A Bi-Objective Integrated Reverse Supply Chain Design for Durable Products

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Abstract

Over the past few years, manufacturers in several countries are faced with legislations on the take-back of their End-Of-Life (EOL) products. Meanwhile, many companies are recognizing the product recovery as an opportunity for saving production costs and accessing new markets. Reverse supply chains (RSCs) process used products returns so as to recover value by re-processing them and redistributing them in the market. This thesis proposes a RSC design model that simultaneously considers forward and reverse flows in the context of durable products. Such products consist of different modules, parts, and materials that can be recovered through several disposition options. Since RSCs deal with multiple quality states of used items, we assume that the returned items fit into two quality categories that differ in the quantities of recoverable components, as well as their available quantity and price. Unlike the majority of contributions in the literature, we focus on all types of recovery options in the network design model. Moreover, rather than considering a single profit maximization objective function, we also consider another objective for maximizing environmental benefits. We formulate this problem as a mixed integer linear programming (MILP) model. We apply the proposed model to an academic case study in the context of EOL washing machines. The bi-objective RSC design model is solved by the aid of the ε-constraint method. Finally, in order to identify the significant factors affecting each objective function, a set of sensitivity analysis tests is conducted. Managerial implications are also provided based on the results of the sensitivity analysis and the ε-constraint method.

Keywords: *Reverse Supply Chain Design*; *Durable Products*; *Bi-Objective Optimization; ε-Constraint Method; Sensitivity Analysis*

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I would like to take this opportunity to express my gratitude and regards to my supervisor Dr. Masoumeh Kazemi for all her supports and guidance during my graduate study and thesis preparation. I really appreciate the time that she spent with me considering her busy schedule that made it possible to develop and complete this work.

I dedicate my thesis to my parents and my dear brothers who always stood beside me in my life.

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List of Acronyms

EOL	-	End-Of-Life
RCS	-	Reverse supply chains
OEM	-	Original equipment manufacturer
CLSC	-	Closed-loop supply chain
MILP	-	Mixed-integer linear programming
RL	-	Reverse logistics
RPS	-	Reverse production system
BD	-	Benders decomposition
MINLP	-	Mixed integer non-linear programming
UIP	-	Uniform incentive policy
MIGP	-	Mixed integer goal programming
MOO	-	Multi-objective optimization
KPI	-	Key performance indicators
R-sq	-	R-squared

Chapter One

Introduction

1.1 Foreword

Over the past few years, the sustainably movements has gained noticeable attention as both managers and consumers start to realize the effects of unsustainable environmental practices on the quality of life standards. The significant effects of environmental issues for many people have been the huge increase in the price of fossil fuels, issues related to energy usage, carbon dioxide emission, climate change and access to clean water. In addition, the problem of landfilling with End-Of-Life (EOL) products that contain depletable raw materials is another concern. Moreover, manufacturers in several countries, such as Germany and Japan, are faced with the legislation on the take-back of their EOL products, including electronic equipment, packaging material, cars, etc. Meanwhile, many companies are recognizing the product recovery as an opportunity with financial benefits by saving production costs and accessing new market segments.

Recently, the logistics aspect of recycling and reuse of products has been brought to the attention. Hence, the remanufacturing companies extend the scope of traditional logistics to include not only the conventional forward flow, but also the backward flow from the customers to the manufacturer. Reverse supply chains (RCSs) collect used products from end-users; consolidate, inspect and sort them as needed; and transport them for various recovery options.

As establishing the reverse network without considering the forward network will reduce the remanufacturing profit and disregard the interdependence of forward and backward flows, it is necessary to consider both forward and backward flow simultaneously for an optimal logistics network design.

1.2 Goal of the Study

In this thesis, our goal is to investigate a RSC which is applicable in the context of durable products, i.e. consumer, commercial, and industrial equipment such as automotive parts, photocopying equipment, ships, aircraft engine, etc. These products are distinguished by their high recoverable value, long product life-cycle, and well-established forward network. In the context of durable products which consist of several modules, parts, and different types of materials, several recovery (disposition) alternatives exist, such as remanufacturing/refurbishing, part harvesting, material recycling, and disposal (i.e., landfilling, incineration, etc.).

We are also interested in a setting where a forward network exists and is managed by the original equipment manufacturer (OEM), i.e. the locations of the new products manufacturing facilities, distribution centers, and retailors are known. Under the described context, the OEM needs to modify the forward supply chain to accommodate the reverse flow to transform their existing supply chain into a closed-loop supply chain (CLSC). Adopting such a strategy, a manufacturer can satisfy demand by both new and remanufactured products. Although a significant initial investment is required to establish a reverse network including remanufacturing, this investment can be justified by effective recovery of high value associated with such products via an integrated network. In the RSC described above, we are looking for qualitative modeling tools that consider the existing infrastructure while designing the reverse network and coordinating the forward and reverse flows accordingly. More precisely, the following questions must be answered for designing a reverse supply chain while coordinating the forward and reverse flows:

1- How the existing forward network should be extended to accommodate remanufacturing and other recovery activities. In other words, where the collection centers and recovery facilities should be installed and what should be their capacity level?
2- How should the forward and reverse flows be routed / coordinated in the extended network?

The configuration (design) of a reverse supply chain may affect both a company's profitability and environmental impacts. Hence, unlike the common practice in the literature, we address two objectives in this problem: *i*) maximization of profit and *ii*) maximization of the total returned products acquisition amount. It is worth mentioning that the overall cost of a reverse supply chain includes: 1) the fixed costs associated with locating the collection centers, as well as product recovery facilities (e.g., remanufacturing facilities) with different capacity levels, 2) the transportation costs associated with forward and reverse flow, 3) the processing costs in forward chain, as well as the collection centers and recovery and disposal facilities.

In this study, we suppose that the returned products can be categorized into two quality levels (high and poor quality) for which the proportion is known *a priori*. Furthermore, the quantities of recoverable modules and parts, as well as the processing costs of recovery activities differ for each quality level. By considering the profit maximization objective, the model might find a solution in which the low quality level return are less acquired by the OEM due to their high cost of recovery and low amount of recoverable items. The latter, on the other hand, will increase the amount of disposal which is in contradiction with the second objective (maximizing the acquisition amount). As a consequence, the network design decisions are made based on the trade-off between the financial and environmental criteria.

We finally aim for formulating the integrated forward and reverse supply chain design problem as a bi-objective mixed-integer linear programming (MILP) model, and developing a solution strategy for solving the resulting complex bi-objective reverse supply chain design model. In a multi-objective optimization problem, a solution that optimizes one objective function will not necessarily optimize any of the other objectives. Therefore, a concept of non-dominated solutions is introduced for solving such problems. The latter incorporates a set of alternative feasible solutions over all objectives. For generating a set of non-dominating solutions, we aim for using the ε-constraint method.

1.3 Research Contribution

The majority of contributions in the literature on RSC design focus exclusively on remanufacturing as the recovery option. Furthermore, addressing the aforementioned problem by considering only financial criteria (profit/cost maximization/minimization) is also a common practice in the literature. Finally, despite the high degree of uncertainty in the quality of EOL products, almost no author takes quality levels into account while designing reverse and closed-loop supply chains. This research extends the current literature on the design of RSC networks in the following aspects:

- A multi-indenture structure is considered for the products, which requires different recovery options, including, remanufacturing, part harvesting, and material recycling.

- Rather than considering one objective function, two objective functions based on financial and environmental criteria are taken into account.
- Two quality levels are considered for the returned products which differ in terms of the acquisition price, processing costs, quantities of recoverable modules and parts, and consequently on the recovery decisions.
- The recovery facilities are assumed to be flexible with different potential capacity levels. This makes the problem more realistic.

This project will contribute to a more efficient tool for designing closed-loop supply chains for durable products that consist of numerous components among which several might be hazardous to the environment. Increased profitability of the company through selling the remanufactured products/ parts and recycled materials in the market in addition to the improved environmental image of the firm through minimizing the disposal amount of returned products are the main advantages of the proposed tool.

1.4 Thesis Outline

This thesis is divided into five chapters. Followed by the introduction in chapter one, chapter two provides a summary on the characteristics of reverse and closed-loop supply chains, in addition to a literature review on RSC design. RSC is the process of transporting products from their final destination for the purpose of capturing value or for proper disposal. CLSC considers both forward and reverse flows activities in a supply chain. Chapter three presents the problem description and model formulation, as well as the solution approach. In chapter four, numerical examples are presented and the results are analyzed. Chapter five presents conclusion, as well as future avenues of research.

Chapter Two

Literature Review

2.1 Introduction

In the past decade, the reverse logistics (RL) has gained significant attention and many studies were conducted regarding the reverse logistics design. In this chapter, we will review the literature of reverse logistics and closed-loop supply chains. This chapter is divided into 6 sections. The first two sections are focused on of the reverse logistics concept and the characteristics of reverse supply chains (RSCs). The subsequent sections are related to the literature review on RSC networks design model, and multi-criteria optimization. The last section analyzes the reviewed literature on RSC design and introduces the topics that need to be further investigated.

2.2 Closed-Loop Supply Chains

According to Dekker and Fleischmann (2004), drivers of the increased interest in CLSCs in recent years can be categorized as follows:

- **Economic factors:** A RL network can be beneficial for a company in term of decreasing the cost of disposal or adding value by recovery. Moreover, by using the recovered components and materials, a company can reduce the production cost. The company also may make money by selling the recovered components in the market.
- **Legislations:** In many countries, the legislations may motivate a company to get involved in EOL product recovery actions. For example, the companies are faced with packaging regulation, recycling quotes and/or product take-back responsibilities.
- **Corporate citizenship:** In some cases, the corporate citizenship principals may force a company to engage in the recovery activities. Recently, many companies have programs on responsible corporate citizenship where environmental and social issues are priorities.

A CLSC is a supply chain, where in addition to the traditional forward supply chain; there is a set of additional activities necessary for the recovery of returned products. The main difference between a CLSC and a traditional forward supply chain is that in a forward supply chain, the customer is at the end of the processes, however, in a CLSC, there is a value from customer or end-user that needs to be recovered (Ferguson and Souza, 2010). According to De Brito and Dekker (2002), there are many reasons for the backward flow (return) of used products, including: manufacturing returns, distribution returns, and customer returns, as illustrated below:

- **Manufacturing returns:** raw material surplus, quality-control returns, production leftovers or by-products.
- **Distribution returns**: product recalls, commercial returns (unsold products and wrong or damaged deliveries), stock adjustments, functional returns (distribution items, carriers, packaging).
- **Customer returns:** reimbursement guarantee/ warranty returns, service returns, end-of-use and EOL return.

According to Ferguson and Souza (2010), the decisions made in regard to the recovery of returned products are denoted as disposition decisions and include:

- **Remanufacturing and refurbishing:** This option is a value-added operation which can be more profitable comparing to the other disposition decisions. Hauser and Lund (2003) define remanufacturing as the process performed for restoring used products to like-new condition which includes: disassembly, cleaning, repairing, replacing parts, and reassembly. Refurbishing is defined as light remanufacturing and involves little disassembly.
- **Internal reuse:** This option is equivalent to light or no refurbishing.
- **Resale (as-is):** This option is attractive when there is a secondary market for the returns.
- **Parts harvesting:** Part harvesting is recovery of selected parts of the return so as to use them as spare parts.

- **Recycling:** This option is suitable for returns with limited or no functionality, which can be economically separated in an environmentally friendly way.
- **Landfilling:** This option might be illegal for some products in some countries.
- **Incineration:** This option will help to reduce the landfilling amount but still it does not close the supply chain loop.

A RL network is the most important component of a CLSC. In the RL networks, the returned products are collected from end users, consolidated, inspected, sorted, and transported to different recovery options. Figure 3-1 depicts a generic CLSC as proposed in (Aras et al., 2010). In this figure, solid arcs show the forward flow and dashed arcs show the reverse flow. Shaded nodes represent the reverse network facilities. The half-shaded nodes represent the possibility of co-locating the forward and reverse network facilities.

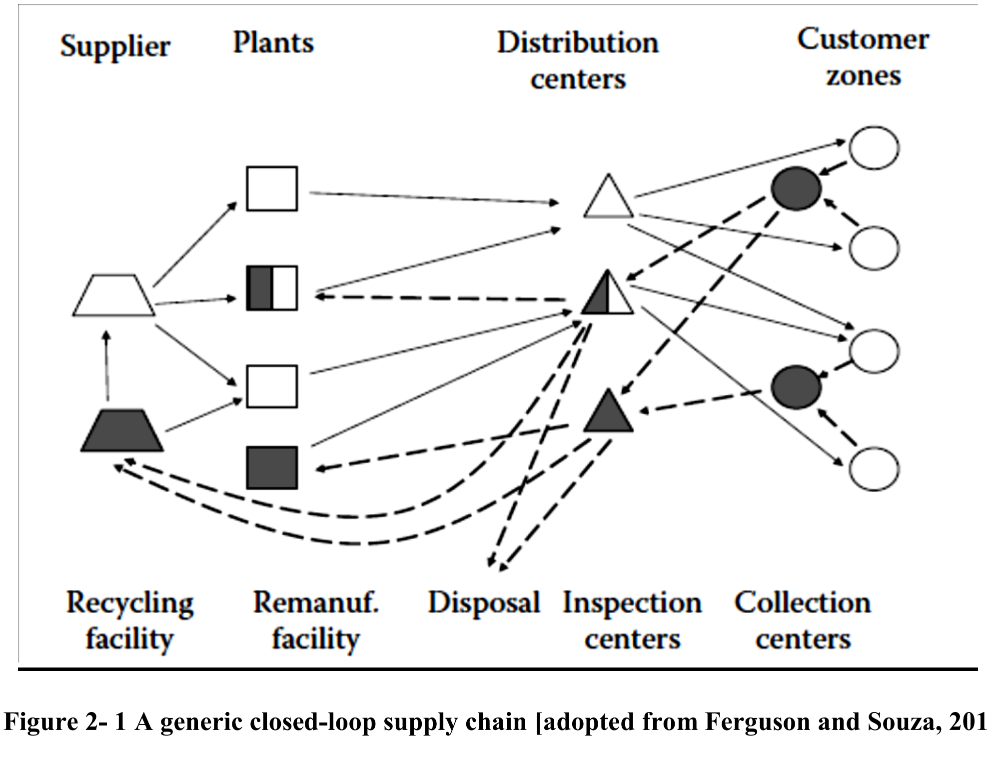

Figure 2- 1 A generic closed-loop supply chain [adopted from Ferguson and Souza, 2010]

According to Fleischmann (2001), a reverse supply chain consists of the following entities:

- **Collection:** Collection is the process of rendering the used products and transporting them for the recovery means. Collection may involve procuring and storing activities as well.
- **Inspection / separation:** The inspection/ separation process is necessary for deciding on the disposition decisions. This activity may involve sorting, disassembly, testing, storage and shredding.
- **Reprocessing:** It is the actual transformation of used product into a usable product, component or material. Recycling, repairing and remanufacturing are considered as reprocessing. This process may include cleaning, reassembly and replacement.
- **Disposal:** For the products or components that are not decided to be reprocessed, disposal is necessary. This process may involve landfilling and incineration.
- **Re-distribution:** This is the process of sending the reusable items to the market for sale. This process may encompass storing and shipping activity.

2.3 Reverse Supply Chain Network Design

There are different configurations for a RL network. The used product type and the recovery option have the major effect on the RL network structure. According to Aras et al. (2010), the high-level decisions regarding RL network design are summarized as follows:

- To directly collect the returned products from end users or to use the existing retail network?
- To set up drop-off facilities for returned products or to pick them up from customers?
- Whether or not to allocate financial incentive for the returned products?

Along with the decisions on collection and recovery strategy, the detailed decisions that need to be made included (Aras et al., 2010):

- Where to locate the RL network facilities?
- What is the flow pattern in RL network?
- What are the tactical decisions such as acquisition prices and inventory level?
- What is the effect of demand and return uncertainties on the RL network?
- Whether to design the RL network independently or together with the forward distribution network?

The majority of the literature in RL network design focuses on the configuration and the location of the reverse network facilities and some of them consider the forward network as well. In the next sub-sections, we will review the literature in RL and CLSCs network design.

2.4 Literature on the Design of RSC/CLSC

Thierry et al. (1995) discussed the strategic issues in product recovery management (PRM). The authors emphasized that for analyzing the issues in PRM, four groups of information is necessary: information on the products' compositions, the value and uncertainty of return flows, the market information regarding reprocessed products, material and components, and information on waste management and actual product recovery operations. They studied the PRM activities of a copier producer, BMW (cars) and IBM (computers) manufacturers and illustrated the production and operations management issues in their PRM system.

