

b_{ik} (Internal resource usage of supplier *k* to produce one unit of part *i*)

i* / *k	**1**	**2**	**3**	**4**	**5**
1	1.5	2	3	1	3
2	2	1	1	3	1
3	2	1.5	1	3	2.5
4	1.5	3	2.5	2	3
5	3	2	3	2	1.5

s_{ik} (Defect rate for part *i* that is produced by supplier *k*)

i* / *k	**1**	**2**	**3**	**4**	**5**
1	0.10	0.05	0.10	0.07	0.11
2	0.05	0.05	0.10	0.10	0.05
3	0.10	0.05	0.10	0.05	0.07
4	0.05	0.10	0.07	0.10	0.06
5	0.10	0.11	0.05	0.10	0.10

Table A.6
B_k (The capacity of supplier *k*), v_k (Minimum purchase quantity from supplier *k*), *A* (The capacity of manufacturer), H_j (Max percent of product *j* returns), O_i (Max percent of reusable part *i*), *C* (Max number of refurbishing sites)

k	**1**	**2**	**3**	**4**	**5**
B_k	10000	75000	90000	60000	125000
v_k	1000	1000	1000	1000	1000
A	200000		H_j	0.5	
C	6		O_i	0.5	

APENDIX B. Data for the illustrative example (Chapter 5)

Table B.1

Product and part related parameters

Product-related parameters

j	**1**	**2**	**3**
a_j	1	2	2
C_j^m	30	35	30
CS_j^r	5	5	5
C_j^{coll}	5	6	7
C_j^r	4	5.5	3.5
W_j^r	500	200	900
e_j^r	1	1	1

Part-related parameters

i	**1**	**2**	**3**	**4**	**5**
C_i^d	3	4	4	4	3
CS_i^{re}	4	4	4	4	4

q_{ij} (The usage of part *i* per unit of product *j*)

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

Table B.2

Remanufacturing subcontractor-related parameters

y_m (Fixed cost associated with remanufacturing subcontractor *m*), W_m^{sub} (The capacity of remanufacturing subcontractor *m*)

m	**1**	**2**	**3**	**4**	**5**
y_m	5	5	5	5	5
W_m^{sub}	90000	90000	90000	90000	90000

C_{jm}^{sub} (Unit remanufacturing cost of remanufacturing subcontractor *m* for product *j*)

j / m	**1**	**2**	**3**	**4**	**5**
1	98	94	100	97	100
2	158	165	164	155	158
3	160	160	155	170	175

b_{jm}^{sub} (Internal resource usage of remanufacturing subcontractor *m* to produce one unit of product *j*)

j / m	**1**	**2**	**3**	**4**	**5**
1	1.5	1.5	1.5	1.5	1.5
2	2	2	2	2	2
3	1	1	1	1	1

WE_{jm}^{sub} (Weight of remanufacturing subcontractor *m* for remanufacturing product *j*)

j / m	**1**	**2**	**3**	**4**	**5**
1	0.18	0.22	0.19	0.21	0.20
2	0.17	0.22	0.20	0.20	0.21
3	0.20	0.23	0.20	0.18	0.19

Table B.3
Refurbishing site-related parameters

h_l (Fixed cost associated with refurbishing site *l*), W_l^{re} (The capacity of refurbishing site *l*)

l	**1**	**2**	**3**	**4**	**5**
h_l	5	5	5	5	5
W_l^{re}	90000	90000	90000	90000	90000

C_{il}^{re} (Unit refurbishing cost for part *i* in refurbishing site *l*)

i / l	**1**	**2**	**3**	**4**	**5**
1	3	2	3	3	4
2	4	4	3	2	4
3	4	3	4	3	4
4	4	3	3	4	3
5	3	3	4	4	4

e_{il}^{re} (Resource usage to refurbish one unit of part *i* in refurbishing site *l*)

i / l	**1**	**2**	**3**	**4**	**5**
1	1	1	1	1	1
2	1	1	1	1	1
3	1	1	1	1	1
4	1	1	1	1	1
5	1	1	1	1	1

