Multi-objective Reverse Logistics Network Design and Analysis

Mohammad Rahmatian

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Abstract

Implementing an efficient closed-loop recovery network requires establishing appropriate logistics systems for flows of new, used, and recovered products. Reverse logistics has received increasing attention from researchers in the last few decades. This research addresses logistics network design in an integrated reverse logistics context. We present a multi-objective facility location and allocation model with multiple commodities. Three objectives are considered: overall cost minimization, product returns collection maximization, and product recovery maximization. The purpose is to obtain a set of non-dominating solutions for facility arrangement among the potential facilities as well as the associated material flows between these facilities and customers. The facility capacities are treated as discrete parameters and are imposed on each product type independently. Numerical examples are presented to analyze the model performance while implementing the constraint method. Finally, the trade-off relationship between the three competing objectives are presented and analyzed.

Keywords: *Reverse logistics; Multi-objective optimization, Constraint method*

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Chapter One

Introduction

1.1 Foreword

In the world of finite resources and great competition over new material sources on the one hand and limited disposal capacities on the other, recovery of used products and materials is inevitable. As environmental consciousness among the society is growing in recent years, waste reduction is increasingly becoming a major concern of governments, consumers, and industries in different ways. Governments require companies to reduce waste and emission and to have more responsibility for their product's life-cycle by legislative measures. Consumers are increasingly expecting companies to reduce the negative environmental impact of their products and operations. Companies have found new business opportunities for value recovery from used products as well as new market opportunities. As the result, reverse logistics has become ever more important as a sustainable and profitable business strategy.

Many countries, especially in Europe and North America, have started to develop systematic product recovery and recycling procedures. Various industries in those countries are involved in this field. Among which, manufacturers of copy machines, carpets, single-use cameras, automobiles, and glasses are taking the lead. Returns not only include end-of–use products brought back by customers but also consist of unsold or defective products from retailers. According to Reverse Logistics Executive Council, logistics costs are estimated to be as large as 10.7 percent of the U.S. economy. Reverse logistics constitutes four percent of this amount and it costs were approximately $58.34 billion in the USA (2004 data). Many firms have captured significant business opportunities for product recovery and remanufacturing. Lund (1996) reported that there were over 70,000 remanufacturing firms in the US with total revenue of $53 billion a year. These firms had over 350,000 workers and their profit margins exceeded 20 percent (Nasr *et al*, 1998).

With that respect, supply chain no longer finishes at the end users, as it does in conventional supply chains. It now includes the consumer returns back to the manufacturers as well. The importance of studying and investigating the logistics aspect of material recovery and recycling is increasing. This recently evolved field in supply chain management is termed as "reverse logistics".

Many researchers have their own definitions for reverse logistics with the most comprehensive terminology proposed in Fleischmann (2000). He defined reverse logistics as "the process of planning, implementing, and controlling the efficient, effective inbound flow and storage of secondary goods and related information opposite to the traditional supply chain direction for the purpose of recovering value or proper disposal." Reverse logistics is not a symmetrical image of forward logistics as it differs in involved parties, facilities, and also its material flow network design.

1.2 Reverse Logistics Characteristics

In this section different characteristics of reverse logistics are discussed and explained. These characteristics can be classified as return types, motivations for recovering products and material, recovery options, and parties involved.

1.2.1 Return Types

There are different types of returns that can be collected from users. Depending on the nature of the return different reverse logistics networks can be designed. Fleischmann (2000) identified five types of returns as: end-of-use returns, commercial returns, warranty returns, production scraps and by- products, and packaging materials. These return types are explained as follows.

- **End-of-use returns**

  This type of returns is the most prominent which had the major impact on reverse logistics initiation in the past few decades. It consists of products that have reached their end-of-usages life, products that their use has been completed, and also leased product returns that can be used further. Companies are interested in this type of returns due to various reasons. First, they can be valuable sources to recover that have economic benefits. Second, a manufacturer might be responsible to collect and recover or recycle their products because of environmental regulations. And finally, producers may want to recover their own products after use for asset protection reasons.

- **Commercial returns**

  These are the returns from the buyer to the seller for a refund. In general, they can be resold in other markets since the product has not been used or it is in a good condition to be reused. Examples of commercial returns can be seasonal products like apparels.

- **Warranty returns**

  This type of returns includes products that are failed during use or damaged while delivered. They are returned to the manufacturer for refund or repair. The manufacturer either repairs the returns or disposes them. Also, product recalls can be a part of this category of returns.

- **Production scrap and by-products**

  In many cases production scraps and by-products are of the nature of a process. However, they need to be recovered or recycled due to resource savings and economic considerations as well as environmental regulations.

- **Packaging materials**

  Return of this type of product is one of the most economically attractive returns for producers since they do not need major processing except for cleaning or minor maintenance. They can be reused directly in the same supply chain network. Examples for this category of returns can be crates, refillable bottles, pallets, and reusable boxes. Aside from above mentioned motivations for reusing packaging material, environmental legislations also promote reusing them. An example for this can be the German "Green Dot" system which obliges manufacturers to take back their product packaging and recover them.

1.2.2 Motivations for Recovering Products and Material

Companies initiate recovering and recycling their products for different reasons. The most important reasons identified are economic, marketing, legislative, and asset protection.

- **Economic**

  Recovery of used material and products is often attractive for companies since they can be a cheap material resource for their processes. Also in some cases recovery of added manufacturing value of a product is a consideration of companies.

- **Marketing**

  Marketing issues are very powerful drivers for companies to start their return and recovery plan. First, growing competition forces companies to make stronger ties with their customers. To do so they may start more relaxed return policies or take back and refund excess products from customers. Another subject that companies are increasingly paying attention to is having a "green" profile which means they take back and recover their used products to reduce the negative environmental impact of their products.

- **Environmental regulations**

  Environmental regulations are another reason for implementing reverse logistics. Manufacturers are obliged more than ever to be responsible for their product's life-cycle. They may be required to take back their products from their customers in order to recover, to reduce waste volumes, or to properly dispose them.

- **Asset protection**

  Some companies take back their products in order to prevent sensitive components to leak into secondary markets or competitors. In this way they need to collect their products from the hand of their customers.

1.2.3 Recovery options

Once products are taken back from customers, depending on the nature of the returned products, different alternatives exist to deal with them. These alternatives can be categorized as: direct reuse, repair, refurbishment, remanufacturing, cannibalization, recycling, and disposal. Each of these options is elaborated in detail below.

- **Direct reuse**

  Items can be directly reused after collection without major processing activities except for cleaning or minor repair. Examples are packaging materials such as pallets and crates.

- **Repair**

  In order to restore failed products to "working order" some products require fixing and/or replacing broken parts. The repaired products often have lower quality than new products.