Fleischmann et al. (1997) provided a systematic overview of the issues arising in reverse logistics. In this paper, the authors subdivided the literature in reverse logistics into three main areas: production planning, inventory control and distribution planning. They reviewed the implication of reuse activities from operation research view and they discussed the traditional and new planning approaches used for dealing with planning problems arising in reverse logistics network based on practical examples.

Spengler et al. (1997) presented MILP models for integrated production and recycling planning problems and their applications on real world case studies. The first case study is focused on the design of integrated dismantling and recycling network for building waste in Germany. The model decides on the number of application of dismantling activities, the number of dismantled components and the amount of each component to be recycled. The objective function of this model is to maximize the total marginal income of the system. They concluded that dismantling strategies result in recycling of more than 90% of demolition of materials. Moreover, it can lead to cost saving of up to 20%, in comparison to disposal, based on the disposal fees and taxes. The second case study is the design of recycling system for by-products in steel industry in Germany. The proposed MILP model is based on the multi-stage capacitated warehouse location problem. In this problem, the model decides on recycling processes, their locations, and their capacities, as well as the flow and routing of by-products. The objective function is to minimize the total cost of the system, which consists of the transportation costs and utilization costs. They decided that establishing a recycling network for iron and steel industry is not economically feasible and the government has to raise the disposal fees and taxes in order to increase the recycling ratio.

Barros et al. (1998) proposed a MILP model for sand recycling problem. In this problem, the recycled sand, resulted from sorting and crushing facilities, is sent to the regional depot. In the regional depot, the recycled sand is classified into three quality levels: clean, half-clean and polluted. The clean and half-clean sand are stored at the regional depot and later reused. The polluted sand, first, is cleaned at treatment facilities, and, then, is stored as clean sand. For the case study, the authors selected 10 strategic sites in Netherland as the demand points. The supply and demand of each sand quality level is known and fixed. Given the potential location and capacities of facilities, the problem is to decide on the number and location of the facilities and transportation links in order to minimize the total cost of the system. The total cost consists of processing and fixed costs of facilities and transportation costs. This study proposed a multi-echelon capacitated warehouse location model and applied heuristics procedures for solving it. The results showed that the establishment of the sand recycling network is mainly affected by location of the demand points. Moreover, this paper revealed the importance of the location theory in recycling management.

Marin and Pelegrin (1998) proposed a MILP location- allocation model for the CLSC design problem. They assumed that the products are sent to customers from the plants, and the return, which is proportional to the demand, is sent to plants by customers. The problem is to decide on the location and number of plants, as well as the flow and routing. The objective function of the problem is to minimize the total cost that includes the fixed costs of opening plants and the transportation costs. For solving the problem, a Lagrangian decomposition-based heuristic approach and an exact solution method were proposed.

Krikke et al. (1999) proposed a MILP model for reverse logistics network re-design problem. The study is conducted based on a copier firm in Netherlands. In this problem, the return process is divided into two stages. The first stage is about the operation of remanufacturing. In this stage, the customers return the machines to the local operating company. The operating company may refurbish the machine itself or return it to the recovery location and receives a fee. The second stage is about the recovery strategy for the machine with three options: revision-strategy, factory produced new model-strategy and scrap-strategy. The return consists of four quality levels, which will affect the selection of the recovery strategy. The aim of the problem is to decide on recovery strategy and reverse logistics network design while minimizing the total cost and to compare three different pregiven network designs.

Louwers et al. (1999) presented a facility location-allocation model for reusing carpet waste. The recovery network studied in this paper consists of collection, reprocessing and redistribution facilities. The aim of the problem is to design the logistics structure of carpet waste by selecting the location and capacity of the storing and reprocessing facilities, as well as the transportation mode and flow allocation. The MILP model proposed in this study is different from other mathematical models developed for recovery logistics design. The main differences of this model are a completely free choice for the preprocessing centers locations and the explicit inclusion of depreciation costs.

The objective function of the problem is to minimize the total cost having constraints on transportation and costs. Finally, the authors described two applications of the model in Europe and the United States. They decided that establishing a reverse network for carpet waste is economically viable.

Fleischmann et al. (2000) investigated the reverse logistics network and reviewed the case studies on logistics network design. The authors presented the general characteristics of recovery network by explaining the commonalities and processes in recovery networks and comparing them with traditional logistics networks. They classified the steps of activities in recovery networks to three parts: i) a convergent part, which is related to collection of used product from market to recovery facilities; ii) an intermediate part that is about necessary recovery steps; and iii) a divergent part that is concerned with distribution to a re-use market. They presented the supply uncertainty as the main difference between traditional logistic structure and recovery networks. In addition, they studied the network modeling and investigated the mixed integer linear programming (MILP) models in different papers.

Realff et al. (2000) investigated the concept of reverse production system (RPS) design and proposed a MILP model, which has the classical form of location-allocation. The objective of the problem is to minimize the maximum deviation of the performance of the network from its optimal value under different scenarios. The problem is to decide on the number and size of collection and processing sites, location of functions in reverse network, routing, mode of transportation, flow of materials to each potential end-use. The authors applied the model in carpet recycling logistics network case study in the United

States. They concluded that the robust approach described in Kouvelis and Ganf (1997) is suitable for the design of RPS.

Fleischmann (2001) studied the logistics network design for CLSCs by investigating different case studies. The author pointed out the management issues in designing and implementing reverse logistics network and indicated the similarities and differences between traditional forward supply chain and CLSC design. The research extends the classification of reverse logistics proposed in Fleischmann et al. (2000) by including two additional classes: driver for product recovery (economics versus legislation) and the owner of the recovery process (OEM versus third party).

Fleischmann et al. (2001) proposed a generic mathematical model for reverse logistics network design and analyzed the impact of product recovery on logistics networks. The developed formulation is a multi-echelon, single-product, uncapacitated facility location model for designing CLSC, considering cost minimization as the objective function. The considered recovery network structure consists of disassembly centers, reprocessing and new production facilities, and distribution warehouses. Two disposition options were considered in this problem: recovery and disposal. They also considered a penalty cost associated with unsatisfied demand and uncollected return. The demand and return are fixed and known. To evaluate the formulated model, they applied it in two case studies: copier remanufacturing and paper recycling. The results showed that, in many cases, implementing product recovery network does not require significant changes in the existing forward network. Moreover, it was found that the supply uncertainty has limited effect on the network design; therefore, deterministic modeling approach is appropriate for reverse logistics network design in most cases.

Krikke et al. (2001) developed a multi-objective MILP model for designing product and the corresponding CLSC. The model decides on the product design structure considering modularity, reparability, recyclability and the CLSC design, including facility location and flow allocation. The objective is to minimize the costs and environmental impacts measured by energy and waste. The paper applied the model in a real life case study by the data from a Japanese consumer electronics company. Finally, the paper compared centralized versus decentralized logistics networks and studied the comparisons of three alternative product designs with centralized logistics networks. Moreover, the paper performed sensitivity analysis to investigate the robustness of management solutions on varying return rate, recovery feasibility and recovery targets forced by legislation. They concluded that the important factors in CLSCs are product design and location-allocation, as well as recovery feasibility and rate of return. They pointed out that the supply chain structure affects costs, while the product design affects energy and waste.

Shih (2001) studied the reverse logistics network design for recycling electrical appliances and computers in Taiwan. The paper formulated a MILP model to optimize the design and flow of reverse logistics network. The objective function is the minimization of the total cost, which is calculated by subtracting the revenue from the sum of processing costs and fixed costs of opening facilities. The reverse logistics network studied in this paper consists of collecting points, storage sites, disassembly/ recycling plants, secondary material markets and disposal facilities. They concluded that increasing the return rate by 20% requires opening a new disassembly plant instead of disassembly plant expansion. Furthermore, a dramatic decrease in the number of storage sites is expected by sharing the facilities in recycling electrical appliances and computers.

De Brito et al. (2003) studied more than sixty case studies in the literature of reverse logistics. In this paper, the authors categorized the case studies under five headlines based on their decision making focus: reverse logistics network structure, reverse logistics network relationships, inventory management, and planning and control of recovery activities, information and technology for reverse logistics. They mentioned that the main driver of the North American case studies is economics; meanwhile in Europe legislation is also important. They suggested studying the impacts of drivers and industry categories on reverse logistics for further investigation.

Jayaraman et al. (2003) developed a MILP model and proposed a heuristic solution method for designing a reverse distribution problem. The authors studied a problem that starts from customer return. The customers will return the used products to the closest origination site. From origination sites, there are two possible transportation routes. The first way is to transport the return from the origin sites to the collection sites and then to the refurbishing sites. The second way, which is more expensive, is to send the return directly from origination sites to refurbishing sites. Given the fixed costs and maximum number of collection and refurbishing sites, the model will select the locations for establishing the collection and refurbishing facilities and the efficient way to transport the return from the origination sites to the collection sites. A heuristic solution methodology was proposed for solving the resulting NP-hard problem.

Listes and Dekker (2003) proposed a stochastic programming approach to extend the deterministic location model for recovery network design in a real case study regarding the recycling of sand. For the uncertainty in unprocessed sand supply, they considered two initial estimations for each supply source: high supply sand and low supply sand.

They solved the model with locational uncertainty of demand and additional supply uncertainty. For approaching the locational uncertainty of demand, the deterministic model is extended to a two-stage stochastic model. In the first stage, the model finds the optimal investment for opening facilities before knowing the random parameters. In the second stage, the model decides on the optimal flow allocation after the values of random parameters are known. In this problem, the net revenue is considered as the objective function. They concluded that the amount and quality of the incoming flow affects the number of newly opened facilities, and the sources and demand points influence the location of new facilities. Moreover, they concluded that, at high material volumes, the network configuration is more flexible regarding the demand locations and the stochastic solution shows small improvement in the objective function. They emphasized capacity as an important restrictive feature in this problem, especially in high supply volumes. At low material volumes, however, the network layout is more dependent on demand location and a balanced solution is suitable.

Salema et al. (2006) proposed a MILP model for a multi-product capacitated CLSC network. In this logistics network, the forward flow starts from factories to warehouses and then customers. The backward flow of return starts from customers to disassembly centers and then goes to either factories or disposal centers. The objective function of the problem is to minimize the total cost consists of opening, transportation, and penalization costs of unsatisfied demand and return. The model decides on unsatisfied amount of demand and return, flow, routing, as well as number and location of facilities. The authors applied the formulated model on two case studies and solved the problems using branch-and-bound method.

Lu and Bostel (2007) proposed a MILP model for designing the reverse logistics network in a CLSC. The reverse logistics network in this problem consists of producers, remanufacturing centers and intermediate centers and customers. For solving the problem, the authors proposed a Lagrangian heuristic approach. Finally, they applied the model and solution approach on classical test problems. They concluded that the reverse flow affect the location-allocation decisions. This influence may vary regarding the amount of reverse flow, their distribution at demand points and their correlation with forward flow.

Salema et al. (2007) formulated a MILP model for designing the CLSC network problem. The authors added three characteristic of real-life problems: multi-product production systems, capacitated facilities, and finally demand and return uncertainties. A scenario-based model, which considers the uncertainty in demand and return, was built. Three different scenarios, based on the demand and return rates, were considered for the previously presented example problem. The first scenario was based on the real data, the second scenario was for the most pessimistic situation, and the last scenario was related to the most optimistic one. The problem was solved for different scenarios using CPLEX and the results were compared to give an insight for decision makers, and to show the impacts of return and demand patterns on the network design.

Üster et al. (2007) proposed a MILP model for a multi-product CLSC network design problem applicable in remanufacturable and durable products context. The CLSC network in this problem consists of suppliers, distribution centers, retailers, collection centers and remanufacturing facilities. The problem considers established forward network. The objective function of the problem is to minimize the total cost, which includes processing, transportation, and fixed location costs. The problem is motivated by an original equipment manufacturer (OEM) that provides parts for vehicle repair in automotive industry. For solving the model, the paper proposes a Bender decomposition (BD) approach with alternative multiple cuts.

Aras and Asken (2008) formulated a mixed integer non-linear programming (MINLP) facility location-allocation model for reverse logistics network design problem. In this problem, the authors assumed a drop-off strategy for the reverse network, in which the customers travel to the collection centers for returning their used products. Therefore, the company offers financial incentives for collecting the used products from customers, which are defined based on the quality level of the return. Thus, the customers decide to return their used products based on their distance to the nearest collection center and the financial incentives offered. The model decides on the number and location of collecting facilities, the financial incentive offered by the company, routing, return amount and the customer zones who return their used products. The objective function of the problem is to maximize the profit from the returns. The paper proposed a nested heuristic method for solving the model. The proposed heuristics is based on tabu and Fibonacci search. The authors discussed three solving methods of using a commercial solver, performing exhaustive search, and applying the proposed heuristic approach to demonstrate the performance of the heuristic solution approach. The results showed that the heuristic approach is superior in terms of running time and solution quality. Finally, the paper applied the heuristic approach to study the effect of uniform incentive policy (UIP) for different quality types. It was concluded that UIP causes greater profit loss when the proportion of lowest quality return is higher.

Demirel and Gökçen (2008) formulated a MILP model for designing the reverse logistics network in a CSLC. The objective function of the model is to minimize the total cost, which is the sum of opening, processing and transportation costs. The authors applied the model on a real-life problem and considered three different scenarios of low, medium and high returns rate. They concluded that the companies should offer proper incentives for customers and retailers to increase the return amount.

Du and Evan (2008) developed a bi-objective MIPL for the design of reverse logistics network. The study explores the trade-offs regarding the two objectives: minimization of the total cost and the minimization of the overall tardiness of cycle time. The problem is to decide on establishing the repair facilities from a set of potential locations, to allocate required repair facilities between these locations and to arrange the flow between collection sites and facility sites. For solving the problem, they designed a solution procedure which consists of three algorithms: scatter search, the dual simplex method and the ε-constraint method. Moreover, the ε-constraint method was applied to find a set of non-dominating solutions for the problem. Finally, the authors performed computational analysis and presented that trade-off relationship between the objective functions. They concluded that the installation and transportation costs in the first objective function both involve in the trade-off with the second objective. They pointed out that the first objective function favors a centralized network structure, while the second objective function desires a decentralized network structure.

Min and Ko (2008) formulated a multi-period, multi-product MINLP model to design the reverse network in a CLSC. The network studied in this paper consists of OEMs, warehouses, repair facilities and customers. Mutha and Pokharel (2009) formulated a multi-product capacitated mathematical model for modularized product reverse logistic network design. They considered products made up of different modules. The logistics network in this problem consists of nine echelons including: retailers/collecting points, warehouses for storage and consolidation, reprocessing centers for inspection and dismantling , new module suppliers, remanufacturing factories, distribution centers, recycling centers, disposal sites and markets for remanufactured products and spare parts. The objective function is to minimize the total cost, which consists of transportation, inventory, disposal and assembly costs. The model should decide on total return quantity, return amount of each product and each module, ordering quantity of each module, the flow of each product and module through facilities. The authors concluded that transportation costs may not be important factors in network design. The costs of reprocessing, remanufacturing, and new modules can be an important factor in the design of reverse logistics network. Considering different return amounts and the cost of new modules found to be important factors in the network design.

Pati et al. (2008) formulated a multi-objective, multi-item, multi-echelon mixed integer goal programming (MIGP) model for designing reverse logistics system for paper recycling in India. Three objective functions have been considered for the problem including: 1) minimizing the total cost, 2) improving the products quality by increasing the separation at source, and 3) increasing the recovery amount for environmental benefits. To solve the problem, the authors partitioned and sorted the objective functions according to their priority levels. Then, they used the obtained solution of each priority level as a constraint at the lower level. The authors considered six possible priority structures of the objective functions to assist the decision makers to understand the impact of target value for each objective function on the solution and make the best decision.

El-Sayed et al. (2010) studied a multi-period, multi-echelon CLSC network design problem under risk, and formulated a stochastic mixed integer linear programming model for solving the problem. The logistics network studied in this problem consists of five echelons, including suppliers, facilities, distribution centers, disassembly centers, and redistribution centers, as well as first and second customer zones. In the first customer zones, the demand is stochastic and in the second customer zones, the demand can be either stochastic or deterministic. The objective of the model is to maximize the total expected profit. The model was applied on a numerical example, and it was concluded that the demand average and the return ratio directly affect the objective function. Moreover, the results showed that only integer number of batches can be shipped during a period, which restrict the application of the model.