WE_{il}^{re} (Weight of refurbishing site *l* for part *i*)

i / l	**1**	**2**	**3**	**4**	**5**
1	0.20	0.20	0.20	0.21	0.19
2	0.20	0.22	0.17	0.20	0.21
3	0.20	0.23	0.20	0.18	0.19
4	0.18	0.22	0.19	0.21	0.20
5	0.19	0.19	0.22	0.18	0.22

DE_{il}^{re} (Defect rate of part *i* that is refurbished in site *l*)

i / l	**1**	**2**	**3**	**4**	**5**
1	0.05	0.05	0.04	0.03	0.07
2	0.06	0.05	0.08	0.05	0.05
3	0.10	0.07	0.08	0.09	0.10
4	0.04	0.05	0.07	0.07	0.06
5	0.05	0.05	0.05	0.07	0.03

OE_{il}^{re} (Rate of on-time delivery of part *i* in refurbishing site *l*)

i / l	**1**	**2**	**3**	**4**	**5**
1	0.88	0.90	0.90	0.90	0.95
2	0.92	0.88	0.90	0.90	0.90
3	0.92	0.92	0.87	0.88	0.90
4	0.88	0.97	0.97	0.90	0.92
5	0.96	0.88	0.92	0.94	0.94

Table B.4

Supplier-related parameters

g_k (Fixed cost associated with supplier *k*), W_k^s (The capacity of supplier *k*)

k	**1**	**2**	**3**	**4**	**5**
g_k	5	5	5	5	5
W_k^s	100000	75000	90000	60000	125000

C_{ik}^p (The cost of purchasing part *i* from external supplier *k*)

i / k	**1**	**2**	**3**	**4**	**5**
1	14	14	18	12	19
2	16	21	13	16	14
3	13	23	20	15	14
4	15	14	18	19	14
5	18	15	14	13	15

b_{ik}^P (Internal resource usage of supplier *k* to produce one unit of part *i*)

i / k	**1**	**2**	**3**	**4**	**5**
1	1.5	2	3	1	3
2	2	1	1	3	1
3	2	1.5	1	3	2.5
4	1.5	3	2.5	2	3
5	3	2	3	2	1.5

WE_{ik}^P (Weight of supplier *k* for part *i*)

i / k	**1**	**2**	**3**	**4**	**5**
1	0.21	0.19	0.20	0.20	0.20
2	0.18	0.21	0.20	0.20	0.21
3	0.20	0.24	0.19	0.17	0.20
4	0.21	0.20	0.20	0.21	0.18
5	0.18	0.18	0.23	0.20	0.21

DE_{ik}^P (Defect rate of part *i* that is produced by supplier *k*)

i / k	**1**	**2**	**3**	**4**	**5**
1	0.10	0.05	0.10	0.07	0.11
2	0.05	0.05	0.10	0.10	0.05
3	0.10	0.05	0.10	0.05	0.07
4	0.05	0.10	0.07	0.10	0.06
5	0.10	0.11	0.05	0.10	0.10

OE_{ik}^P (Rate of on-time delivery of part *i* by supplier *k*)

i / k	**1**	**2**	**3**	**4**	**5**
1	0.90	0.88	0.90	0.89	0.90
2	0.92	0.90	0.90	0.90	0.90
3	0.92	0.90	0.85	0.90	0.88
4	0.90	0.95	0.95	0.93	0.92
5	0.95	0.90	0.90	0.88	0.95

Table B.5

Customer-related parameters

S_{jn} (Unit selling price of the product *j* for customer *n*)

j / n	1	2	3	4	5
1	150	150	150	150	150
2	200	200	200	200	200
3	230	230	230	230	230

$\mu_{x_{jn}}$ (Mean demand of product *j* for customer *n*)

j / n	1	2	3	4	5
1	500	600	100	200	300
2	320	220	300	320	120
3	220	330	220	430	220