- **Refurbishment**

  The goal of refurbishing is to bring back used products up to a quality standard level. These products are disassembled and critical parts are fixed or replaced. Then, they are reassembled as refurbished products. Examples are refurbished computers and laptops.

- **Remanufacturing**

  The purpose of remanufacturing is to process used products in order to retain product's identity and functionality by bring them back into "as new" condition. They are disassembled and extensive part inspection is carried out. Broken and outdated parts are fixed or replaced. Finally they are reassembled and sold as remanufactured products. Machine tools or car engines are examples for this type of products.

- **Cannibalization**

  In contrast to the above mentioned recovery options, in cannibalization only a limited amount of parts is being reused. Products are disassembled and after inspection a certain number of parts are selected to be reused in remanufacturing, refurbishing, or repairing other used products. The rest would be recycled or disposed.

- **Recycling**

  Recycling is to reuse the materials of used products in production of the original parts or in production of other parts. In recycling the identity, structure, and functionality of the original product are lost. Recycling of metal parts of discarded cars is an example of this category of recovery.

1.2.4 Parties involved

Different parties can be involved in reverse logistics and recovery of used products. The original product manufacturer plays the main role in the reverse logistics. Also products might be taken back and reprocessed by some specialized parties such as specialized remanufacturing companies. In the former case the used product returns to the original supply chain after recovered while in the latter case it enters an alternative chain.

In reverse logistics network design it is crucial to identify the parties involved since it has a significant impact on designing an integrated supply chain network which contains forward and reverse flows.

1.2.5 Recovery Network Stages

A recovery network may start from the collection stage where the used material or product is collected and moved to some point of further treatment. It can include activities such as purchasing, transportation, and storage.

Inspection and separation are the next stages in a recovery network. They are the operations to determine whether the collected products are reusable or not. Based on the available recovery options the reusable returned products can be sorted in this stage and they are either stored or sent to the next stage.

Re-processing stage is to transform used products into useable ones. The activities can be remanufacturing, repair, and recycling. After this stage the transformed products enter either the original supply chain or an alternative chain.

Disposal is required for products decided in inspection/separation stage as non-reusable because of technical or economical reasons. This stage may consist of landfilling and incineration.

The last stage, re-use, is to redirect the recovered products into the original supply chain or alternative chain for reuse. This stage contains sales, storage, and transportation activities.

Figure 1.1 depicts a typical integrated supply chain as proposed in Fleischmann (2000). Forward and reverse networks are graphically presented. The different stages discussed above and the network arrangements are shown.

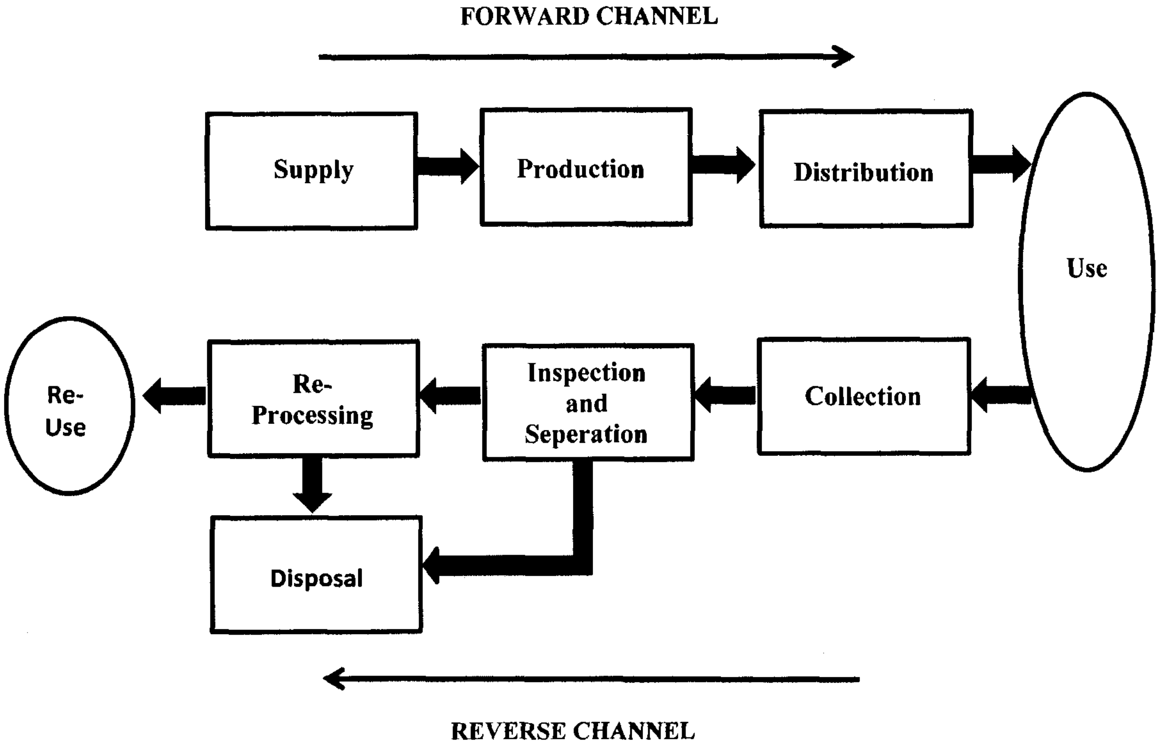

Figure 1.1. The Recovery Chain

1.3 Research Background

Fleischmann (2000) comprehensively studied reverse logistics network design and developed a quantitative model formulation to optimize material flow in an integrated supply chain which consists of forward and reverse chains. Salema *et al* (2006) extended the above mentioned model by adding capacity constraints to each facility. Furthermore, they developed the earlier model by considering a multiple-product recovery network model. This research presents a decision model for design of logistics network in a product recovery system. It generalizes and extends the earlier work by Salema *et al* (2006) into a multiple objective model which simultaneously considers three different attributes; capacity limits are considered for each product type; and a new material flow route is introduced to the model to add more flexibility to the model application.

1.4 Scope and Objectives of this Thesis

In this research, a multi-objective mixed integer programming model for logistics network design in an integrated multiple-product supply chain network is developed. Three objectives, minimization of the overall cost, maximization of the total return collection rate, and maximization of total returned goods recovery, are addressed. Interactions between the above mentioned economic, environmental, and technological considerations are studied. The purpose is to identify a set of non-dominating solutions for the potential facility locations as well as the associated material flows between the parties involved in the network. A numerical example is presented to illustrate the developed model and trade-off relationships between the three objectives.