Pishvaee et al. (2010) proposed a bi-objective MINLP model for CLSC design. The CLSC network studied in this problem consists of production/recovery, distribution, customer zones, collection/inspection, and disposal centers with multi-level capacities. The objective functions of the problem are minimizing the total cost, and maximizing the responsiveness of the logistics network. For solving the model, the authors proposed a multi-objective memetic algorithm with dynamic local search mechanism to find the set of non-dominating solutions.

2.5 Multi-Criteria Optimization

Many real-world optimization problems are confronted with multiple objectives at the same time. Since these objectives might be in conflict with each other, we cannot find a solution that simultaneously optimizes all the objectives. Therefore, we need to find the trade-off solutions. Multi-objective optimization (MOO) techniques are aimed to optimize all the objectives at the same time, which result in a set of non-dominating solutions. A set of non-dominating solutions, also known as Pareto front or Pareto optimal set, are the solutions that by improving one objective function value the other objective gets worse. Thus, the decision makers might be able to identify the optimal or desirable solution, based on their preference, between the obtained efficient solutions (Sawaragi et al., 1985).

According to Cohon (1978), MOO provides three major improvements over single-objective analysis: 1) considering many objectives will make the problem more realistic, 2) using a MOO methodology will result in several efficient solutions instead of a single solution. This will result in better evaluation of the problem and making a more balanced decision considering the important factors, and 3) having different objectives will eliminate the need for transforming the measurement units of different objectives so as to have only one unit of measurement.

The most commonly used approach for solving a MOO problem is scalarization. Ehrgott, (2006) explained scalarization as converting the multi-objective problem to a single-objective problem which depends on some additional parameters and then solving the single-objective problem considering different parameters values. As some of scalarization methods, we can refer to weighted sum, ε-constraint, and compromise programming methods.

The weighted sum method solves a multi-objective problem by assigning non-negative weight to each objective and combining them into one objective function. A set of non-dominating solutions are obtained by changing the set of weights and solving the single-objective problem over and over.

Besides the weighted sum method, another approach to solve a MOO problem is the ε-constraint method, proposed by Chankong and Haimes in 1983. The ε-constraint method optimizes the problem with one objective while considering the other objectives as constraints. A set of non-dominating solutions are then attained by changing the bounds of the constrained objectives.

Another scalarization method is the compromise programming. The idea is to find an approximation of the ideal point. When the objectives are in conflict with each other, the ideal point is not feasible. The idea of compromise programming is to find the solutions that minimize the distance to the ideal point (Ehrgott, 2006).

2.6 Conclusion

The literature review in this chapter covered the studies carried out on the reverse logistics design field. These problems range from simple single-product uncapacitated problems to complex capacitated multi-product problems. As the review of the literature shows, MILP is the most commonly used technique for forward, reverse and integrated supply chains design problems. Most of these models are aimed at maximization of the profit or minimization of the total cost in the system.

Because of the increasing importance of environmental impacts, this has recently been considered as an important additional objective for reverse logistics design problems. The available literature reveals that a few papers have suggested multi-objective models for design of reverse logistics systems; however, they did not considered environmental impacts in the objective function.

Most of the papers have only focused on simple used products (e.g. sand, paper, carpet), while a few have recognized the used products that consist of modules and parts requiring various recovery options. Consequently, almost all of the reviewed papers have considered limited number of recovery options (e.g., remanufacturing and disposal) and none has studied a complete CLSC network with all possible recovery options.

To date, only a few contributions have considered different quality levels for the returned products while designing the RSCs. Furthermore, none of these studies allocated various processing costs based on the quality of items.

In this thesis, we study a CLSC network design problem that considers both financial and environmental criteria as the objective functions. The returned items are also assumed to belong to different quality levels. We assume a multi-indenture structure for the returned products. Consequently, all possible recovery options, based on the module/ part type and its quality level, are required.

Next chapter provides the description of the problem investigated in this thesis, along with the problem formulation. The solution method is introduced at the end of chapter 3.

Chapter Three

Problem Description and Formulation

3.1 Introduction

In this chapter, we present the details of CLSC network design problem studied in this research. We will define the context that our formulated model can be applied, as well as the specific characteristics and structure of the CLSC network under discussion. Later on, we formulate the CLSC design as a MILP model. Finally, the solution methodology applied for solving the resulting bi-objective model is provided.

3.2 Problem Definition

In the section, we first present the details of the product features under investigation, as well as the corresponding CLSC characteristics.

3.2.1 Product Features

In this research, we focus on durable and remanufacturable products. Such products are featured for their long life cycle and high recoverable value, among which we can refer to cars, home appliance, consumer electronics, etc. These products are also assumed to have a multi-indenture structure that can be disassembled into several components, namely, modules, parts and materials. Consequently, different recovery options can be considered for each component type. More precisely, the products are dismantled to remove harmful and disposable substances and to separate reusable parts, remanufacturable modules, and recoverable residues and materials.

We also assume that the return is from two quality levels: poor/ high quality. The choice of recovery operations on different components of a product (i.e., remanufacturing, disposal, recycling, or bulk recycling), hence depends on the returned product quality level. For example, for high quality returned product, a higher percentage of the components are sent to remanufacturing and/or part harvesting. Meanwhile, for low quality returned product, the recycling percentage is greater. Also, the remanufacturing cost depends on the component quality level.

The structure of the product in addition to the recovery option for each component is depicted in figure 3-1. As it is shown in this figure, returned product will be dismantled in the disassembly facilities and their harmful components are sent to hazardous material safe disposal centers. Useful modules are remanufactured and marketable parts are cleaned to be sold in the spare part market. Residues (mixed material components) should be treated in bulk recycling facilities in order to separate their recoverable materials and disposable substances through crushing and separation operations (Spengler et al., 2003). Other materials, namely, metal, glass and plastic parts are sent to corresponding recycling facilities.

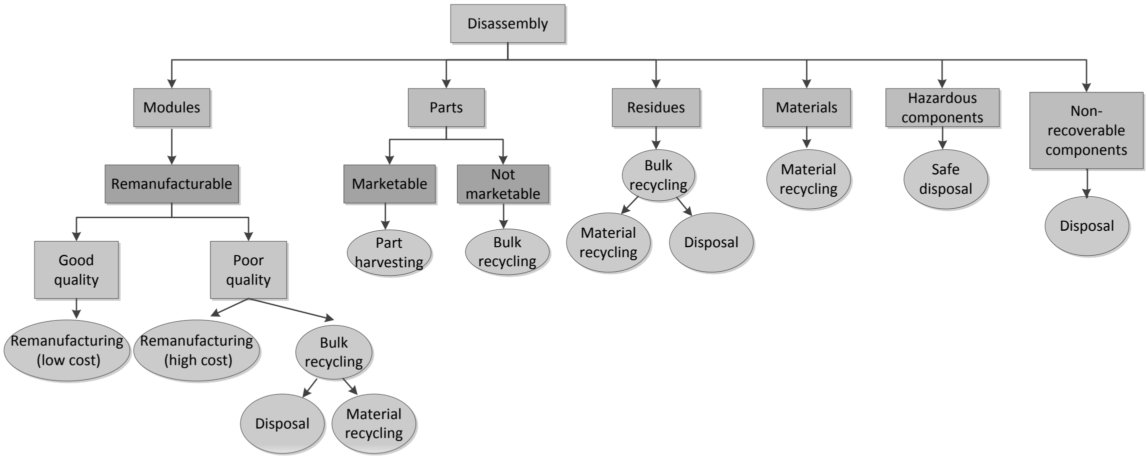

Figure 3- 1 Durable product disassembly tree

As figure 3-1 displays, modules, depending on the quality of the original returned product, will be sent either to remanufacturing or to bulk recycling operations. If both quality levels of a module are decided to be remanufactured, the remanufacturing cost will be different for each quality level. The non-remanufacturable components are separated as parts and residues. The marketable parts will be sent for part harvesting and later to the spare part market or OEM. The rest will be sent for bulk recycling, material recycling or disposal.

3.2.2 RSC Network Structure

Under the context described in previous sub-section, we are interested to design a RSC network that incorporates facility location, and flow routing decisions in this network. The structure of the supply chain network under discussion is depicted in figure 3-2. In this figure, the nodes correspond to the facilities and the arcs represent the flow. The flow starts from the suppliers, goes through the manufacturers, distribution centers and then customers. A fraction of products received by customers will be returned to the collection centers.

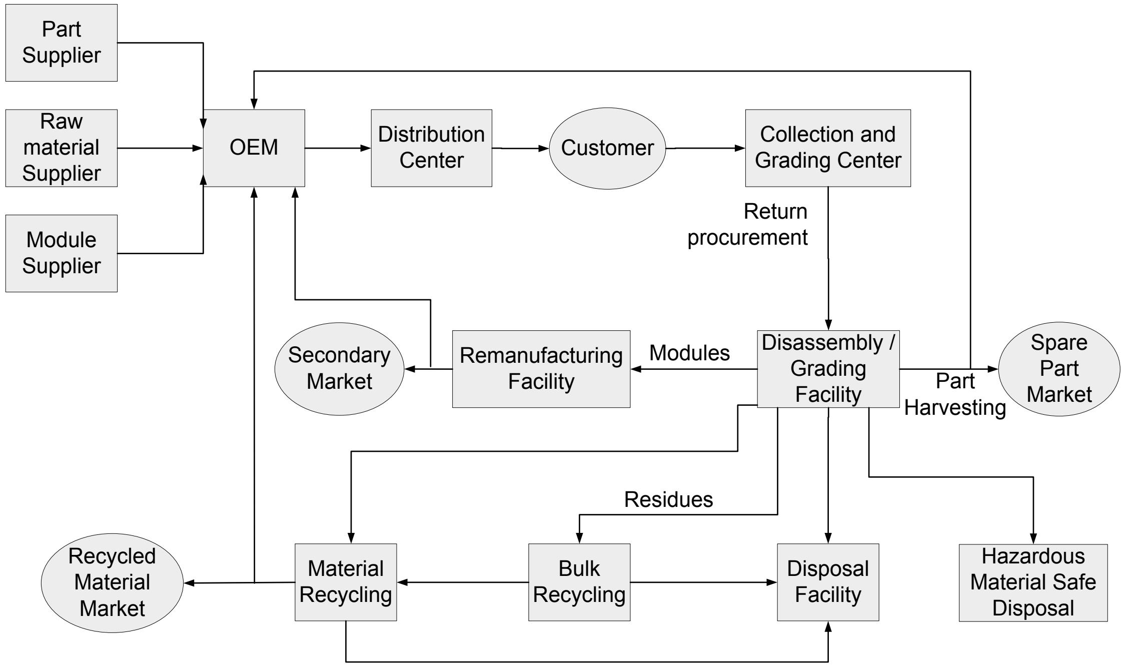

Figure 3- 2 CLSC network structure for durable products

The collection center is the center where all the used products are returned and divided into different quality groups. After classification, there is a procurement based on the returned products' prices associated with their quality group. Then, the procured returns will be sent to disassembly centers.

In the disassembly center, the returned products are dismantled in order to separate harmful substances, reusable parts, remanufacturable modules, recyclable materials, and residues based on the returned product quality level. Next, the components will be sent to different recovery/ disposal facilities, including: remanufacturing, part harvesting, bulk recycling, material recycling, disposal and hazardous disposal centers.

From disassembly centers, parts that can be used without major recovery will be sent to part harvesting facilities, where they are cleaned and then are sent to either the spare part market or to the OEM. Remanufacturable modules will be transported to remanufacturing centers. In remanufacturing facilities, extensive process of restoring used modules to “like-new” condition is performed. This process may involve disassembly, cleaning repairing, replacing parts, and reassembly. After remanufacturing they can be sold at the secondary market or can be used for production of new products at the OEM.

Recyclable residues (i.e. the components that are made up of mixed materials) will be sent to bulk recycling centers, where the components are separated to their consisting materials and they will be sent for either recycling or disposal, where the ratio of each component depends on the quality of returned product. Recyclable materials (e.g., metal, plastic, glass) will be transported to recycling centers. The recycled materials, then, will be sent to the recycled material market or the OEM for new products manufacturing. We have assumed that the recovered items will be offered with lower prices to the OEM comparing to the suppliers’ prices. We also consider a demand for these items in the secondary market. The demand values in all the markets are assumed to be deterministic.

In a disposal facility, the disposal activities such as landfilling and incineration are performed. Disposal is necessary for the components that cannot be economically recovered.

3.3 Problem Formulation

Given the number and location of suppliers, OEM and distribution centers, the goal of the RSC design problem is to determine the number, location and capacity level of the collection, disassembly, remanufacturing, material recycling, bulk recycling, disposal and hazardous disposal centers, as well as the forward and reverse flow in the network.

The logistics network design problems have been generally formulated as single-objective models in many researches, by considering only financial criteria. However, the recent concerns regarding the recovery of End-of- life (EOL) products, and the increasing need to meet the governmental targets on the recovery of EOL products has motivated us to study this problem in a multi-objective optimization (MOO) framework. To do this, in addition to profit maximization, we will consider the maximization of acquisition amount of returned products as the second objective function. Therefore, we will be able to investigate both financial and environmental aspects in order to find the best recovery network design.

3.4 Mathematical Formulation

Prior to provide the mathematical model proposed for the RSC design problem, we first summarize the model assumptions, followed by the notations.

3.4.1 Model Assumptions

1) We consider a single- period and single- product design problem.
2) Demands are deterministic, known and different for each item type. Return amount is a percentage of distributed products.
3) The number and location of markets are known as well.
4) The flow of items to each market is less than the demand at that market.
5) The forward network is already established and the model will select the backward facilities from a given set of potential locations. The reason lies behind the fact that

the majority of companies do not find it beneficial to redesign an established forward supply chain while adding the reverse flow to the network.

6) The model selects the capacity level of facilities from a given set of potential capacity levels which are defined regarding each facility and its location. The capacity levels for remanufacturing and material recycling centers are based on the type of module and material, respectively.
7) The capacity of supplier is also dependent on the type of part, module and material provided.
8) The recycled materials, remanufactured modules and separated parts are treated like new units and can be sent to the market or to the manufacturing plants as a second resource of supply. However, they are offered to markets at lower prices compared to the new items prices.
9) The fixed costs of establishing the new facilities are given considering their capacity level and type. A variable cost occurs in processing of each unit based on the type of process. For remanufacturing modules, the processing cost is also dependent on module type and its quality. For recycling materials, this cost is affected by the material type.
10) The transportation costs are based on the shipping amount and the distances between the facilities. Transportation costs of modules and parts are also dependent on the item type.

3.4.2 Mathematical Model

Before presenting the mathematical model, we define the notations that have been used throughout the model. The parameters are represented in appendix A.

Decision variables:

QC_{kc}^{q}	quantity of returned products with quality level q shipped from customer zone k to collection center c
QA_{ca}^{q}	quantity of returned products with quality level q shipped from collection center c to disassembly/ grading center a
NQA_{c}^{q}	quantity of returned products with quality level q not shipped from collection center c to disassembly/ grading center a
QS_{asp}	quantity of part p shipped from disassembly/ grading center a to spare market s
QZ_{aip}	quantity of part p shipped from disassembly/ grading center a to the OEM i
QD_{ad}	quantity of components shipped from disassembly/ grading center a to disposal center d
QO_{ao}	quantity of hazardous component shipped from disassembly/ grading center a to hazardous disposal center o
QG_{agr}	quantity of recoverable material r shipped from disassembly/ grading center a to material recycling center g
QE_{ger}	quantity of recycled material r shipped from recycling center g to recycled material market e
QU_{gir}	quantity of recycled material r shipped from material recycling center g to the OEM i
XD_{gdr}	quantity of material r shipped from material recycling center g to disposal center d
QB_{ab}	quantity of residues shipped from disassembly/ grading center a to bulk recycling center b
NG_{bgr}	quantity of recoverable material r shipped from bulk recycling center b to material recycling center g
ND_{bd}	quantity of components shipped from bulk recycling center b to disposal center d
QM_{aml}^{q}	quantity of module l with quality level q shipped from disassembly/ grading center a to remanufacturing center m
QW_{mwl}	quantity of module l shipped from remanufacturing center m to secondary market w

QX_{mil} quantity of module l shipped from remanufacturing center m to the OEM i

QI_{zip} quantity of part p shipped from part supplier z to the OEM i

NI_{uir} quantity of material r shipped from material supplier u to the OEM i

XI_{xil} quantity of modules l shipped from module supplier x to the OEM i

QJ_{ij} quantity of products shipped from the OEM i to distributor j

QK_{jk} quantity of products shipped from distributor j to customer zone k

$$YC_c^n = \begin{cases} 1 & \text{if a collection center with capacity level } n \text{ is opened at location } c \\ 0 & \text{otherwise} \end{cases}$$

$$YA_a^n = \begin{cases} 1 & \text{if a disassembly center with capacity level } n \text{ is opened at location } a \\ 0 & \text{otherwise} \end{cases}$$

$$YO_o^n = \begin{cases} 1 & \text{if a hazardous disposal center with capacity level } n \text{ is opened at location } o \\ 0 & \text{otherwise} \end{cases}$$

$$YD_d^n = \begin{cases} 1 & \text{if a disposal center with capacity level } n \text{ is opened at location } d \\ 0 & \text{otherwise} \end{cases}$$

$$YB_b^n = \begin{cases} 1 & \text{if a bulk recycling center with capacity level } n \text{ is opened at location } b \\ 0 & \text{otherwise} \end{cases}$$

$$YG_g^n = \begin{cases} 1 & \text{if a recycling center with capacity level } n \text{ is opened at location } g \\ 0 & \text{otherwise} \end{cases}$$

$$YM_m^n = \begin{cases} 1 & \text{if a remanufacturing center with capacity level } n \text{ is opened at location } m \\ 0 & \text{otherwise} \end{cases}$$

Objective Functions:

In this study, we have considered two objectives for our model. The first objective is related to the financial concerns of the company (i.e., maximizing the profit). The other objective considers the environmental and governmental targets and regulations regarding the amount of recovery. The formulations of these two objectives are as follows:

1) The first objective function of the model is to maximize the profit.