$\sigma_{x_{jn}}$ (Standard deviation of demand for product *j* and customer *n*)

j / n	1	2	3	4	5
1	80	80	80	80	80
2	60	60	60	60	60
3	60	60	60	60	60

u_{jn} (Under stocking cost of product *j* for customer *n*)

j / n	1	2	3	4	5
1	100	100	100	100	100
2	90	90	90	90	90
3	90	90	90	90	90

v_{jn} (Overstocking cost of product *j* for customer *n*)

j / n	1	2	3	4	5
1	60	60	60	60	60
2	40	40	40	40	40
3	10	10	10	10	10

Table B.6

W^m (The capacity of manufacturer), *Z* (Maximum percent of returns), *E* (Maximum percent of reusable parts), *G* (Maximum number of suppliers), *T* (Maximum number of remanufacturing subcontractors), *F* (Maximum number of refurbishing sites)

W^m	200000	Z	0.5
G	5	E	0.5
T	5	F	5

APENDIX C. Data for the computational testing (Chapter 6)

Table C.1
Product-related parameters

j	**1**	**2**	**3**	**4**	**5**
S_j	150	200	220	230	250
a_j	1	2	2	2	3
H_j	2.5	2.5	3.5	2.5	3.5
y_j	30	35	30	30	35
e_j	1	2	1	1	1
C_j	9000	10000	8500	10000	9500
D_j	1400	1500	1400	1400	1500
c_j	4	5.5	2.5	3.5	3.5
d_j	1	2	1	2	1
f_j	5	5	4	5	4
g_j	5	5	4	5	4

Table C.2
Part-related parameters

i	**1**	**2**	**3**	**4**	**5**
B_i	9000	10000	8500	10000	9500
h_i	4	5.5	2.5	3.5	3.5
m_i	3	4	4	4	3
r_i	1	1	1	1	1

Table C.3
q_{ij} (The usage of part *i* per unit of product *j*)

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

Table C.4
Recycling site-related parameters

n_{il} (Unit recycling cost for part *i* in recycling site *l*)

i / l	**1**	**2**	**3**	**4**	**5**
1	3	2	3	3	4
2	4	4	3	2	4
3	4	3	4	3	4
4	4	3	3	4	3
5	3	3	4	4	4

o_{il} (Set-up cost of recycling site *l* for part *i*)

i / l	**1**	**2**	**3**	**4**	**5**
1	4	5	4	4	4
2	4	4	4	4	5
3	5	5	4	5	5
4	4	5	5	5	5
5	4	4	4	5	4

s_{il} (Resource usage to recycle one unit of part *i* in recycling site *l*)

i / l	**1**	**2**	**3**	**4**	**5**
1	1	1	1	1	1
2	1	1	1	1	1
3	1	1	1	1	1
4	1	1	1	1	1
5	1	1	1	1	1

O_{il} (Max capacity of recycling site *l* to recycle part *i*)

i / l	**1**	**2**	**3**	**4**	**5**
1	9000	10000	8500	10000	9500
2	10000	9000	8500	10000	9500
3	9000	10000	8000	9500	10000
4	8500	9000	10000	9500	8500
5	9000	9500	10000	9000	8500

Table C.5

Supplier-related parameters

p_{ik} (The cost of purchasing part *i* from external supplier *k*)

i / k	**1**	**2**	**3**	**4**	**5**
1	8	8	12	6	15
2	10	15	8	10	5
3	5	7	14	9	8
4	9	5	10	13	8
5	12	9	5	7	6

b_{ik} (Internal resource usage of supplier *k* to produce one unit of part *i*)

i / k	**1**	**2**	**3**	**4**	**5**
1	1.5	2	3	1	3
2	2	1	1	3	1
3	2	1.5	1	3	2.5
4	1.5	3	2.5	2	3
5	3	2	3	2	1.5

T_k (The capacity of supplier *k*)

k	**1**	**2**	**3**	**4**	**5**
T_k	100000	75000	90000	60000	125000

Table C.6

A (Max capacity of manufacturer plant), M_1 (Max percent of end of use returns), M_2 (Max percent of end of life returns), *N* (Max percent of total returns), *z* (Max percent of commercial returns), *t* (Max number of recycling sites)

A	200000	N	0.5
M_1	0.333	z	0.5
M_2	0.333	t	6

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