1.5 Research contributions

This research is conducted as an extension to the one proposed in Salema *et al* (2006), the first model considering multiple-product capacitated integral logistics system problem with forward and backward material flows. In this thesis, the work presented in Salema *et al* (2006) is extended in three aspects. First, three objective functions are addresses. These objectives consider three important aspects of reverse logistics systems namely economical, technological, and environmental. Second, a new material route is introduced which adds to the flexibility of the above mentioned work and makes it more realistic. This is done by introducing new variables and developing new constraints to the model. Third, for each facility, capacity constraints for each product type are considered independently.

The main contribution of this thesis is to develop a more extensive and flexible recovery network design model, to identify the impact of the three objectives on reverse logistics network design and to determine their interactions and trade-offs.

1.6 Organization of the thesis

This thesis is organized into five chapters. Following the introductory Chapter 1, Chapter two provides a review of the literature in reverse logistics and recovery network design. In Chapter three, problem description and model formulation are presented and the solution approach is discussed. A numerical example is presented and solved in Chapter four and results are analyzed. Finally, in Chapter five, concluding remarks and directions for future research are presented.

Chapter Two

Literature Review

2.1 Introduction

In this chapter, relevant literature of reverse logistics and recovery network design is discussed. The growing concerns about material take-back for recovering and recycling motivated researchers to study reverse supply chain. Although in the context of supply chain management forward chain has been extensively studied in the last few decades, reverse chain is relatively new and there are many areas that have not been fully studied. One of these areas is reverse logistics and recovery network design which is the focus of this study. The problem of reverse logistics and network design can be categorized into single product, multiple product, and multi-objective models.

2.2 General Characteristics of Recovery Networks

Fleischmann *et al* (1997) presented a survey of quantitative models in reverse logistics and divided the field into three main areas: distribution planning, inventory control, and production planning. In reverse distribution planning, the authors considered the design of the reverse distribution network and pointed out that it is not necessarily a symmetrical picture of forward distribution networks. Therefore, it is essential to modify and extend the traditional network design models to fit the new implication. In this work, distinct characteristics of reverse distribution networks were discussed such as the "many-to-few" convergent network structure and high system uncertainty regarding material supply and product demand. The high inventory systems uncertainty may partially counterbalance the material value savings and complicates the analysis of the system performance. The authors also noted that production planning in reuse supply chain had not yet been well investigated. They also pointed out that traditional MRP systems fail to handle integrated reuse network production planning. Two main characteristics of the reverse logistics add complexity to this task: an additional disassembly level as well as high uncertainty of timing, quantity, and quality of the returned material.

Krikke (2003) studied product life-cycles and circular supply chains and their interactions. The author discussed circular supply chains in different categories. All products may be returned at certain stage of their life-cycle so they can be categorized as commercial returns, end-of-use returns, repairable returns, reusable carriers, refillable units, and end-of-life returns. Each return type requires special reverse chain depending on internal and external factors such as legislations, obsolescence risk, cost, environmental control, and efficiency.

Fleischmann (2000) studied design problems of physical recovery networks. The main characteristics of product recovery networks were identified and compared to traditional logistics structures such as production-distribution and waste disposal networks. Comparing characteristics of recovery networks with traditional production-distribution networks highlights some major differences. One difference arises from supply points. In traditional production-distribution networks, supply is controllable in many cases by means of timing, quality, and quantity; however, in recovery networks it is difficult to forecast them. The other difference is the demand estimation for the recovered product/material which suffers from high uncertainty. Therefore traditional forecasting methods do not give a good estimation in recovery networks.

2.3 Single Product Problems

Barros *et al* (1998) studied the problem of sand recycling from demolition waste. They proposed a two-level capacitated mixed integer linear programming facility location model for solving the problem of used sand reverse distribution network in the Netherlands. The open-loop reverse channel, in this problem, consists of construction waste sources at different points, sorting facilities where the waste is separated to reusable and non-reusable materials, and processing sites where the usable waste is crushed into recyclable sand. The objective of the sand recycling network problem is to minimize the total cost of the network while determining type, number, and location of processing sites. Moreover, the proposed model determines the amount of construction waste to process in order to achieve the above objective. The model was solved using a heuristic based linear relaxation method.

Marin and Pelegrin (1998) developed a mixed integer linear programming location-allocation model. In the closed-loop model the authors proposed two types of products, primary and secondary. Customers are supplied with primary product which comes directly from the factories. Then they return a portion of the used primary products as secondary products back to the factories. The objective of the proposed network model is to minimize the total cost. This is achieved by determining which potential factories to be opened and their specific locations in the network, the amount of primary product needed to supply each customer by the open factories as well as the amount of secondary product returning from each customer back to the factories. To solve the problem, Marin and Pelegrin (1998) used branch and bound method and a heuristic procedure which are both based on Lagrangian decomposition. They validated their model and solution methods using a set of test problems with different structures.

Jayaraman *et al* (1999) proposed a capacitated 0-1 mixed integer programming model for a closed-loop reverse distribution network. Their model solves for the location of remanufacturing and distribution facilities and the amount of product to supply from each open facility to customers. It also determines the rate of production, and the stocking of the optimal quantities of the remanufactured products. The objective is to minimizing the sum of fixed and variable costs. Furthermore, they tested the model on a set of problems based on the parameters of an existing electronic equipment remanufacturer firm.

Ammons *et al* (1999) developed a mixed integer programming model for strategic infrastructure decision making in reverse production systems (RPS) for electronics assemblies. The proposed model includes key features such as complexity in design, manufacture, and materials content of the final products as well as the product cycle frequency. The objective of the proposed model is to maximize the net profit. The model determines facility locations and their capacities, the reverse flow routs for products and materials to be processed and their optimal quantities. The model also allocates recycling tasks to the potential recycling facilities. Further on in their work, the authors presented two case studies in network routing with demanufacturing and carpet recycling.

Le Blanc *et al* (2002) conducted a case study in redesigning the recycling system for LPG-tanks in auto recycling industry in the Netherlands. In their case study they considered two strategic alternatives, central and regional. In order to obtain a reliable estimation of transportation costs for each candidate location, the authors solved a vehicle routing model by applying a heuristic procedure. The facility location integer linear programming model is solved to determine the optimal number and location of the recycling facilities while minimizing the total cost.

Jayaraman *et al* (2003) developed a mixed integer programming model for design of reverse distribution networks. The objective is to minimize the sum of transportation costs from sources through collection sites to the destination facilities and the fixed cost associated with opening collection sites and the destination facilities. Based on the MILP model, a weak and strong formulation is proposed. They applied the proposed model formulation to five sets of twenty randomly generated problems and solved them using a heuristic concentration procedure. Their work considers the reverse flow of material only and excludes the forward flow.