   Maximize Z_1 = Total Revenue – Total Cost

Total Revenue = Products sale + Spare parts sale + Recycled materials sale + Remanufactured modules sale, where:

Products sale:

$$\sum_{j\in J}\sum_{\mathrm{k}\in K} QK_{jk}Pk \tag{3.1}$$

Spare parts sale:

$$\sum_{\mathrm{a}\in A}\sum_{s\in S}\sum_{p\in P} QS_{asp}Ps_{p} \tag{3.3}$$

Recycled materials sale:

$$\sum_{\mathrm{g}\in G}\sum_{\mathrm{e}\in E}\sum_{r\in R} QE_{ger}Pe_{r} \tag{3.3}$$

Remanufactured modules sale:

$$\sum_{\mathrm{m}\in M}\sum_{\mathrm{w}\in W}\sum_{l\in L} QW_{mwl}Pw_{l} \tag{3.4}$$

The total cost = Fixed cost + Procurement cost + Processing, transportation and handling costs

The total fixed cost consists of the fixed costs for opening collection, disassembly, disposal, hazardous disposal, material recycling, bulk recycling, and remanufacturing centers which is calculated as follows:

$$\sum_{c\in C}\sum_{n\in N} fc_{c}^{n}YC_{c}^{n} + \sum_{a\in A}\sum_{n\in N} fa_{a}^{n}YA_{a}^{n} + \sum_{d\in D}\sum_{n\in N} fd_{d}^{n}YD_{d}^{n} + \sum_{o\in O}\sum_{n\in N} fo_{o}^{n}YO_{o}^{n} + \sum_{g\in G}\sum_{n\in N} fg_{g}^{n}YG_{g}^{n} \tag{3.5}$$

$$+\sum_{b\in B}\sum_{n\in N} fb_{b}^{n}YB_{b}^{n} + \sum_{m\in M}\sum_{n\in N} fm_{m}^{n}YM_{m}^{n}$$

The procurement cost encompasses the total costs incurred in providing the resources from the suppliers and purchasing the return and is calculated as follows:

$$\sum_{z\in Z}\sum_{i\in I}\sum_{p\in P}QI_{zip}cz_{zp}+\sum_{u\in U}\sum_{i\in I}\sum_{r\in R}NI_{uir}cu_{ur}+\sum_{x\in X}\sum_{i\in I}\sum_{l\in L}XI_{xil}cx_{xl}+\sum_{c\in C}\sum_{a\in A}\sum_{q\in Q}QA_{ca}^{q}Pr^{q} \tag{3.6}$$

The processing, transportation and handling costs represent the costs incurred in processing and transportation of each unit of item and are calculated as follows:

Production cost:

$$\sum_{i\in I}\sum_{j\in J}QJ_{ij}ci_{i} \tag{3.7}$$

Distribution cost:

$$\sum_{j\in J}\sum_{k\in K}QK_{jk}cj_{j} \tag{3.8}$$

Collection cost:

$$\sum_{k\in K}\sum_{c\in C}QC_{kc}^{q}cc_{c} \tag{3.9}$$

Disassembly cost:

$$\sum_{c\in C}\sum_{a\in A}QA_{ca}^{q}ca_{a} \tag{3.10}$$

Hazardous material safe disposal cost:

$$\sum_{a\in A}\sum_{o\in O}QO_{ao}co_{o} \tag{3.11}$$

Disposal cost:

$$\sum_{a\in A}\sum_{d\in D}QD_{ad}cd_{d}+\sum_{b\in B}\sum_{d\in D}ND_{bd}cd_{d}+\sum_{g\in G}\sum_{d\in D}XD_{gdr}cd_{d} \tag{3.12}$$

Bulk recycling cost:

$$\sum_{a\in A}\sum_{b\in B}QB_{ab}cb_{b} \tag{3.13}$$

Recycling cost:

$$\sum_{a\in A}\sum_{g\in G}\sum_{r\in R}QG_{agr}cg_{gr}+\sum_{b\in B}\sum_{g\in G}\sum_{r\in R}NG_{bgr}cg_{gr} \tag{3.14}$$

Remanufacturing cost:

$$\sum_{a\in A}\sum_{m\in M}\sum_{l\in L}\sum_{q\in Q} QM^{q}_{aml} cm^{q}_{ml} \tag{3.15}$$

Transportation cost:

$$\sum_{z\in Z}\sum_{i\in I}\sum_{p\in P} QI_{zip} ti^{p}_{zi} + \sum_{u\in U}\sum_{i\in I}\sum_{r\in R} NI_{uir} ri_{ui} + \sum_{x\in X}\sum_{i\in I}\sum_{l\in L} XI_{xil} si^{l}_{xi} \tag{3.16}$$

$$+\sum_{i\in I}\sum_{j\in J} QJ_{ij} tj_{ij} + \sum_{j\in J}\sum_{k\in K} QK_{jk} tk_{jk} + \sum_{k\in K}\sum_{c\in C} QC^{q}_{kc} tc_{kc}$$

$$+\sum_{c\in C}\sum_{a\in A} QA^{q}_{ca} ta_{ca} + \sum_{a\in A}\sum_{s\in S}\sum_{p\in P} QS_{asp} ts^{p}_{as} + \sum_{a\in A}\sum_{o\in O} QO_{ao} to_{ao}$$

$$+\sum_{a\in A}\sum_{dvD} QD_{ad} td_{ad} + \sum_{a\in A}\sum_{g\in G}\sum_{r\in R} QG_{agr} tg_{ag} + \sum_{a\in A}\sum_{b\in B} QB_{ab} tb_{ab}$$

$$+\sum_{a\in A}\sum_{m\in M}\sum_{l\in L}\sum_{q\in Q} QM^{q}_{aml} tm^{l}_{am} + \sum_{a\in A}\sum_{i\in I}\sum_{p\in P} QZ_{aip} tz^{p}_{ai} + \sum_{m\in M}\sum_{w\in W}\sum_{l\in L} QW_{mwl} tw^{l}_{mw}$$

$$+\sum_{m\in M}\sum_{i\in I}\sum_{l\in L} QX_{mil} tx^{l}_{mi} + \sum_{b\in B}\sum_{d\in D} ND_{bd} rd_{bd} + \sum_{b\in B}\sum_{g\in G}\sum_{r\in R} NG_{bgr} rg_{bg}$$

$$+\sum_{g\in G}\sum_{d\in D} XD_{gd} sd_{gd} + \sum_{g\in G}\sum_{e\in E}\sum_{r\in R} QE_{ger} te_{ge} + \sum_{g\in G}\sum_{i\in I}\sum_{r\in R} QU_{gir} tu_{gi}$$

2) The second objective function of the model is to maximize the return acquisition.

$$\text{Maximize } Z_2 = \sum_{c\in C}\sum_{a\in A}\sum_{q\in Q} QA^{q}_{ca} \tag{3.17}$$

Constraints:

<u>Flow balance constraints:</u>

OEM centers:

$$\sum_{z\in Z} QI_{zip} + \sum_{a\in A} QZ_{aip} = \phi_p \sum_{j\in J} QJ_{ij}, \qquad \forall \mathrm{i} \in I,\ \forall p \in P \tag{3.18}$$

$$\sum_{u\in U} NI_{uir} + \sum_{g\in G} QU_{gir} = \mu_r \sum_{j\in J} QJ_{ij}, \qquad \forall i \in I,\ \forall r \in R \tag{3.19}$$

$$\sum_{x\in X} XI_{xil} + \sum_{m\in M} QX_{mil} = \omega_l \sum_{j\in J} QJ_{ij}, \qquad \forall i \in I,\ \forall l \in L \tag{3.20}$$

The above constraints ensure that the sum of flow entering to each OEM, from suppliers and reverse network is equal to the sum of the exiting flow from the OEM to all distribution centers. The first equation formulates the flow of parts from part suppliers and part harvesting centers to the OEM. The second equation corresponds to materials and the last one corresponds to the flow of modules. The coefficients in the right sides of equations (i.e., ϕ_p, μ_r, ω_l) show the quantity of each part, material and module in each product. The constraints also ensure that each product gets enough number of parts, materials and modules.

Distributor centers:

$$\sum_{i\in I} QJ_{ij} = \sum_{k\in K} QK_{jk}, \qquad \forall j \in J \tag{3.21}$$

This constraint ensures that the sum of the flow entering to each distribution center is equal to the sum of the exiting flow to all customers.

Product demand:

$$\sum_{j\in J} QK_{jk} \le d_k, \qquad \forall k \in K \tag{3.22}$$

This constraint ensures that the sum of the flow entering to each customer zone does not exceed the sum of the demand in that zone.

Return:

$$\sum_{c\in C} QC^q_{kc} = £^q \sum_{j\in J} QK_{jk}, \qquad \forall k \in K,\ \forall q \in Q \tag{3.23}$$

This constraint ensures that the sum of flow exiting from each customer zone to all collection centers is a ratio of the sum of the entering flow to each customer zone. The return ratio is defined based on the return quality level.

Collection and procurement centers:

$$\sum_{a\in A} QA_{ca}^{q} + NQA_{c}^{q} = \sum_{k\in K} QC_{kc}^{q}, \qquad \forall c \in C, \forall q \in Q \tag{3.24}$$

This constraint ensures that the sum of the flow exiting from each collection center is equal to the sum of flow entering to each collection center. The flow from collection centers might be sent to disassembly centers for recovery or to disposal centers. The term $\sum_{a\in A} QA_{ca}^{q}$ represents the amount of returned product that will be sent to disassembly centers.

Disassembly to part harvesting centers:

$$\sum_{c\in C}\sum_{q\in Q} QA_{ca}^{q}\gamma_{p}^{q} = \sum_{i\in I} QZ_{aip} + \sum_{s\in S} QS_{asp}, \qquad \forall a \in A,\ \forall p \in P \tag{3.25}$$

This constraint ensures that the sum of flow exiting from the disassembly facilities to all the OEMs and spare part markets is equal to the entering flow to each disassembly center from all collection centers multiplied by the number of each part type in the returned product. The quantity of each part in the returned product (γ_{p}^{q}) is different depending on the returned product quality level.

Parts demand:

$$\sum_{a\in A} QS_{asp} \le ds_{sp}, \qquad \forall s \in S,\ \forall p \in P \tag{3.26}$$

This constraint ensures that the sum of the flow entering to each spare part market from all disassembly centers does not exceed the demand.

Disassembly to hazardous material safe disposal centers:

$$\sum_{c\in C}\sum_{q\in Q} QA_{ca}^{q}\rho^{q} = \sum_{o\in O} QO_{ao}, \qquad \forall a \in A \tag{3.27}$$

This constraint ensures that the sum of flow exiting from disassembly centers to all hazardous material safe disposal centers is equal to the flow entering to each disassembly facility from all collection centers, multiplied by hazardous mass coefficient. The hazardous mass coefficient (ρ^{q}) is defined based on the returned product quality level.

Disassembly to disposal centers:

$$\sum_{c\in C}\sum_{q\in Q} QA_{ca}^{q}\sigma^{q} = \sum_{d\in D} QD_{ad}, \qquad \forall a \in A \tag{3.28}$$

This constraint ensures that the flow exiting from disassembly centers to all disposal centers is equal to the entering flow to each disassembly center from all collection centers, multiplied by non-recoverable mass coefficient. The non-recoverable mass coefficient (σ^{q}) is different for various returned product quality level.

Disassembly to recycling centers:

$$\sum_{c\in C}\sum_{q\in Q} QA_{ca}^{q}\alpha_{r}^{q} = \sum_{g\in G} QG_{agr}, \qquad \forall a \in A,\ \forall r \in R \tag{3.29}$$

This constraint ensures that the flow exiting from disassembly centers to all recycling centers is equal to the entering flow to each disassembly center from all collection centers, multiplied by recyclable mass coefficient. The recyclable mass coefficient (α_{r}^{q}) is a value that shows the amount of each recyclable material in the returned product with quality level q. This ratio is defined based on the returned product quality level.

Disassembly to bulk recycling centers:

$$\sum_{c\in C}\sum_{q\in Q} QA_{ca}^{q}\beta^{q} = \sum_{b\in B} QB_{ab}, \qquad \forall a \in A \tag{3.30}$$

This constraint ensures that the flow exiting from disassembly centers to all bulk recycling centers is equal to the entering flow to each disassembly center from all collection centers, multiplied by the recyclable residue ratio (β^q). The recyclable residue ratio for each product is dependent on the product quality level.

Disassembly to remanufacturing centers:

$$\sum_{c \in C} QA_{ca}^q \delta_l^q = \sum_{m \in M} QM_{aml}^q, \qquad \forall a \in A, \forall l \in L, \forall q \in Q \tag{3.31}$$

This constraint ensures that the flow exiting from disassembly center to all remanufacturing centers is equal to the entering flow to each disassembly location from all collection centers, multiplied by the quantity of each remanufacturable module in the product (δ_l^q). The quantity of each remanufacturable module is defined based on the module type and its quality level.

$$\sum_{a \in A} \sum_{q \in Q} QM_{aml}^q = \sum_{w \in W} QW_{mwl} + \sum_{i \in I} QX_{mil}, \qquad \forall m \in M, \forall l \in L \tag{3.32}$$

This constraint ensures that the flow of each module type from a remanufacturing center to all secondary markets and OEMs is equal to the flow of that module with all possible quality levels entering to that remanufacturing center.

Modules demand:

$$\sum_{m \in M} QW_{mwl} \le dw_{wl}, \qquad \forall w \in W, \forall l \in L \tag{3.33}$$

This constraint ensures that the sum of the flow entering to each secondary market from all remanufacturing centers does not exceed the demand.

Bulk recycling to recycling centers:

$$\sum_{a \in A} QB_{ab} \eta_r = \sum_{g \in G} NG_{bgr}, \qquad \forall b \in B, \ \forall r \in R \tag{3.34}$$

This constraint ensures that the flow of material r exiting from bulk recycling centers to all recycling centers is equal to the entering amount of residues to each bulk recycling center from all disassembly centers, multiplied by recyclable material ratio (η_r) of residues. The recyclable material ratio in this constraint represents the mass of each material type in the residues sent to bulk recycling.

Bulk recycling centers:

$$\sum_{a \in A} QB_{ab} = \sum_{d \in D} ND_{bd} + \sum_{g \in G} \sum_{r \in R} NG_{bgr}, \qquad \forall b \in B \tag{3.35}$$

This constraint ensures that the sum of the flow entering to each bulk recycling center is equal to the sum of the exiting flow to disposal and recycling centers.

Recycling to disposal centers:

$$(\sum_{a \in A} QG_{agr} + \sum_{b \in B} NG_{bgr})\tau_r = \sum_{d \in D} XD_{gd}, \qquad \forall g \in G, \forall r \in R \tag{3.36}$$

This constraint ensures that the flow exiting from recycling centers to all disposal centers is equal to the entering flow to each recycling center from all disassembly centers, multiplied by non-recoverable material ratio (τ_r). The non-recoverable material ratio of materials in this constraint represents the mass of each material type that needs to be disposed of.

Materials demand:

$$\sum_{g \in G} QE_{ger} \leq de_{er}, \qquad \forall e \in E, \ \forall r \in R \tag{3.37}$$

This constraint ensures that the sum of the flow entering to each recycled material market from all recycling centers does not exceed the demand.

Recycling centers:

$$\sum_{a\in A} QG_{agr} + \sum_{b\in B} NG_{bgr} = \sum_{d\in D} XD_{gdr} + \sum_{e\in E} QE_{ger} + \sum_{i\in I} QU_{gir}, \qquad \forall g \in G, \forall r \in R \tag{3.38}$$

This constraint ensures that the sum of the flow entering to each recycling center is equal to the sum of the exiting flow to the disposal centers, recycled material markets and OEMs.

<u>Capacity Constraints:</u>

Suppliers' capacity:

$$\sum_{i\in I} QI_{zip} \leq caz_{zp}, \qquad \forall z \in Z,\ \forall p \in P \tag{3.39}$$

$$\sum_{i\in I} NI_{uir} \leq cau_{ur}, \qquad \forall u \in U,\ \forall r \in R \tag{3.40}$$

$$\sum_{i\in I} XI_{xil} \leq cax_{xl}, \qquad \forall x \in X,\ \forall l \in L \tag{3.41}$$

The above constraints ensure that the sum of flow exiting from each supplier to all the OEMs does not exceed the supplier's capacity.

OEMs' capacity:

$$\sum_{j\in J} QJ_{ij} \leq cai_{i}, \qquad \forall i \in I \tag{3.42}$$

This constraint ensures that the sum of flow exiting from each OEM to all distribution centers does not exceed that capacity.

Distribution centers' capacity:

$$\sum_{i\in I} QJ_{ij} \leq caj_{j}, \qquad \forall j \in J \tag{3.43}$$

This constraint ensures that the sum of flow entering to each distributor from the OEMs does not exceed that center's capacity.

Collection centers' capacity:

$$\sum_{k\in K} QC_{kc}^{q} \le \sum_{n\in N} cac_{c}^{n} YC_{c}^{n}, \qquad \forall c \in C \tag{3.44}$$

This constraint ensures that the sum of flow entering to each collection center from all the customer zones does not exceed that center's capacity.

Disassembly centers' capacity:

$$\sum_{c\in C} QA_{ca}^{q} \le \sum_{n\in N} caa_{a}^{n} YA_{a}^{n}, \qquad \forall a \in A \tag{3.45}$$

This constraint ensures that the sum of flow entering to each disassembly center from the collection centers does not exceed the disassembly center's capacity.

Hazardous material safe disposal centers' capacity:

$$\sum_{a\in A} QO_{ao} \le \sum_{n\in N} cao_{o}^{n} YO_{o}^{n}, \qquad \forall o \in O \tag{3.46}$$

This constraint ensures that the sum of flow entering to each hazardous material safe disposal center from the disassembly centers does not exceed that center's capacity.

Disposal center's capacity:

$$\sum_{a\in A} QD_{ad} + \sum_{b\in B} ND_{bd} + \sum_{g\in G}\sum_{r\in R} XD_{gdr} \le \sum_{n\in N} cad_{d}^{n} YD_{d}^{n}, \qquad \forall d \in D \tag{3.47}$$

This constraint ensures that the sum of flow entering to each disposal center from the disassembly, material recycling and bulk recycling centers does not exceed the disposal center's capacity.

Recycling centers' capacity:

$$\sum_{a\in A} QG_{agr} + \sum_{b\in B} NG_{bgr} \le \sum_{n\in N} cag_{gr}^{n} YG_{g}^{n}, \qquad \forall g \in G,\ \forall r \in R \tag{3.48}$$

This constraint ensures that the sum of flow entering to each recycling center from the disassembly and bulk recycling centers does not exceed the recycling center's capacity.

Bulk recycling centers' capacity:

$$\sum_{a\in A} QB_{ab} \le \sum_{n\in N} cab_b^n YB_b^n, \qquad \forall b \in B \tag{3.49}$$

This constraint ensures that the sum of flow entering to each bulk recycling center from the disassembly centers does not exceed the recycling center capacity.

Remanufacturing centers' capacity:

$$\sum_{a\in A} QM_{aml}^q \le \sum_{n\in N} cam_{ml}^{nq} YM_m^n, \qquad \forall m \in M,\ \forall l \in L,\ \forall q \in Q \tag{3.50}$$

This constraint ensures that the sum of flow entering to each remanufacturing center from the disassembly centers does not exceed the remanufacturing center's capacity.

It is worth mentioning that constraints (3.39)-(3.50) also ensure that a flow can be shipped between two locations, if facilities are built on those locations.

Capacity level:

$$\sum_{n\in N} YC_c^n \le 1, \qquad \forall c \in C \tag{3.51}$$

$$\sum_{n\in N} YA_a^n \le 1 \qquad \forall a \in A \tag{3.52}$$

$$\sum_{n\in N} YO_o^n \le 1 \qquad \forall o \in O \tag{3.53}$$

$$\sum_{n\in N} YD_d^n \le 1 \qquad \forall d \in D \tag{3.54}$$

$$\sum_{n\in N} YB_b^n \le 1 \qquad \forall b \in B \tag{3.55}$$

$$\sum_{n\in N} YG_g^n \le 1 \qquad \forall g \in G \tag{3.56}$$

$$\sum_{n\in N} YM_m^n \le 1 \qquad \forall m \in M \tag{3.57}$$

The above constraints ensure that only one capacity level can be assigned to each facility.

3.5 Solution Methodology

In this research, we applied the ε- constraint method to solve the bi-objective CLSC design problem. The applied ε- constraint method in this study is similar to the method discussed in (Du and Evans, 2008). The steps for solving a bi-objective problem based on ε-constraint are as follows: Given a maximization bi-objective problem:

Maximize $\{Z_1(X), Z_2(X)\}$

$s.t.\ X \in F_d$

, where F_d is feasible region.

Step (1): Construct a payoff table:

a. Solve the optimization model for each of the objective functions separately, while removing the other objective function. Let X^1 and X^2 denote the optimal solutions for the first and second objective functions, respectively. Then, $Z_1^*(X^1)$ and $Z_2(X^1)$ denote the values of first and second objective functions associated with the solution X^1, respectively; $Z_1(X^2)$ and $Z_2^*(X^2)$ denote the value of first and second objective functions relate to the solution X^2, respectively.

b. Construct a payoff table as it is shown in table 3-1.

Table 3- 1 Payoff table

	$Z_1(X)$	$Z_2(X)$
X^1	$Z_1^*(X^1)$	$Z_2(X^1)$
X^2	$Z_1(X^2)$	$Z_2^*(X^2)$

Step (2): Convert the bi-objective model to its corresponding constrained model as follows:

Maximize $\{Z_1(X)\}$

$$s.t.\ X \in F_d$$

$$Z_2(X) \geq L_l$$

In this single-objective model, the first objective is considered for maximization and the second objective is decided to be a constraint. The feasible region F_d is the same as the primary problem and L_l is the lower bound for $Z_2(X)$.

<u>Step (3):</u> The candidate non-dominated solutions will be generated by arbitrarily choosing a value for γ in the formula below:

$$Z_2^*(X^2) - [h/(\gamma - 1)]\ [Z_2^*(X^2) - Z_2(X^1)],$$

where $h = 0, 1, 2, \ldots, (\gamma - 1)$.

The formula shows that the lower bound value L_l for the added constraint starts from the optimal value of the second objective function. Then, by gradually decreasing the L_l, the set of candidate non-dominated solutions will be generated. The non-dominated solutions show the relation between the two objective functions. They demonstrate that how decreasing one objective function affects the value of the other objective function. It should be noted that larger γ will result in more candidate solutions.

Step (4): Solve the constrained single-objective problem by different L_l considering a value for γ. As a result, a set of candidate solutions will be generated. Finally, from the candidate solutions generated, a set of non-dominated solution will be selected.

The curve in figure 3-3 represents a set of non-dominating solutions for the bi-objective minimization problem. The points on the curve represent different solutions. Two extreme points of the curve show two optimal solutions for the two objective functions, respectively. Different solutions lead to change in the value of objective functions.

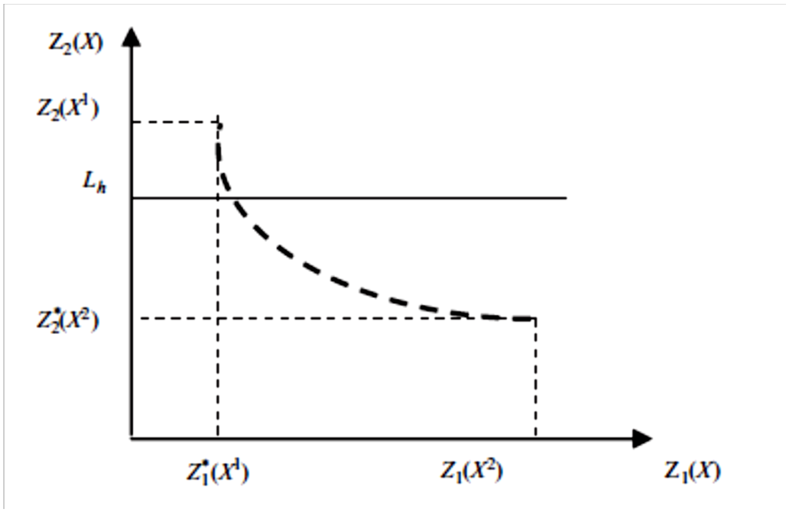

Figure 3- 3 The illustration of the ε-constraint method [adopted from Du and Evans, 2008]

Chapter Four

Experimental Results and Analysis

4.1 Introduction

In this chapter, we use a case study to examine and explain the formulated model proposed in chapter 3. The presented case study is hypothetical with modified realistic data and assumptions extracted from Canada's market and current literature (Park et al. (2006) and Sibel et al. (2012)). It is worth mentioning that the considered case study is only for validating the model. All of the coefficient and quality ratios are flexible and can be selected based on the specific product and industry. The number of parameters considered in this model is noticeably great comparing to other literature in this field. Therefore, there were huge effort and careful investigation for gathering data. As mentioned in previous chapter, we have considered two objectives: maximization of profit and return acquisition amount. In this chapter, we solve two problems considering each objective and one including both objectives. The problem is solved by CPLEX 12.3 on a PC platform with 2.80 GHz and 4 GB RAM. Furthermore, we analyze the results and perform sensitivity analysis for the single-objective problems by Minitab 16.1.1. Finally, the results of the ε-constraint method on the bi-objective model are analyzed.

4.2 Case Study

To validate the model introduced in previous chapter, we have applied our model on a supply chain corresponding to the manufacturing of washing machines. The washing machine, considered in our case study, consists of two modules, ten parts and three types of materials. Table 4-1 displays the separable components of a returned washing machine. We have used the data from Canada's market and current literate: Park et al. (2006) and Sibel et al. (2012).

Table 4- 1 Separable components of a returned washing machines

Number of part p in each unit of product	Washing tube (PP): 1, cover (ABS): 1, balance (PP): 1, frame (steel): 1, hose: 1, small electric parts: 1, condenser: 1, electric wire: 1, transformer: 1, PCB board: 1
Mass of material r in each unit of product	5.5 kg plastics, 1.6 kg steel, 0 kg copper
Number of module l in each unit of product	Motor:1 , clutch: 1

In the case study, we assume that the forward chain is already established in one city. As for establishing the backward chain, the company aims to decide on five potential locations, each with two possible capacity levels. The products are sold in three different cities with known demand. A fraction of distributed products will be collected as the return flow in the collection centers. The returned stream consists of two quality levels (high/ low), based on which the acquisition prices differ. Next, the returned items of different quality levels are procured and sent to the disassembly centers. In the disassembly centers, the returned product will be dismantled to its remanufacturable modules, spare parts, recyclable materials, residues, non-recoverable parts, and hazardous materials based on the product quality. In the high quality returned products, the modules can become reusable through remanufacturing process. However, the low quality returned products are mostly used for recycling purposes and fewer components can be reused. From disassembly centers, the separated parts can be sold in the spare parts markets or can be sent to the OEMs. The residues will be sent to the bulk recycling centers and then to the recycling and disposal centers. The recyclable materials are sent to recycling centers. Finally, the remanufacturable modules will be transported to remanufacturing centers and then are shipped either to the secondary markets or to the OEM. We considered the demand in all markets to be deterministic and different based on the items' types. The recovered components are assumed to be offered with lower prices comparing to the suppliers' prices. Table 4-2 and 4-3 shows the disassembly ratios, as well as the ratio of high and low quality return. The rest of data are presented in the appendix B. The shipping costs are considered to be U [8, 10] for each unit of product and U [4, 6] for each unit of components.

Table 4- 2 Case study data (return disassembly ratios)

Parameters	High Quality	Low Quality
Mass (kg) of residues in returned product with quality level *q* that will be sent to bulk recycling centers from disassembly centers	2.8	3.8
Number of module *l* in returned product with quality level *q* that will be sent to the manufacturing centers from disassembly centers	L_1=1, L_2=1	L_1=1, L_2=1
Number of part *p* in returned product with quality level *q* that can be sent to the spare markets or OEM from disassembly centers	P_1=1, P_2=1, P_3=1, P_4=1, P_5=1	P_4=1

Table 4- 3 Case study data (returned products ratios)

Parameters	High Quality	Low Quality
Percentage of return products with quality level *q* in total return	30%	70%
Ratio of return products with quality level *q* in distributed product	0.11	0.24

4.3 Experimental Results

In this section, we represent the experimental details of our case study and the results.

4.3.1 Experimental Details

The bi-objective CLSC design model has been coded by OPL and solved by CPLEX 12.3. The data is linked to CPLEX using Microsoft Access. Finally, we have performed sensitivity analysis on the results by performing factorial design using Minitab 16.1.1. The size of the case study is presented in table 4- 4.

Table 4- 4 Size of the case study

Number of constraints	418
Number of variables	1241
Number of binary variables	105

4.3.2 Results for ε-Constraint Method

As previously explained, first we solve two single-objective problems considering each of profit maximization and return acquisition amount maximization objectives. Then, we solve the bi-objective problem using the ε-constraint methodology. The detailed procedure for solving the bi-objective model is given as follows:

Step (1): Construct a payoff table as explained in chapter 3. The payoff table for our example problem is given in table 4-5. The $Z_1(X)$ objective function represents the profit, and $Z_2(X)$ represents the total return acquisition.

Table 4- 5 Payoff table for case study

	$Z_1(X)$	$Z_2(X)$
X^1	85,119,488	332,790
X^2	-70,309,081	750,000

A systematic way for finding ranges for the objective functions in the non-dominated set is provided by the payoff table as follows:

$-70{,}309{,}081 \leq Z_1(X) \leq 85{,}119{,}488$

$332{,}790 \leq Z_2(X) \leq 750{,}000$

Step (2): Convert the bi-objective problem to its corresponding constrained single-objective problem as follows:

$$\text{Maximize } \{Z_1(X)\}$$

$$s.t.\ X \in F_d$$

$$Z_2(X) \geq L_l$$

The first objective, maximization of profit, is chosen as the objective function for our single-objective model. The second objective, total return acquisition, is modeled as the constraint. The maximum of L_l is 750,000 and the minimum is 332,790.

Step (3): Generate a set of non-dominating solution by arbitrarily choosing the value of γ in the formula below:

$$L_l = Z_2^*(X^2) - [h/(\gamma - 1)]\,[Z_2^*(X^2) - Z_2(X^1)],$$

where $h = 0, 1, 2, \ldots, (\gamma - 1)$.

We set $\gamma = 20$ while solving our problem.

Step (4): Solve the single-objective model for 19 combinations of L_l. Each of the feasible candidate solution is a non-dominating solution for our bi-objective problem.

4.3.3 Numerical Results

The feasible non-dominating solutions and their trade-offs for our case study are presented in table 4-6. The table presents the two objective values and the solutions for the facility configuration.

There are several points that need more attention in table 4-6. First, the profit reaches its maximum when the total acquisition is 44% of the possible amount, which is the lowest amount among all the solutions. This happens since establishing the backward chain and also recovery processes are cost consuming. Therefore, the company is not willing to use all of the potential recovery capacities due to the financial aspects. Second, as expected, the number and capacity level of the backward chain facilities are related to the return acquisition amounts and has an ascending trend as the acquisition amount increases. Third, whenever there is not enough capacity, the model first tries to increase the capacity level; if not possible it decides to open an extra facility. It can be justified since opening a new facility is much more expensive comparing to increasing the capacity level of an existing facility. Fourth, the high quality return acquisition amount is 100% of the possible amount in all solutions indicating that the company favors the recovery of high quality return as it is more profitable. Finally, the minimum profit is achieved when the acquisition amount reaches its maximum value (100% of collected return is procured by company).