Krikke *et al* (1999) presented a case study implemented at Océ copier manufacturer in Venlo, the Netherlands. This study concerns installing a remanufacturing process for a certain type of copier machine. There are two location options in Venlo close to the production site and one location option in Prague, Czech Republic. The recovery procedure is divided into three sectors namely disassembly, preparation, and re-assembly. There exist other supportive processes such as central stock keeping, external repair, and recycling. Location analysis is conducted to reach a decision for preparation and re-assembly facility locations. The dismantling location is fixed and has to be in close range of stock keeping. A closed-loop mixed integer linear programming model is developed to minimize the total operational costs. The authors used solver LINDO to solve the problem and compared the three potential location results with a number of pre-selected managerial solutions. With respect to operational costs, locating all processes in Prague appears to be the optimal choice. However, Krikke *et al* (1999) concluded that due to the high investments required and the small relevant costs differences with other two location options, there should be a strategic managerial incentive to justify this business decision.

Kroon and Vrijens (1995) considered the design of a closed-loop return logistics system for collapsible plastic containers in the Netherlands. The drive for the use of reusable secondary packaging material in the Netherlands is mainly the environmental and governmental regulations. The system consists of five parties: the central agency, a logistics service organization, the sender of the containers, the recipients, and the carriers that transport the full containers from senders to recipients. The central agency is the owner of the containers and deals with all non logistics operations. Logistics service organization is responsible for logistics operations and sorting empty containers. Carriers are transporting full containers from senders to recipients. The study considers the role of the logistics service organization. In order to minimize the total operational costs, a mixed integer linear programming model was developed. By solving the model, the optimal number of containers needed to operate the system and shipment fees as well as the depot locations for empty containers are determined.

Louwers *et al* (1999) developed a continuous location allocation model for carpet waste recycling system. The model consists of three stages: collection, preprocessing, and redistribution. High carpet waste volumes generated from households, office buildings, carpet retailers, aircraft and automotive industries on the one hand and valuable potential resources on the other hand motivated carpet industries in Europe to design and implement recovery networks for used carpet. The authors presented an open-loop non-linear location allocation programming model for collecting and preprocessing used carpet. The objective of the model is to determine the optimal locations and capacities of recovery centers while minimizing the total investment, processing, and transportation costs. The model presented in this study differs in two aspects from other location allocation models. The first difference is the free choice of preprocessing locations. The second one is the inclusion of depreciation cost of buildings and facilities. After formulating the recovery network model, two practical models were solved to optimality using standard software (Fortran 90). At the end of the study, Louwers *et al* (1999) presented two practical applications of the model. One of them is in Europe where governmental regulations require that everything supplied has to be collected and processed. The other application is one in the US where everything collected has to be processed.

Shih (2001) proposed a mixed integer linear programming model to determine the optimal reverse logistics design and network flow for electrical appliances and computers in Taiwan. The environmental legislations in Taiwan urge manufacturers and importers to take back their products. The proposed reverse logistics system model by Shih (2001) consists of collection and storage sites, disassembly and recycling plants, and the final disposition and reclaimed material market. The objective of the model is to minimize the total cost which consists of operational cost, fixed cost, transportation cost, and disposal cost minus the revenue from selling the reclaimed materials. The objective is fulfilled by obtaining the optimal recovery network design which can be done by finding the best number of facilities needed and their locations as well as the network optimal material flows. Lack of information and existence of uncertainty for system parameters made the author to present several scenarios and simulate each of them.

Spengler *et al* (1997) developed an open-loop mixed integer linear programming model for two planning problems: dismantling and recycling of end of lifetime products and recycling industrial by-products in steel industry. For each problem they presented a case study and formulated them accordingly. In the first case they considered dismantling and recycling of buildings and to develop and implement an integrated dismantling and recycling planning systems for domestic buildings demolition waste in the German-French region of Baden-Alsac. A MILP model is formulated and solved using LINDO software to maximize the total marginal income; it is the income from reusable building components minus dismantling and demolition costs. By solving the model, the optimal integrated dismantling and recycling planning system, which includes all demolition sites in the geographical region in a certain planning period, is obtained. The second case deals with location and allocation planning of recycling facilities for by-products generated in iron and steel industry in Germany. Every year great amounts of residuals are produced that have to be recycled to meet the terms of environmental regulations and to reduce disposal costs. Given a set of potential facility locations with different capacities and corresponding fixed and variable costs, the authors proposed a modified multi-level MILP warehouse location model in order to find the optimal recycling network design and material flows while minimizing the overall cost.

Fleischmann (2001) developed a general quantitative model for product recovery network design. The study is the first generic model for the reverse logistics network design which considers both forward and reverse logistics networks. An uncapacitated single-product mixed integer linear programming model is proposed where two networks are integrated: the forward chain which links factories to customers via warehouses, and the reverse chain where customers are connected to factories through disassembly centers. The two networks are integrated by means of a balance constraint which ensures that for each factory, the total return flow is not greater than its total production. Based on the total cost minimization objective, the model is developed to obtain the optimal facility locations and the corresponding material flow. Two case studies were conducted, one in a copier remanufacturing and one in paper recycling industry, to illustrate the model and to study the impact of return rates on the total network design. Finally, the author concluded that in many cases it is beneficial to include the reverse chain in the forward chain.

Logozar *et al* (2006) studied the impact of fixed and variable transportation costs as well as returned material flow quantities on the design of recovery network in aluminum industry. The authors developed a linear optimization model in a case of five aluminum scrap sources and two reprocessing units. Two different models of scrap collection and transportation are considered and formulated accordingly. The first model consists of only sources and sinks which means there are five scrap generation points and two reprocessing units and the materials are transported directly to the sinks. However, in the second model there is a collection site between those in the first model. The objective of the proposed model is to determine the minimum cost of in-plant aluminum recycling, subject to constraints of collected scrap quantities, capacity of reprocessing units, and availability of transportation routes. The two models were solved based on a real situation in a Slovenian aluminum manufacturer and were compared to show the impact of fixed and variable transportation costs and material quantity on the network design.

Lu *et al* (2007) presented a two-level facility location problem in reverse logistics network design in which three facility types are to be located: producers, remanufacturers, and intermediate centers. They proposed an integrated mixed integer linear programming model which simultaneously considers forward and reverse flows and their mutual interactions. Producers are providers of new products in the system. Remanufacturing centers receive the returns from intermediate centers and remanufacture the products; together with producers, they are responsible to meet the product demand. Intermediate centers are only available in the reverse chain and are responsible for processes such as cleaning, disassembling, sorting, and inspecting. The objective of the proposed model is to minimize the total cost consisting of fixed and variable costs. The problem is solved by an algorithm based on Lagrangian heuristics approach. Through numerical examples the authors concluded that reverse flows influence the decisions on facility location and allocation. The influence varies with the magnitude of the reverse flows, their distribution at demand sites, and their correlation with forward flows.