We should mention that the profit is from both forward and reverse networks. This is the reason of great value for the profit. The other point is that the recovery of low quality returned product is much more costly comparing to high quality returns. Also, the recoverable value of the low quality returned products is less in comparison to high quality ones. Therefore, considering the profit objective function, the model favors the recovery of high quality returned products.

Table 4- 6 Trade-off solutions

Acquisition bound (L_l)	Profit (million dollars)	HQ[1] acquisition percentage of total return	LQ[2] acquisition percentage of total return	Total acquisition percentage of total return	# of disassembly center	# of bulk recycling center	# of collection center	# of disposal center	# of hazardous material safe disposal center	# of recycling center	# of remanufacturing center
750,000	47	100%	100%	100%	3	2	3	1	1	3	3
728,042	50	100%	96%	97%	3	2	3	1	1	3	3
706,083	54	100%	92%	94%	3	2	3	1	1	3	3
684,125	57	100%	87%	91%	3	2	3	1	1	3	3
662,166	60	100%	83%	88%	3	2	3	1	1	3	3
640,208	61	100%	79%	85%	3	2	3	1	1	3	3
618,249	64	100%	75%	82%	3	2	3	1	1	3	3
596,291	67	100%	70%	80%	3	2	3	1	1	3	2
574,333	70	100%	66%	77%	3	2	3	1	1	3	2
552,374	71	100%	62%	74%	3	2	3	1	1	3	2
530,416	74	100%	58%	71%	3	1	3	1	1	2	2
508,457	76	100%	54%	68%	3	1	3	1	1	2	2
486,499	78	100%	49%	65%	2	1	3	1	1	2	2
464,540	79	100%	45%	62%	2	1	3	1	1	2	2
442,582	80	100%	41%	59%	2	1	3	1	1	2	2
420,624	81	100%	37%	56%	2	1	3	1	1	2	2
398,665	82	100%	32%	53%	2	1	3	1	1	2	2
376,707	83	100%	28%	50%	2	1	3	1	1	2	2
354,748	85	100%	24%	47%	2	1	3	1	1	2	1
332,790	85	100%	20%	44%	2	1	3	1	1	1	1

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[1] HQ= High Quality

[2] LQ= Low Quality

The Pareto front graph for the case study is presented in figure 4-1. It displays the relation between the two objectives. The top point of the curve denotes the lowest profit value corresponding to the situation when the company is acquiring all the existing return for the recovery purposes. The bottom point represents the maximum profit with the lowest acquisition amount. The curve shows a descending trend in the profit as more return is recovered in the system. In other words, it indicates that the profit gradually decreases when more return is recovered in the network. The profit is in conflict with return acquisition amount, since the process of acquiring and recovery of the used product is cost consuming.

Based on the obtained results, the best recovery decision for the company seems to be the point with the highest profit value. However, bearing in mind that the regulation will directly affect the company's decision in recovery amount, the maximum profit value will not anymore count as the best solution. To this end, the company should make a decision with full comprehension of governmental regulation. Therefore, all of the graph points can be a best recovery solution for a company depending on the regulations on the recovery target percentage which affects that specific product and industry.

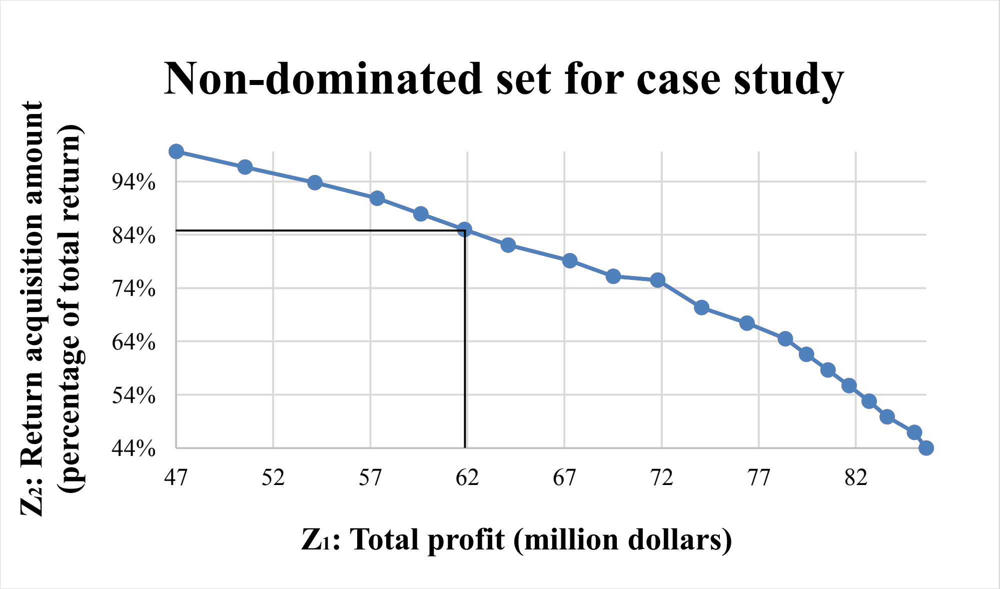

Figure 4- 1 The illustration of the non-dominated set for the case study

The highlighted point on the graph is an example of a decision made by a company which is faced with legislations to recycle at least 85% of waste equipment. The company have to pay an annual fee if the target is not achieved. As it can be seen in the graph, if a company decides on 85% recovery of their returned products they will lose a profit of about 20 million dollars. Depending on the value of the imposed penalty, the managers will plan their recovery target.

4.4 Sensitivity Analysis

4.4.1 Single Objective Problem: Profit Maximization

4.4.1.1 Experimental Specifications

For sensitivity analysis of the single-objective problem with profit maximization objective, we first defined our potential significant factors through examining all model parameters individually. As a result, we came up with six potential significant factors including: demand level, quality ratio, product sale price, high quality return acquisition cost, production capacity and production cost.

Table 4- 7 Potential significant factor levels in the experimental designs for the problem with profit maximization

Factor level / Factor	-	+
Total product demand	864,000	1,296,000
Sale price	$280	$420
Production cost	$24	$36
Production capacity	8,000,000	12,000,000
Quality ratio	LQ[1]: 0.126 , HQ[2]:0.624	LQ: 0.334, HQ: 0.416
HQ acquisition cost	$40	$60

There are two levels considered for each factor which are defined as ± % 20 of the nominal value, as provided in table 4-7. These values are experimental based on current references and the nominal values of our data. It is worth mentioning that, the quality ratio is the ratio of low quality to high quality returned products. We have considered demand as a random variable uniformly distributed with a variation equal to ± % 5 of the mean. Consequently, we considered two replications for each experiment by generating a random demand value for each replication.

To evaluate the experimental results, we have defined three key performance indicators (KPIs): “profit”, “low quality return acquisition amount” and “total return acquisition amount”. For specifying the influence of significant factors and their interactions on our

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[1] LQ= Low Quality

[2] HQ=High Quality

KPIs, we have performed a full factorial design which is discussed in the next sub-section.

4.4.1.2 Full Factorial Design

As we mentioned before, we have considered two levels for our factors. Each experiment was replicated for two times. Therefore, we ran 120 experiments in total. To analyze the results, we have used the analysis of variance (ANOVA). The regression model, which is achieved by using ANOVA, helps us to identify the influence of factors and their interactions on the KPIs. The fitness of the regression model to our data is measured by the R-squared (R-sq) values. As it is shown in table 4-8, the values of R-sq are acceptable in order to continue analyzing the results based on achieved regression models.

Table 4- 8 Adjusted R-squared of the full factorial experiment for the problem with profit maximization

KPI	R-sq. (adj.)
Profit	99.95%
Low quality return acquisition amount	99.83%
Total return acquisition amount	99.59%

For studying the influence of factors and their interactions, we need to analyze P-values. As the experimental error (α-error) is set at 5%, any factor or interaction with a P-value less than 0.05 can be considered to be highly effective. Table 4-9, 4-10 and 4-11 incorporate significant factors, interactions and the associated P-values based on ANOVA results for the profit, low quality acquisition amount and total acquisition amount, respectively.

Table 4- 9 P-value regarding profit of the full factorial experiment

Factor/ Interaction	P-Value
HQ Acquisition Cost	0%
Quality Ratio	0%
Sale Price	0%
Production Cost	0%
Production Capacity	0%
Product Demand	0%
HQ Acquisition Cost*Quality Ratio	0%
Quality Ratio*Production Capacity	1%
Quality Ratio*Product Demand	0%
Sale Price*Production Capacity	0%
Sale Price*Product Demand	0%
Production Cost*Production Capacity	0%
Production Capacity*Product Demand	0%

Table 4- 10 P-value regarding low quality acquisition amount of the full factorial experiment

Factor/ Interaction	P-Value
Quality Ratio	0%
Sale Price	0%
Production Cost	1%
Production Capacity	0%
Product Demand	0%
Quality Ratio*Sale Price	0%
Quality Ratio*Production Capacity	0%
Quality Ratio*Product Demand	0%
Sale Price*Production Cost	1%
Sale Price*Production Capacity	0%
Production Cost*Production Capacity	1%
Production Cost*Product Demand	2%
Production Capacity*Product Demand	0%

Table 4- 11 P-value regarding total acquisition amount of the full factorial experiment

Factor/ Interaction	P-Value
Quality Ratio	0%
Sale Price	0%
Production Cost	0%
Production Capacity	0%
Product Demand	0%
Quality Ratio*Sale Price	5%
Quality Ratio*Production Capacity	0%
Quality Ratio*Product Demand	0%
Sale Price*Production Cost	1%
Sale Price*Production Capacity	0%
Production Cost*Production Capacity	0%
Production Capacity*Product Demand	0%

The important factors influencing profit include: quality ratio, sale price, production cost, production capacity, product demand and high quality acquisition cost. The significant factors on low quality acquisition amount consist of: quality ratio, sale price, production cost, production capacity and product demand. The influencing factors on total acquisition amount are: quality ratio, sale price, production cost, production capacity and product demand.

ANOVA results for one of the KPIs the total acquisition amount are represented in table 4-12. As it can be seen in the table, the coefficient for significant factors and interactions are pretty greater compare to the rest.

Table 4- 12 ANOVA result for total acquisition amount

Factor/ Interaction	Coefficient
HQ Acquisition Cost	305
Quality Ratio	-53500
Sale Price	1020
Production Cost	-1178
Production Capacity	21011
Product Demand	10942
HQ Acquisition Cost*Quality Ratio	-153
HQ Acquisition Cost*Sale Price	376
HQ Acquisition Cost*Production Cost	-87
HQ Acquisition Cost* Production Capacity	305
HQ Acquisition Cost*Product Demand	-305
Quality Ratio*Sale Price	690
Quality Ratio*Production Cost	55
Quality Ratio*Production Capacity	-4244
Quality Ratio*Product Demand	-3239
Sale Price*Production Cost	863
Sale Price*Production Capacity	1020
Sale Price*Product Demand	306
Production Cost*Production Capacity	-1178
Production Cost*Product Demand	-148
Production Capacity*Product Demand	10942

The impacts of factors on profit are represented in figure 4-2. As it can be seen in this figure, high quality acquisition cost, quality ratio and production cost have negative effect on profit. As explained previously, the quality ratio shows the ratio of low quality return to high quality return. By increasing this factor, the ratio of low quality products in the return amount will increase which cause a reduction in the amount of high quality returned product. The effect of this factor on profit can be justified as follows: since the recoverable value of low quality return product is much lower in comparison to high quality return and the recovery cost of low quality return is higher comparing to the high quality return, increasing the quality ratio will result in reduction of profit. In contrary, product sale price, production capacity and demand level have positive impact on the profit. As it is shown in figure 4-2, the product sale price is the most influencing factor on the profit.

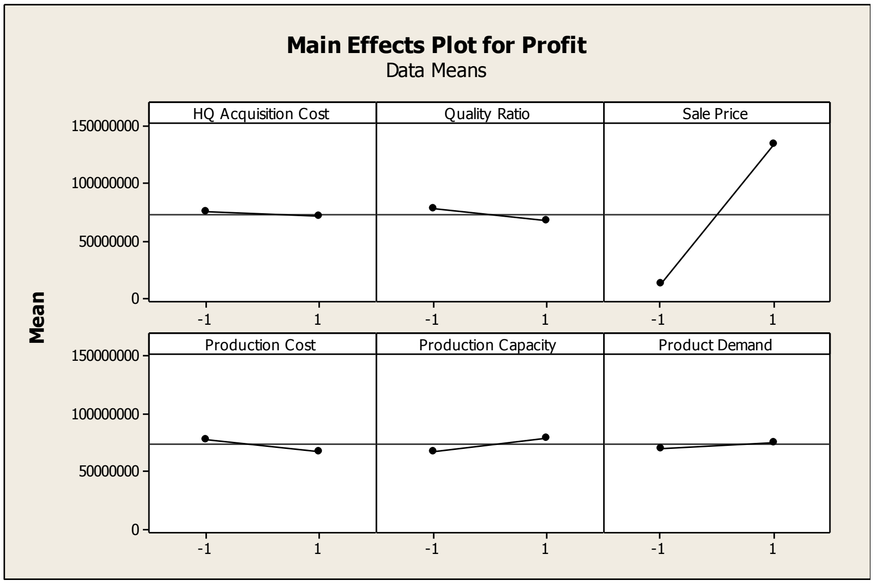

Figure 4- 2 The main effect plot of factors on profit

The interaction of factors regarding the profit can be seen in figure 4-3. As it is shown in this figure, the interaction of demand level and production capacity is the most significant interaction. We can interpret that, at the higher level of demand, the profit will be significantly affected by production capacity. However, in the lower level of demand, this effect is almost negligible.

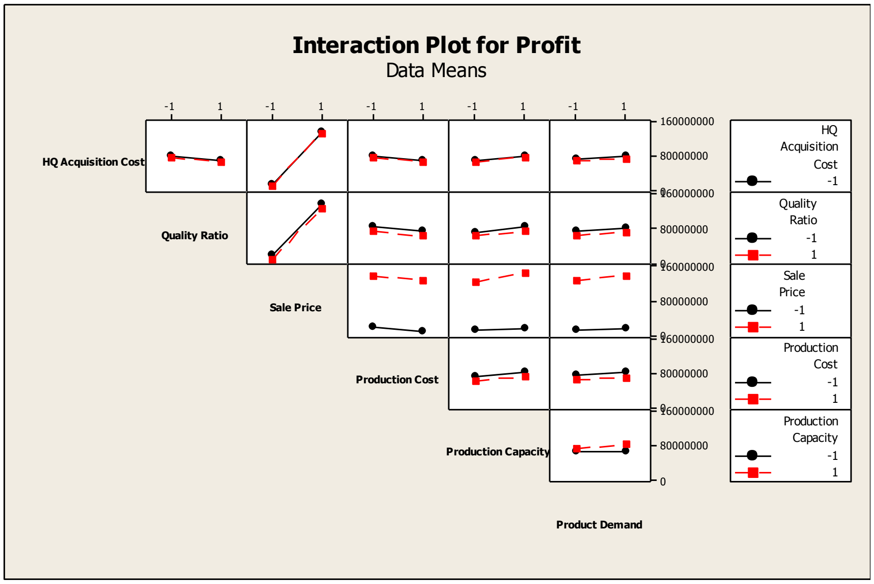

Figure 4- 3 The interaction plot of factors influencing profit

Figure 4-4 illustrates the impact of factors on the acquisition amount of low quality return. As it can be seen in this figure, the acquisition amount of low quality products will raise by increasing production capacity, product demand and quality ratio. The positive impacts of production cost and product demand on low quality acquisition amount are reasonable as these factors directly affect the available amount of return. The positive impact of quality ratio is rational, since the growth in quality ratio increases available amount of low quality return, and thus, the acquisition amount of this quality level. High quality return acquisition cost has almost no effect on this KPI and production cost has a negligible negative effect. It is obvious that the impacts of quality ratio and product capacity are the significant ones on the mentioned KPI.