2.4 Multiple Product Problems

Salema *et al* (2006) proposed a mixed integer linear programming model formulation for design of integrated recovery network. Based on the warehouse location-allocation model formulation the objective is to simultaneously optimize facility locations and network flows in forward and reverse networks. The model is a generalization of the proposed recovery network model in Fleischmann (2001) with two important extensions. It is a multi-product model and also all facilities in the model have minimum and maximum capacities. In order to gain a better insight into the proposed model, two case studies, two-level and single level design of reverse logistics network, were conducted and solved using Branch and Bound technique.

Salema *et al* (2007) presented a mixed integer linear programming model, an extension to their previous work in recovery network design (Salema *et al*, 2006). In their study they considered three characteristics of a real world problem which are production capacity constraints, multi-product production system, and demand/return uncertainty. They developed a generic model formulation for product recovery network design proposed in Fleischmann (2001) to a multi product and capacitated MILP model. In order to tackle the uncertainty associated with demand and return, they considered three scenarios with different demand and return rates in a given case study and compared them. The first scenario is based on real data for an Iberian company; the second scenario models the most pessimistic situation; and the last scenario presents the most optimistic one. For each scenario, there is an associated probability value. The model is solved for each scenario and the results obtained were compared with each other in order to have an illustration for decision makers regarding different patterns of product demand and return and their impact on the recovery network design.

2.5 Multi-Objective Model Formulation

Nozick and Turnquist (2001) developed a multi-objective facility location integer programming model to locate facilities from a set of potential sites. The purpose of this study is to investigate the trade-offs among facility investment costs, inventory costs, transportation costs, and customer responsiveness. In the proposed model, cost minimization objectives would lead to centralization of facilities. However, customer responsiveness maximization would require having goods as close to the final customers as possible which leads to decentralization of facilities. An effective balance between cost and customer responsiveness is to be obtained. The problem was solved by weighting method. A weight number was considered in demand coverage objective to transform the multi-objective model into a single objective one. By varying the values of the weight number a variety of non-dominating solutions would be achieved. A high value of the weight number will result in better demand coverage and high customer responsiveness level. In contrast, a low weight value will result in total cost minimization. The authors presented an example in US automotive industry to illustrate the model application.

Krikke *et al* (2003) presented a multi-objective closed-loop mixed integer linear programming model for solving integrated supply chain design problem. They considered forward and reverse flows inclusively with multiple product and multiple product recovery options. The objective of this study is two folded. It simultaneously supports optimization of supply chain overall costs and its environmental impact. This is done by reaching the optimal facility locations and material flow allocation in the logistics system as well as product design structure of the product such as modularity, reparability, and recyclability. In order to analyze mutual interactions of the product design and the network design and to test the robustness of results, a case study in a Japanese refrigerator manufacturer is conducted. Different scenarios with different parameter settings like centralized and decentralized logistics, various product designs, and various product return quantities and qualities are considered and compared for managerial use.

Du *et al* (2008) proposed a bi-objective mixed integer programming optimization model for design of reverse logistics network. The problem is to decide on opening repair facilities for post-sale warranty returns from a set of potential locations and to allocate repair capacities among these locations. In this model, transportation is outsourced to a third-party logistics provider which already had established logistics network. The logistics provider can support transportation services for the manufacturer and its customers and also can act as the collector of the returns. The two objectives considered are minimization of total cost and total tardiness of cycle time. The study investigates the trade-offs associated with these two objectives in design of reverse logistics network. A solution approach which consists of a combination of three algorithms was designed for solving the model. First, scatter search was applied to decide on the binary decision variables representing the capacity arrangement among the potential facilities. Second, based on a set of determined binary variables, the dual simplex method was used to find the optimal solutions for continuous variables representing the transportation arrangement with respect to the two objective functions. Finally, to obtain a set of non-dominating solutions, the constraint method was applied.

Pati *et al* (2008) presented a mixed integer goal programming model in paper recycling logistics network design. The model considers three objectives, total cost minimization, product quality maximization, and wastepaper recovery maximization. The problem is to determine facility locations as well as route and flow of different varieties of recyclable wastepaper. Based on the three objectives, six priority structures were constructed by considering different combinations of the three objectives arrangements. By doing so, the trade-offs between the objectives in different scenarios can be investigated to assist policy makers to understand the effect of each objective on the system behavior. In order to illustrate the use of the proposed model, a real world problem in paper recycling in India was solved.

Erkut *et al* (2008) developed a multi-objective mixed integer programming model to solve the location-allocation problem of solid waste management in north Greece. The model consists of five conflicting objectives with respect to economic and environmental criteria. These objectives are: Greenhouse effect minimization, landfill disposal minimization, energy recovery maximization, material recovery maximization, and total cost minimization. The greenhouse effect is translated as the product of the amount of waste produced in facilities based on the greenhouse emission coefficient associated with those facilities. Landfill disposal is defined as to minimize the amount of waste that cannot be recovered. Finally, total cost includes facility opening cost, transportation costs, and treatment costs. The problem is to find the locations of the facilities as well as the waste flows between these locations based on a non-dominating solution. The problem was solved applying the lexicographic minimax approach to obtain a "fair" non-dominating solution.

2.6 Summary

The literature discussed in this chapter covers the research work carried out in the area of reverse logistics and recovery network design. Much research work has been conducted in cases of uncapacitated single product problems and models have been formulated using operations research tools. Few recent studies have been carried out to present integer programming models for capacitated multiple-product problems. Most of the above mentioned research works deal with cost minimization objective function disregarding environmental, legislative, and service level issues.

Since reverse logistics network design problems explicitly involve more than one attribute or objective, multi-objective model formulations are more favorable for decision and policy makers. Multi-objective model has several advantages over a single objective one. It allows various criteria to be investigated in their natural measurement units. Moreover, multi-objective analysis presents a set of non-inferior or non-dominated solutions which make it easy to investigate the impact of any objective on the overall solution and the trade-offs between the objectives.

In next chapter, a mathematical model formulation for solving capacitated multi-objective, multiple-product facility location/allocation problem for the design of reverse logistics network is developed. The interactions between cost, environmental legislation, and technological capabilities are studied.

Chapter Three

Model Formulation and Solution Approach

In this chapter, we present details of the problem studied in this research and develop a mathematical model formulation for design of an integrated reverse logistics network.

3.1 Problem Introduction

The problem studied in this research is to design an integrated logistics network in product recovery context. Based on the problem characteristics identified in previous chapters, the recovery network consists of four components: plants, warehouses, disassembly, and customers. The problem is to select the facilities to be opened in such a way that:

- The facilities and transportation links between facilities in the network have sufficient capacity.
- The internal and external obligations regarding the material collection and disposal amounts are satisfied.