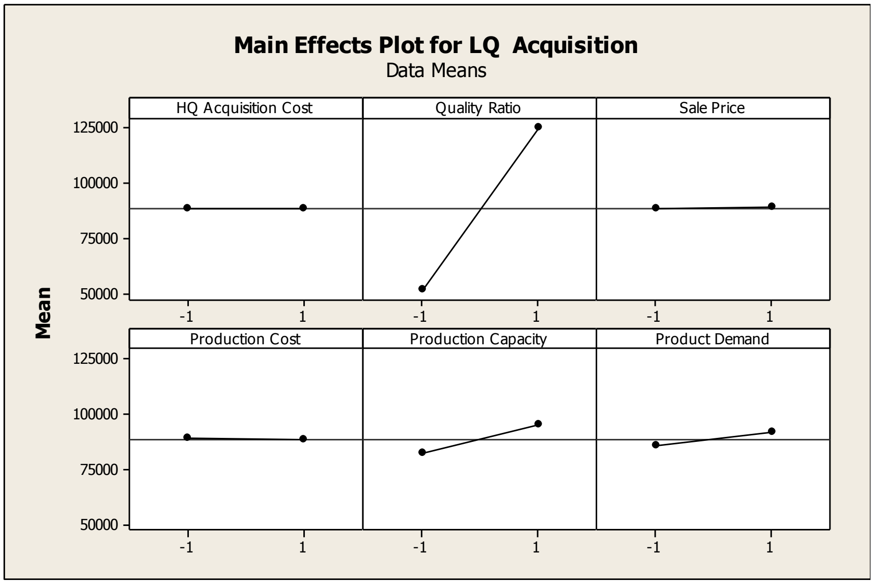

Figure 4- 4 The main effect plot of factors on the low quality return acquisition amount

The interaction between factors influencing acquisition amount of low quality return is displayed in figure 4-5. The interaction between demand level and production capacity regarding this KPI is more noticeable. It displays that the effect of production capacity on acquisition amount of low quality return, is more significant in higher demand levels, comparing to the lower levels.

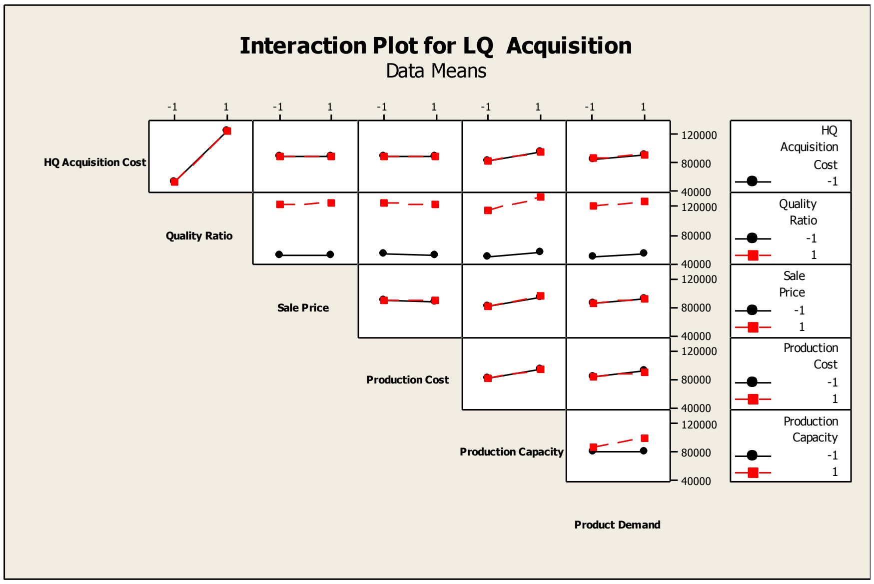

Figure 4- 5 The interaction plot of factors influencing low quality return acquisition amount

Figure 4-6 reflects the main effect plot of factors on the total acquisition amount. As it can be seen in figure, increasing sale price, production capacity and product demand will result in a growth in total acquisition amount. Increasing quality ratio and product cost will decrease the total acquisition amount. We can see that quality ratio, production capacity and production demand are the most significant ones among all. The effect of quality ratio is reasonable, as the recovery of high quality return is much more beneficial for the company. Therefore, by increasing low quality ratio and decreasing high quality ratio, the total acquisition amount will be greatly affected. It also shows that the model greatly favors the recovery of high quality returned products.

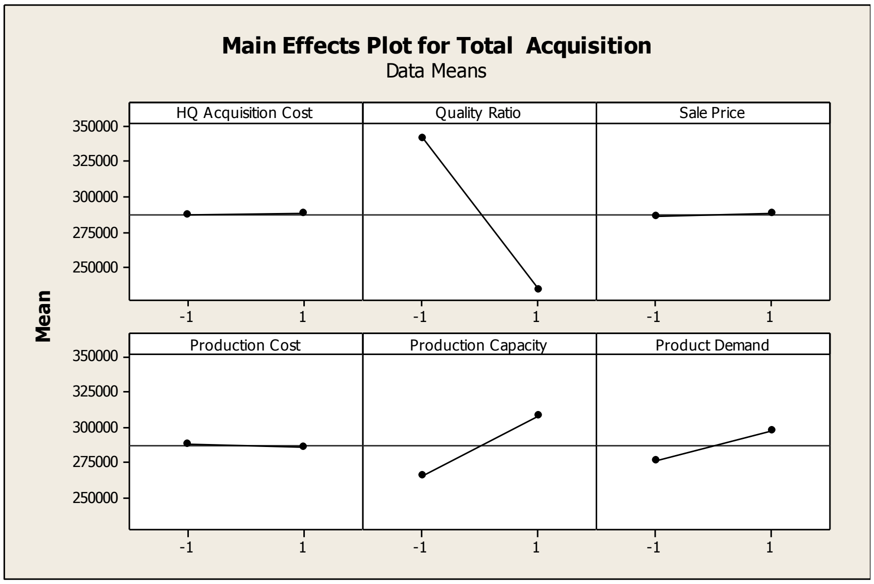

Figure 4- 6 The main effect plot of factors on the total acquisition amount

Figure 4-7 demonstrates the interaction between the factors influencing total acquisition amount. As it is shown in this figure, the most noticeable interaction regarding this KPI is the interaction between demand level and production capacity. We can see that, the impact of production capacity on the total acquisition amount is more significant in higher demand levels comparing to the lower levels.

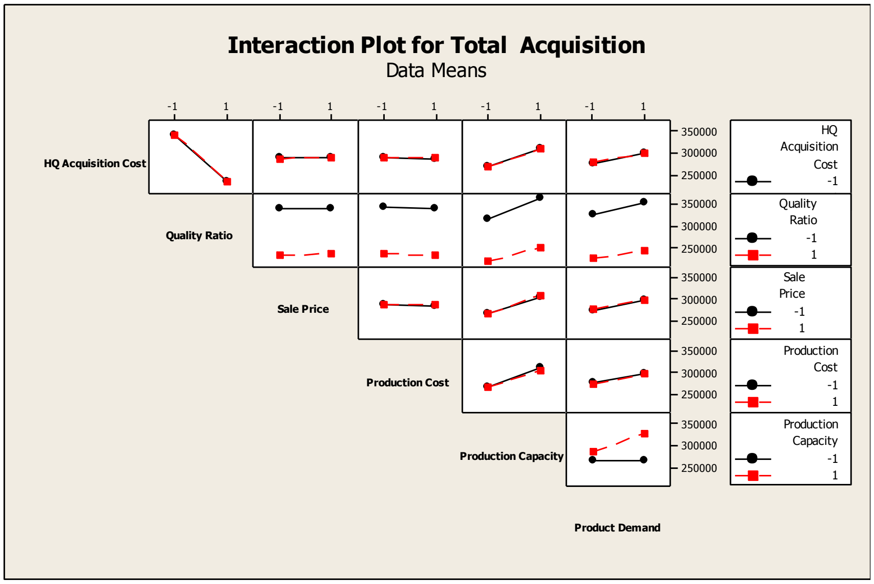

Figure 4- 7 The interaction plot of factors influencing the total acquisition amount

4.4.2 Single Objective Problem: Return Acquisition Amount Maximization

4.4.2.1 Experimental Specifications

In this section, we represent the sensitivity analysis of the single-objective optimization problem, considering maximization of the total return acquisition amount. In this problem, the potential significant factors found to be the demand level, quality ratio and production capacity. As showed in table 4-13, there were two levels considered for each factor which are equal to ± % 20 of their nominal values. These values are experimental and based on current references and the nominal values of our data.

Table 4- 13 Potential significant factor levels in experimental designs for the problem with acquisition maximization

Factor level Factor	-	+
Total product demand	864,000	1,296,000
Production capacity	8,000,000	12,000,000
Quality ratio	LQ[1]: 0.126 , HQ[2]:0.624	LQ: 0.334, HQ: 0.416

We have considered the demand as a random variable uniformly distributed with a variation equal to ± % 5 of the mean as stated in the above table. We had two replications for each experiment by generating a random demand value for each replication. Therefore, we ran 16 experiments in total. To evaluate the experimental results, we have defined two KPIs: "low quality product return acquisition amount" and "total return acquisition amount". For specifying the influence of significant factors and their interactions on our KPIs, we have performed a full factorial design which is discussed in next section.

4.4.2.2 Full factorial design

To analyze the results, we have used ANOVA. As it is shown in table 4-14, the values of R-sq are acceptable to continue analyzing the results based on achieved regression models.

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[1] LQ= Low Quality

[2] HQ= High Quality

Table 4- 14 Adjusted R-squared of the full factorial experiment for the problem with acquisition maximization

KPI	R-sq. (adj.)
Low quality return acquisition amount	99.95%
Total return acquisition amount	99.80%

Table 4-15 and 4-16 incorporate the significant factors, interactions and the associated P-values based on ANOVA results for the low quality acquisition amount and total acquisition amount, respectively. The significant factors on low quality acquisition amount include: quality ratio, production capacity and product demand. The influencing factors on total acquisition amount involve: production capacity and product demand.

Table 4- 15 Resulting P-value regarding low quality acquisition amount of the full factorial experiment

Factor/ Interaction	P Value
Quality Ratio	0%
Production Capacity	0%
Product Demand	0%
Quality Ratio*Production Capacity	0%
Quality Ratio*Product Demand	0%
Production Capacity*Product Demand	0%

Table 4- 16 Resulting P-value regarding total acquisition amount of the full factorial experiment

Factor/ Interaction	P Value
Production Capacity	0%
Product Demand	0%
Production Capacity*Product Demand	0%

The impacts of the significant factors on low quality return acquisition amount are represented in figure 4-8. It shows that the low quality return acquisition amount will grow by increasing any of the considered factors. Since increasing all of these factors will raise the amount of available low quality return, their positive impact on low quality acquisition is justifiable.

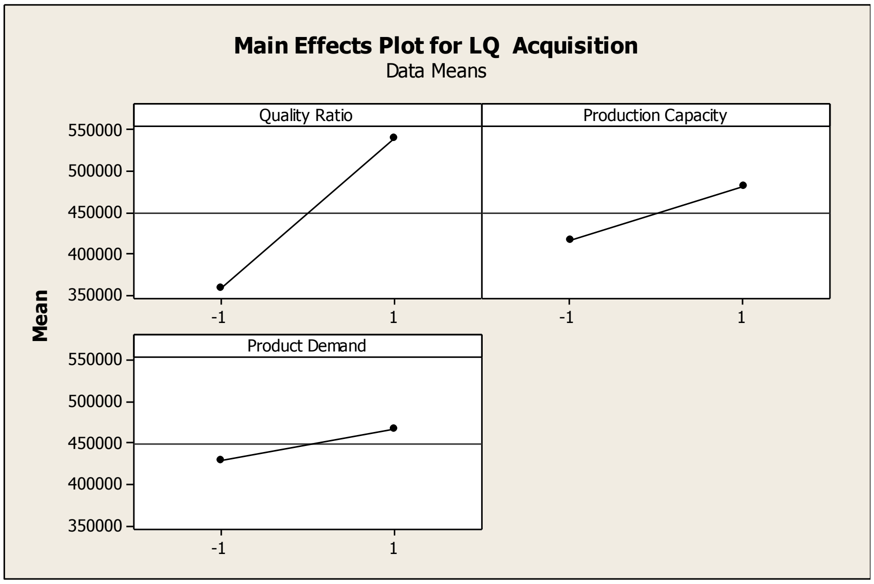

Figure 4- 8 The main effect plot of factors on low quality return acquisition amount

The significant interaction between factors regarding the acquisition amount of low quality return can be explained by figure 4-9. It displays that the effect of production capacity on this KPI, is more significant in higher demand levels, comparing to the lower levels.

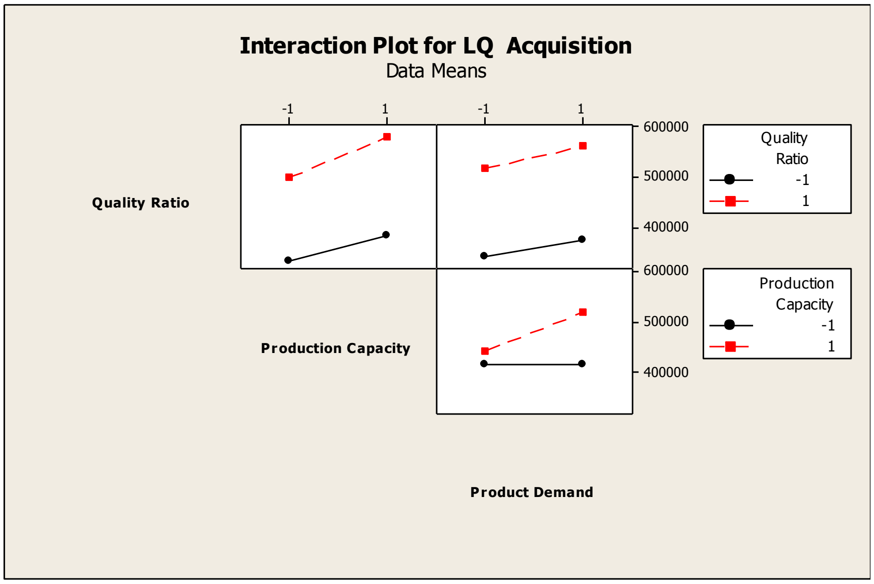

Figure 4- 9 The interaction plot of factors influencing low quality return acquisition amount

The impacts of the significant factors on total acquisition amount are represented in figure 4-10. As it can be seen in this figure, the acquisition amount will grow by increasing any of these factors. However, the quality ratio is the least significant factor compared to others. It is justifiable since the most important effect of quality ratio is on the profit. Therefore, without having a financial objective function, this factor does not affect the total acquisition amount significantly.

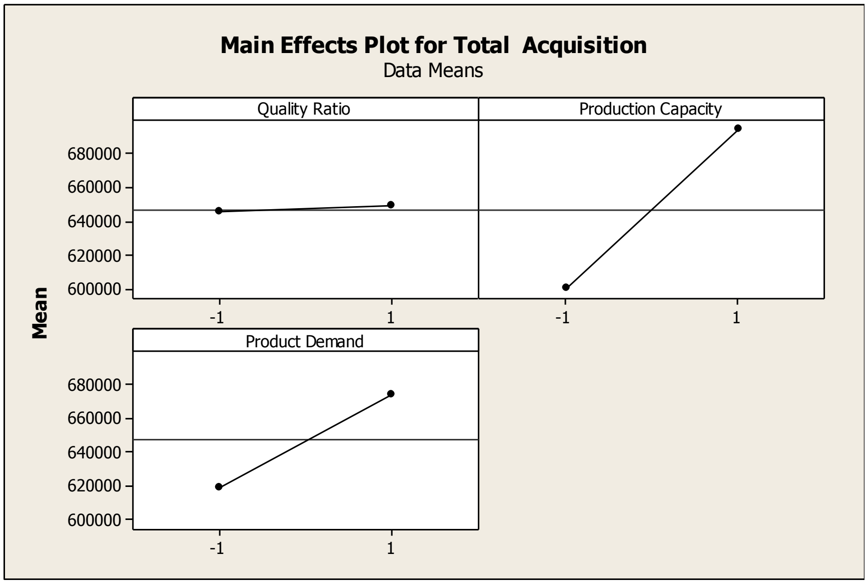

Figure 4- 10 The main effect plot of factors on the total acquisition amount

The interaction between factors regarding total acquisition amount are explained by figure 4-11. It indicates that the effect of production capacity on total acquisition is much more significant in higher demand levels, comparing to the lower levels.