The general structure of a recovery network is shown in Figure 3.1.This network structure is based on and extended the one presented in Fleischmann (2000). In this network, nodes correspond to facilities and arcs correspond to transportation channels. Three intermediate levels of facilities are considered. These levels correspond to plants for production of new products and re-processing of used products, warehouses for distribution of the products, and disassembly centers for collection, inspection and separation of the returns.

Materials are moved in both forward and backward directions. The forward channel starts from plants at level where production and re-processing are carried out. Goods are moved from the plants to warehouses at level for distribution to customers at level . Customers could be regional warehouses, retailers, or individuals.

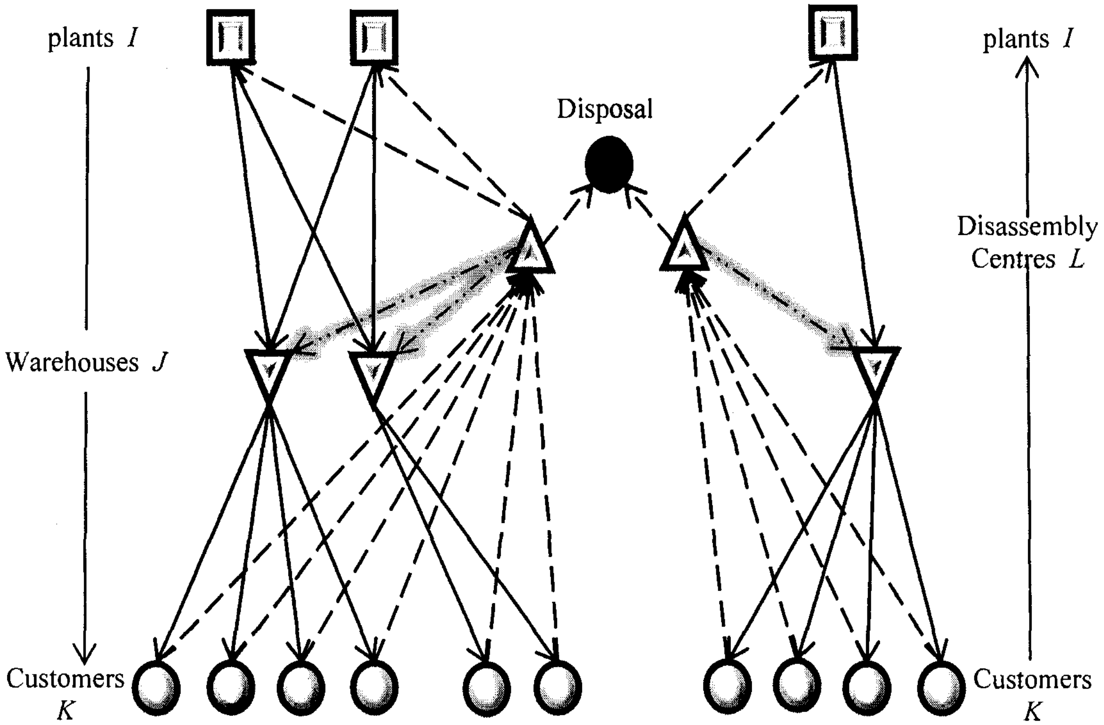

Figure 3.1.Recovery Network Structure

As discussed earlier, a fraction of the goods received by customers would be returned. The returns can be in different forms. They can be end-of-life products, damaged goods, recalls, unsold merchandise, etc. After the returns are collected, they are transported to the disassembly centers where the returned goods are inspected and separated. The returns that can be used without any major recovery function are sent directly to the warehouses for reuse. Others are sent to the plants for recovery or to disposed site.

Within this framework, the considered network design problem is to decide the number and locations of the facilities and to allocate corresponding material flows through the network channels to these facilities. The problem is formulated as a multi-objective, capacitated, multiple-product mixed integer linear programming model. Three objectives are explicitly considered concerning economic, environmental and legislative, and technical requirements.

Multi-objective analysis has several advantages over single objective analysis. First, it provides a systematic methodology to analyze the impacts of strategic decisions. Second, it allows various criteria to be evaluated in their natural units of measurement. This eliminates the necessity of transforming various objectives to a common unit of measurement such as dollars. Finally, such technique provides the information of all possibilities of alternative solutions for a given set of objectives. The non-dominating solution set and the trade-offs of the objectives assist the decision-makers in making more balanced decisions considering different and important factors.

The first objective is to minimize the total cost. It is the sum of fixed costs of opening the facilities (plants, warehouses, and disassembly centers), the total transportation costs between each pair of facilities and between facilities and customers, and the penalty cost of not satisfying customer's demand.

The second objective concerns the environmental and legislative aspects of the problem. The goal is to maximize the returned goods collection. The main drivers of this objective are environmental and governmental obligations.

The third objective is to maximize the total recovered amount of the collected used goods. The technical and proficiency level of the recovery facilities and employees have direct impact on the ability to recover value from the collected products.

In the next section, the assumptions used in developing the mathematical programming model are presented.

3.2 Model Assumptions

1. The model is based on a single-period of time.
2. The model is deterministic so that demand and return quantities are fixed and known. The location of each customer is also known.
3. The model selects plants, warehouses, disassembly centers from a given set of potential locations.
4. The disassembly centers perform inspection and separation functions. Also, minor maintenance and re-processing activities can be done in those centers.
5. The disposed returned goods can be sources to a third party, i.e. material recycling, landfilling, or incineration.
6. Each facility (plant, warehouse, and disassembly center) has a capacity limit for each product type.
7. The recovered products are treated as new and can enter the same supply chain along with the new products.
8. Required raw materials to produce new products are available in the plants. In that sense, there is no need to incorporate suppliers and their delivery means to the model.

3.3 Model Notations

Index sets

$I = \{1, \dots, N_p\}$	Set of potential plants;
$J = \{1, \dots, N_w\}$	Set of potential warehouses;
$K = \{1, \dots, N_c\}$	Set of potential customers;
$L = \{1, \dots, N_r\}$	Set of potential disassembly centers;
$S = \{0\}$	Disposal site;

Variables

X_{mij}^{f1} = Forward flow: demand of product m served from plant i to warehouse j;

$m \in M, i \in I, j \in J$

X_{mjk}^{f2} = Forward flow: demand of product m served from warehouse j to customer$k$;

$m \in M, j \in J, k \in K$

X_{mkl}^{r1} = Reverse flow: returns of product m from customer k to disassembly centre l;

$m \in M, k \in K, l \in L$

X_{mli}^{r2} = Reverse flow: returns of product m from disassembly centre l to plant i;

$m \in M, l \in L, i \in I$

X_{mlj}^{r3} = Reverse flow: returns of product m from disassembly centre l to warehouse j;

$m \in M, l \in L, j \in J$

X_{mls}^{d} = Reverse flow: returns of product m from Disassembly center l to disposal site s;

$m \in M, l \in L, s \in S$

U_{mk} = Unsatisfied demand of customer k for product m; $m \in M, k \in K$

Y_i^p = 1 if factory i is opened, 0 otherwise; $i \in I$,

Y_j^w = 1 if warehouse j is opened, 0 otherwise; $j \in J$,

Y_l^d = 1 if disassembly centre l is opened, 0 otherwise; $l \in L$,

Costs

C_{mij}^{f1} = Unit variable cost for serving demand of product m from plant i to warehouse j, including transportation, production, and handling costs; $m \in M, i \in I, j \in J$

C_{mjk}^{f2} =Unit variable cost for serving demand of product m from warehouse j to customer k, including transportation and handling costs; $m \in M, j \in J, k \in K$

C_{mkl}^{r1} =Unit variable cost for return of product m from customer k to disassembly center l, including transportation and handling costs; $m \in M, k \in K, l \in L$

C_{mli}^{r2} = Unit variable cost for return of product m from disassembly center l to plant i, including transportation and handling cost minus production cost savings;

$m \in M, l \in L, i \in I$

C^{r3}_{mlj} = Unit variable cost for return of product m from disassembly center l to warehouse$j$; $m \in M, l \in L, j \in J$

C^{d}_{mls} = Unit variable cost of disposing return of product m from disassembly centre l; $m \in M, l \in L, s \in S$

C^{u}_{mk} = Unit penalty cost of not satisfying demand of customer k for product m; $m \in M, k \in K$

f^{p}_{i} = Fixed cost of opening plant i; $i \in I$

f^{w}_{j} = Fixed cost of opening warehouse j; $j \in J$

f^{d}_{l} = Fixed cost of opening disassembly centre l; $l \in L$

Parameters

α = Minimum disposal fraction;

β = Maximum direct reusable return fraction;

d_{mk} = Demand of customer k for product m; $m \in M, k \in K$

r_{mk} = Return of product m from customer k; $m \in M, k \in K$

g^{p}_{mi} = Capacity of plant i to produce product m; $m \in M, i \in I$

g^{w}_{mj} = Capacity of warehouse j for product m; $m \in M, j \in J$

g^{d}_{ml} = Capacity of disassembly centre l for product m; $m \in M, l \in L$

3.4 Model Formulation

In this research the multi-objective reverse logistics network design model is formulated as follows:

3.4.1 Objective Functions

Many practical optimization need to meet multiple goals at the same time. Multi-objective analysis presents a set of non-inferior or non-dominating solutions. Generally, in multi-objective decision models, the objectives are in conflict. For example, in this model there is a trade-off between the decisions to minimize the total cost and to maximize returned goods collection. Thus, there may not exist any solution that is optimal for both objectives. The decision maker is to find a set of non-dominating solutions instead of optimal solutions. In that respect, a non-dominating solution is the one that improvement in value of one objective would result in degradation of at least one of the other objective's value. Hence, multi-objective models are used to obtain various non-dominating solutions for the problem rather than reaching optimum solutions.

Moreover, in multi-objective problems the interactions of the objectives can be studied. Therefore, these types of problems are more favorable for decision makers. In this research, different issues are considered in design of a recovery system. These issues are cost efficiency, environmental adoptability, and technological capability. In this model formulation these three objectives are considered as follows:

$$
\begin{aligned}
Min\, Z_1 = {} & \sum_{i\in I} f_i^p Y_i^p + \sum_{j\in J} f_j^w Y_j^w + \sum_{l\in L} f_l^d Y_l^d \\
& + \sum_{m\in M} \sum_{i\in I} \sum_{j\in J} C_{mij}^{f1} X_{mij}^{f1} + \sum_{m\in M} \sum_{j\in J} \sum_{k\in K} C_{mjk}^{f2} X_{mjk}^{f2} \\
& + \sum_{m\in M} \sum_{k\in K} \sum_{l\in L} C_{mkl}^{r1} X_{mkl}^{r1} + \sum_{m\in M} \sum_{l\in L} \sum_{i\in I} C_{mli}^{r2} X_{mli}^{r2} \\
& + \sum_{m\in M} \sum_{l\in L} \sum_{j\in J} C_{mlj}^{r3} X_{mlj}^{r3} + \sum_{m\in M} \sum_{l\in L} \sum_{s\in S} C_{mls}^{d} X_{mls}^{d} \\
& + \sum_{m\in M} \sum_{k\in K} C_{mk}^{u} U_{mk}
\end{aligned}
\tag{3.1}
$$

The first objective is to minimize Z_1, the total cost which consists of fixed costs and variable costs. The first three terms correspond to the fixed cost associated with facility investments. The decision variable to open a facility equals to 1 if the facility is decided to be open and 0 when it is not to be opened. The total fixed cost is composed of the fixed costs of all open facilities (plants, warehouses, and disassembly centers).

The fourth term corresponds to the total forward transportation cost between factories and warehouses. The fifth term defines the total forward transportation cost between warehouses and customers. The sixth term sets the reverse transportation cost of returned products from customers to disassembly centers. The seventh term identifies the total transportation cost of returns from each pair of disassembly center and plant. The eighth term corresponds to the total transportation costs of transporting reusable returns from disassembly centers to the warehouses. The ninth term defines the total transportation cost of disposable products to be transferred from disassembly centers to the disposal site. Finally the last term defines the penalty costs of not satisfying a customer's demand. It has to be noted that the transportation costs may vary for each different type of product.

The second objective, Z_2, is to maximize the total collected returns. This is to follow with environmental and legislative requirements to increase recovering value from returned product as an alternative supply source.

$$Max\ Z_2 = \sum_{m\in M}\sum_{k\in K}\sum_{l\in L} X^{r1}_{mkl} \Big/ \sum_{m\in M}\sum_{k\in K} r_{mk} \tag{3.2}$$

This objective is defined as the ratio of the total amount of returns actually collected to the total amount of returns available from each customer for each product type.

The third objective, Z_3, is to maximize the total amount of recovered returns. This objective is defined as technical proficiency of the recovery system and the ability to recover returns and bring them back into the reuse market.

$$Max\ Z_3 = \sum_{m\in M}\sum_{k\in K}\sum_{l\in L} X^{r1}_{mkl} - \sum_{m\in M}\sum_{l\in L}\sum_{s\in S} X^{d}_{mls} \tag{3.3}$$

This objective is the difference between total amounts of collected returns and the total amount of disposed returns for each product type.