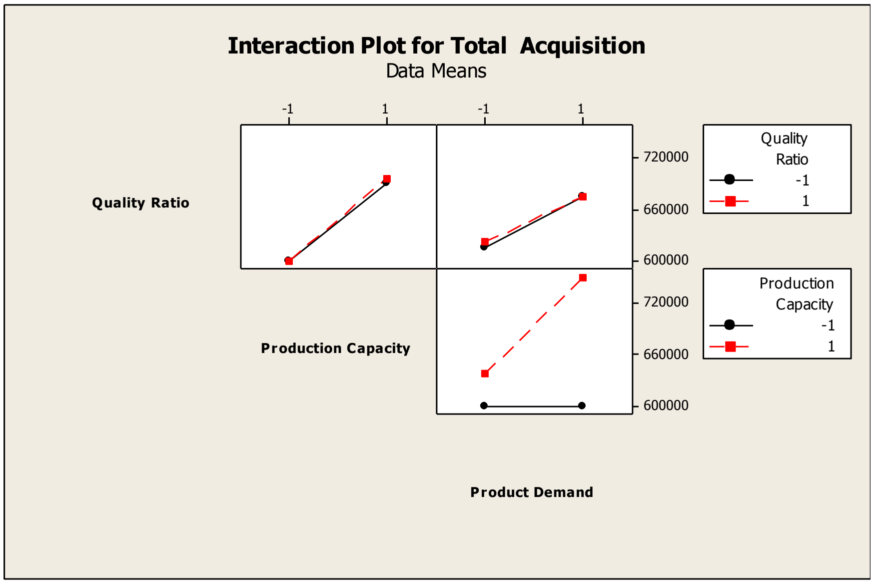

Figure 4- 11 The interaction plot of factors influencing the total acquisition amount

4.5 Conclusion

In this chapter, we applied the model formulated in chapter 3, on an EOL washing machine case study. We solved three problems by considering each objective separately and both objectives as a bi-objective problem. For solving the bi-objective problem, we used the ε-constraint methodology. Later, we presented the results for the bi-objective problem. We displayed the trade-off table for the bi-objective problem and we studied the relation between the two objectives and facilities configuration for corresponding solutions. The results showed that the profit is negatively related to the acquisition amount.

Finally, we performed sensitivity analysis for the single-objective problems. We investigated the significant factors and their interactions affecting each objective function. The results showed that in the problem with profit maximization objective, the sale price is the most significant factor on the profit value. The more expensive the product, the more profit is expected. In this problem, quality ratio has the highest impact on the low quality acquisition amount, followed by production capacity and demand level. All of these factors have positive effect on low quality acquisition amount. It is justified since the growth of quality ratio will positively impact the available amount of low quality returned products and consequently, this will lead to an increase in their acquisition quantity. Considering the total acquisition amount, we observed that the quality ratio is the most significant factor that negatively affects this KPI. It can be justified since the recoverable value of low quality return is much less comparing to recovery of high quality return. Moreover, the recovery cost of low quality return is greater. Therefore, considering the financial objective function, greater amount of available low quality return and less amount of high quality return drop the total acquisition amount. Production capacity and demand have the highest positive effect on total acquisition amount in the second place.

For the single-objective problem with maximizing the acquisition amount, the most important factor on low quality acquisition amount is the quality ratio, followed by production capacity and product demand. It is justifiable since increasing quality ratio rises the available amount of low quality returned products, which leads to growth in their acquisition amount. Regarding the total acquisition amount, the production capacity and product demand are the most significant factors, which positively affect this KPI.

Chapter Five

Conclusion and Future Research

5.1 Conclusion

In this thesis, a mathematical programming model was developed for designing a reverse supply chain for the recovery of durable products, while integrating the forward logistics network. The presented model is a bi-objective MILP model that considers profit maximization, as well as product recovery amount maximization as the objective functions. In this problem, the returned products are assumed to belong to different quality levels. They are also supposed to have a multi-indenture structure, including different types of modules, parts, and materials. Consequently, all possible recovery options were taken into account in the RSC. The forward chain including: suppliers, OEMs, distribution centers are assumed to be already established. The proposed model decides on the reverse supply chain configuration in terms of: location and capacity level of collection, disassembly/ grading, remanufacturing, bulk recycling, material recycling, disposal and hazardous disposal facilities, as well as the flow between facilities. The model also investigates the relation between the two objective functions while deciding on the configuration of RSC network as well as the flow in this network. Adding the above features into the RSC design model increases its complexity in terms of number of decision variables and constraints.

The proposed model was applied on an academic case study in the context of EOL washing machines. The resulting model was first solved by considering each objective function, separately. Then, it was solved with both objective functions by the aid of ε-constraint method and the following results were obtained:

- The profit reaches its maximum when the total acquisition is the lowest amount among all solutions. This happens since establishing the backward chain and also recovery processes are cost consuming. Therefore, the company is not willing to use all of the potential recovery capacity due to the financial aspects.
- The number and capacity level of the backward chain facilities are related to return acquisition amounts and has an ascending trend as the acquisition amount increases.
- Whenever there are not enough capacities, the model first tries to increase the capacity level; if not possible it decides to open an extra facility. It can be justified since opening a new facility is much more expensive comparing to increasing the capacity level of an existing facility.
- The high quality return acquisition amount is 100% of possible amount in all solutions, indicating that the company favors the recovery of high quality return as it is more profitable.
- The minimum profit is achieved when the acquisition amount reaches its maximum (100% of collected return is procured by the company).
- The Pareto front curve shows a descending trend in the profit as more return is recovered in the system. In other words, it indicates that the profit gradually decreases when more return is recovered in the network.

Based on the obtained results, the best recovery decision for the company seems to be the point with the highest profit value. However, bearing in mind that the regulation will directly affect the company's decision in recovery amount, the maximum profit value will not count as the best solution anymore. To this end, the company should make a decision with full comprehension of governmental regulation. Therefore, any of the graph points can be a best recovery solution for a company depending on the regulations on the recovery target percentage which affects that specific product and industry.

Regarding each objective function, a set of sensitivity analysis tests was conducted so as to investigate the impact of different model parameters on that objective and other KPIs. These tests were run as full factorial designed experiments. The following results were obtained for the single-objective problem with profit maximization objective:

- The sale price is the most significant factor on the profit value. The more expensive the product, the more profit is expected.
- Quality ratio (ratio of low to high quality return) has the highest impact on low the quality acquisition amount, followed by production capacity and demand level. All of these factors have positive effect on the low quality acquisition amount.
- Considering the total acquisition amount, we observed that the quality ratio is the most significant factor that negatively affects this KPI. It can be justified since the recoverable value of low quality return is much lower comparing to recovery of high quality return. Moreover, the recovery cost of low quality return is greater. Therefore, considering the financial objective function, greater amount of low quality return and less amount of high quality return drop the total acquisition

amount. Production capacity and demand have the highest positive effect on total acquisition amount in the second place.

The following results were obtained regarding to the problem with acquisition amount maximization objective:

- The most important factors on low quality acquisition amount is the quality ratio, followed by production capacity and product demand. It is justifiable since increasing quality ratio rises the available amount of low quality returned products, which leads to growth in their acquisition amount.

The main contributions of this research can be summarized as follows:

- A multi-indenture structure is considered for the products, which requires different recovery options, including, manufacturing, part harvesting, and material recycling.
- Rather than considering one objective function, two objective functions based on financial and environmental criteria are taken into account.
- Two quality levels are considered for the returned products which differ in terms of the acquisition price, processing costs, quantities of recoverable modules and parts, and consequently on the recovery decisions.
- The recovery facilities are assumed to be flexible with different potential capacity levels. This makes the problem more realistic.

5.2 Future Research

Future research can extend the existing study toward the following directions:

- The proposed model can be easily extended to a multi-product setting. Adding the product diversity will increase the complexity of the model due to different types and quantity of modules/ parts involved in each product.
- Current model can be solved by commercial solvers, namely CPLEX, for small instances. While trying to apply it for large networks, CPLEX is not able to solve it due to memory shortage. Hence, efficient heuristic algorithm based on decomposition methods can be developed to solve the model in a reasonable time for large case studies.
- In this study, the uncertainty in the quality of returned items is modeled through considering certain classes of quality; each encompasses deterministic number of modules and parts. A more realistic approach for modeling such an uncertainty would consider random proportions of recoverable items in different products. Adding such uncertain ratios in the model will result a MIP model with uncertain parameters. Consequently, the problem must be reformulated as a stochastic programming or a robust optimization model.
- Other source of uncertainty can also be integrated into the model, namely, the available quantity of returned items in each quality category, in addition to the demand for recovered modules, spare parts, and recycled materials.
- Finally, the proposed RSC design model can be integrated into a forward supply chain design model. Designing both forward and reverse networks simultaneously

will result in a very complex model with many binary variables. The latter would provide a useful tool for designing more sustainable supply chains.

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Appendix A – Model Notations

Index Table

Index	Definition
Z	Set of part suppliers in the network, $z \in Z$
U	Set of raw material suppliers in the network, $u \in U$
X	Set of module suppliers in the network, $x \in X$
I	Set of OEM in the network, $i \in I$
J	Set of distributors in the network, $j \in J$
K	fixed location of customer zones, $k \in K$
C	Set of potential collection centers in the network, $c \in C$
A	Set of potential disassembly/ grading centers in the network, $a \in A$
S	Set of markets for spare parts, $s \in S$
D	Set of potential disposal centers, $d \in D$
O	Set of potential hazardous disposal centers, $o \in O$
G	Set of potential recycling centers, $g \in G$
E	Set of markets for recycled materials, $e \in E$
B	Set of potential bulk recycling centers, $b \in B$
M	Set of potential remanufacturing centers, $m \in M$
W	Set of markets for remanufactured modules, $w \in W$
N	set of capacity levels available for facilities, $n \in N$
P	set of parts in the product, $p \in P$
R	set of materials in the product, $r \in R$
L	set of modules in the product, $l \in L$
Q	set of quality levels in the returned *products,* $q \in Q$

Parameter Table

Parameters	Definition
Φ_p	number of part *p* in each unit of product
μ_r	mass (kg) of material *r* in each unit of product
ω_l	number of module *l* in each unit of product
β^q	mass (kg) of residues in returned product with quality level *q* that will be sent to bulk recycling centers from disassembly centers
α_r^q	mass (kg) of recyclable material *r* in returned product with quality level *q* that will be sent to recycling centers from disassembly centers
σ^q	mass (kg) of returned product with quality level *q* that will be sent to disposal centers from disassembly centers (non-recoverable mass)
ρ^q	mass (kg) of returned product with quality level *q* that will be sent to hazardous disposal centers from disassembly centers (hazardous mass)
γ_p^q	number of part *p* in returned product with quality level *q* that can be sent either to the spare markets or OEMs from disassembly centers (spare part)
δ_l^q	number of remanufacturable module *l* in returned product with quality level *q* that will be sent to the remanufacturing centers from disassembly centers
η_r	ratio of recyclable material *r* that will be sent to the recycling centers from bulk recycling centers
τ_r	ratio of non-recoverable material *r* that will be sent to the disposal centers from recycling centers
$£^q$	ratio of returned products with quality level *q* in the distributed product
fc_c^n	fixed cost of opening collection center *c* with capacity level *n*
fa_a^n	fixed cost of opening disassembly/grading center *a* with capacity level *n*
fd_d^n	fixed cost of opening disposal center *d* with capacity level *n*
fo_o^n	fixed cost of opening hazardous disposal center *o* with capacity level *n*
fg_g^n	fixed cost of opening recycling center *g* with capacity level *n*
fb_b^n	fixed cost of opening bulk recycling center *b* with capacity level *n*
fm_m^n	fixed cost of opening remanufacturing center *m* with capacity level *n*
tc_{kc}	shipping cost per unit of returned product sent from customer zone *k* to collection center *c*
ta_{ca}	shipping cost per unit of returned product sent from collection center *c* to disassembly/ grading center *a*

Parameter Table

Parameters	Definition
ts_{as}^{p}	shipping cost per unit of part *p* sent from disassembly/ grading center *a* to spare market *s*
tz_{ai}^{p}	shipping cost per unit of part *p* sent from disassembly/ grading center *a* to OEM *i*
td_{ad}	shipping cost per kg of materials sent from disassembly/ grading center *a* to disposal center *d*
to_{ao}	shipping cost per kg of hazardous materials sent from disassembly/ grading center *a* to hazardous disposal center *o*
tg_{ag}	shipping cost per kg of recoverable materials sent from disassembly/ grading center *a* to material recycling center *g*
te_{ge}	shipping cost per kg of recovered materials sent from recycling center *g* to recycled material market *e*
tu_{gi}	shipping cost per kg of materials sent from material recycling center *g* to OEM *i*
sd_{gd}	shipping cost per kg of materials sent from material recycling center *g* to disposal center *d*
tb_{ab}	shipping cost per kg of residues sent from disassembly/ grading center *a* to bulk recycling center *b*
rg_{bg}	shipping cost per kg of recoverable materials sent from bulk recycling center *b* to material recycling center *g*
rd_{bd}	shipping cost per kg of materials sent from bulk recycling center *b* to disposal center *d*
tm_{am}^{l}	shipping cost per unit of module *l* sent from disassembly/ grading center *a* to remanufacturing center *m*
tw_{mw}^{l}	shipping cost per unit of module *l* sent from remanufacturing center *m* to secondary market *w*
tx_{mi}^{l}	shipping cost per unit of module *l* sent from remanufacturing center *m* to OEM *i*
ti_{zi}^{p}	shipping cost per unit of part *p* sent from part supplier *z* to OEM *i*
ri_{ui}	shipping cost per kg of materials sent from material supplier *u* to OEM *i*
si_{xi}^{l}	shipping cost per unit of module l sent from module supplier *x* to OEM *i*
tj_{ij}	shipping cost per unit of products sent from OEM *i* to distributor *j*
tk_{jk}	shipping cost per unit of products sent from distributor *j* to customer zone *k*
caz_{zp}	capacity for part *p* in part supplier *z*
cau_{ur}	capacity for material *r* in raw material supplier *u*
cax_{xl}	capacity for module *l* in module supplier *x*

Parameter Table

Parameters	Definition
cai_i	production capacity of OEM *i*
caj_j	capacity of distributor *j*
cac_c^n	capacity with level *n* for collection center *c*
caa_a^n	capacity with level *n* for disassembly/ grading center *a*
cad_d^n	capacity with level *n* for disposal center *d* (kg)
cao_o^n	capacity with level *n* for hazardous disposal center *o* (kg)
cab_b^n	capacity with level *n* for bulk recycling center *b* (kg)
cag_{gr}^n	capacity with level *n* for material *r* in recycling center *g* (kg)
cam_{ml}^{nq}	capacity with level *n* for module *l* with quality level *q* in remanufacturing center *m*
d_k	demand of customer zone *k*
ds_{sp}	demand for part *p* at spare market *s*
de_{er}	demand for material *r* at recycled material market *e*
dw_{wl}	demand for module *l* at secondary market *w*
cz_{zp}	part cost per unit of part *p* supplied by part supplier *z*
cu_{ur}	material cost per kg of raw material *r* supplied by raw material supplier *u*
cx_{xl}	module cost per unit of module *l* supplied by supplier *x*
ci_i	production cost per unit of product produced at OEM *i*
cj_j	distribution cost per unit of product distributed at distribution center *j*
cc_c	collection cost per unit of product collected by collection center *c*
ca_a	disassembly cost per unit of product disassembled by disassembly center *a*
cd_d	disposal cost per kg of product disposed by disposal center *d*
co_o	disposal cost per kilogram of product disposed by hazardous disposal location *o*
cg_{gr}	recycling cost per kg of material *r* recycled by recycling center *g*
cb_b	recycling cost per kg recycled by bulk recycling center *b*
cm_{ml}^q	remanufacturing cost per unit of module *l* with quality level *q* remanufactured by remanufacturing center *m*

Parameter Table

Parameters	Definition
Pk	unit price of product at customer centers
Ps_p	unit price of part p at spare markets
Pn	unit penalty of not recovered products
Pe_r	unit price of material r at recycled material markets
Pw_l	unit price of module l at secondary markets
Pr^q	unit price for buying returned product with quality q

Appendix B – Case Study Data

Index Table

Index	Value
Z	1
U	1
X	1
I	1
J	1
K	3
C	5
A	5
S	2
D	5
O	5
G	5
E	2
B	5
M	5
W	2
N	2
P	10
R	3
L	2
Q	2

Parameter Table

Parameter	Value
fc_c^1	212,000
fc_c^2	220,000
fa_a^1	424,000
fa_a^2	440,000
fm_m^1	1,040,000
fm_m^2	1,120,000
$£^1$	0.23
$£^2$	0.52
cac_c^1	200,000
cac_c^2	250,000
caa_a^1	200,000
caa_a^2	250,000
$cam_{ml}^{1\ 1}$	4,000,000
$cam_{ml}^{1\ 1}$	5,000,000
d_k	3,600
cc_c	1
ca_a	1
cm_{ml}^1	1.5
cm_{ml}^2	3
Pw_2	12.87
$cx_{x\ 2}$	17.1
α_1^1	5.5
α_1^2	14.7
Pk	350
Pr^1	50
Pr^2	40