3.4.2 Constraints

$$\sum_{j\in J} X^{f_2}_{mjk} + U_{mk} = d_{mk} \qquad \forall m \in M, k \in K \tag{3.4}$$

$$\sum_{l\in L} X^{r1}_{mkl} \le r_{mk} \qquad \forall m \in M, k \in K \tag{3.5}$$

$$\alpha \sum_{k\in K} X^{r1}_{mkl} \le \sum_{s\in S} X^{d}_{mls} \qquad \forall m \in M, l \in L \tag{3.6}$$

$$\sum_{j\in J} X^{r3}_{mlj} \le \beta \sum_{k\in K} X^{r1}_{mkl} \qquad \forall m \in M, l \in L \tag{3.7}$$

$$\sum_{i\in I} X^{f_1}_{mij} + \sum_{l\in L} X^{r3}_{mlj} = \sum_{k\in K} X^{f_2}_{mjk} \qquad \forall m \in M, j \in J \tag{3.8}$$

$$\textstyle\sum_{i\in I} X^{r_2}_{mli} + \sum_{j\in J} X^{r3}_{mlj} + \sum_{s\in S} X^{d}_{mls} = \sum_{k\in K} X^{r_1}_{mkl} \qquad \forall m \in M\,, l \in L \tag{3.9}$$

$$\textstyle\sum_{k\in K} \sum_{l\in L} X^{r_1}_{mkl} \leq \sum_{j\in J} \sum_{k\in K} X^{f_2}_{mjk} \qquad \forall m \in M \tag{3.10}$$

$$\textstyle\sum_{j\in J} X^{f_1}_{mij} \leq g^{p}_{mi} Y^{p}_{i} \qquad \forall m \in M\,, i \in I \tag{3.11}$$

$$\textstyle\sum_{k\in K} X^{f_2}_{mjk} \leq g^{w}_{mj} Y^{w}_{j} \qquad \forall m \in M\,, j \in J \tag{3.12}$$

$$\textstyle\sum_{k\in K} X^{r_1}_{mkl} \leq g^{d}_{ml} Y^{d}_{l} \qquad \forall m \in M\,, l \in L \tag{3.13}$$

$$\textstyle\sum_{m\in M} \sum_{l\in L} X^{r_2}_{mli} \leq Big\ M\ Y^{p}_{i} \qquad \forall i \in I \tag{3.14}$$

$$\textstyle\sum_{m\in M} \sum_{j\in J} X^{r3}_{mlj} \leq Big\ M\ Y^{w}_{j} \qquad \forall j \in J \tag{3.15}$$

$$X^{f_1}_{mij}\,, X^{f_2}_{mjk}\,, X^{r_1}_{mkl}\,, X^{r_2}_{mli}, X^{r3}_{mlj}, X^{d}_{mls} \in R_0^{+} \tag{3.16}$$

$$Y^{p}_{mi}\,, Y^{w}_{mj}\,, Y^{d}_{ml} \in \{0,1\} \tag{3.17}$$

Constraint 3.4 ensures that for each product all the customer's demand is met. This constraint includes all the supplied and non-supplied amounts of products in forward channel. Constraint 3.5 guarantees that the return amounts collected from each customer for each product are not exceeded the return amounts available to collect. Constraint 3.6 models the minimum disposal fraction for each product return. This is defined as a fraction of all the returned products received by each disassembly center that must be disposed. This fraction is defined by α which is a fixed value between $[0,1]$. If $\alpha = 0$, there is no obligation for disposal. If $\alpha = 1$ then all the returns have to undergo disposal. Constraint 3.7 reflects a fraction of each product's return, received by each disassembly centre that can be reused without going through major recovery processes. This fraction, namely β, is a fixed value between $[0,1]$. When $\beta = 0$, there is no flow between the disassembly centers and the warehouses. Whereas, for $\beta = 1$ all the returns can be used directly in forward supply chain. Constraint 3.8 ensures that every product that enters warehouse j will be sent to a customer. Similar requirement for disassembly centers is enforced by constraint 3.9, where every product goes through disassembly center l will be sent to a plant, a warehouse, or the disposal site. Constraint 3.10 coordinates the forward and reverse flows. The total amount of each product returned to all disassembly centers should not be greater than the total amount of each product supplied to the customers. In other words, each factory cannot receive more returns than the produced amount. This constraint ensures the system balance. The gap between these two amounts represents the production of new products. Constraints 3.11 – 3.13 define opening conditions for the facilities in this model which are plants, warehouses, and disassembly centers. These constraints also impose facility capacity limits of production or storage for each product type. Constraints 3.14 and 3.15 ensure that used products would only be sent to open plants and warehouses. Constraints 3.16 and 3.17 determine the domain of the variables.

The above model is quite general and flexible and can be easily applied to different situations. The model considers demand and return of each product independently. Each product and customer can only belong to the forward chain or both supply chains. In that case both closed-loop and open-loop networks can be modeled. If $d_{mk} \times r_{mk} > 0$, then product m and customer k belong to both forward and reverse networks which makes a closed-loop network. However, when $d_{mk} \times r_{mk} = 0$ then there is a division between the two networks to form an open-loop network.

The model includes push and pull market drivers for both forward and reverse networks. In forward network, large penalty costs of not satisfying the demand (C_{mk}^{u}) will result in small unsatisfied demand amount (U_{mk}) which indicates a demand-push situation. In contrast, lower values for C_{mk}^{u} will lead to demand-pull situation. In the reverse chain, the second objective function provides a return-push condition.

The integrated reverse logistics network characteristics in this study are summarized in Table 3.1.

Table 3.1.Model characteristics

Reverse/ integral network	Integral
Open/closed loop	Both
Market driver	Push/pull
# of network levels	5
Capacities	Capacitated
# of periods	1
# of commodities	Multiple
Mathematical programming	MOLP

3.5 Solution Approach

Different solution methods can be utilized to generate a set of non-dominating solutions in solving multi-objective problems. The most commonly used methods of solving this type of problems are weighing method, constraint method, and goal programming approach.

In weighting method, conflicting objective functions in a multi-objective problem are transformed into a single-objective. To do so, a single objective function is obtained by combining the original objective functions and assigning a weight to each of them. By varying the weights and applying a conventional solution approach to solve the single-objective problem, a set of non-dominating solutions for the multi-objective problem can be obtained.

In constraint method, the problem is solved by optimizing one objective function while other objective functions are treated as constraints and bounded with some values. By varying the bounds of the constrained objective functions, a set of non-dominating solutions can be obtained. Again, the resulted single-objective model can be solved using a conventional solution scheme.

Another well-known solution method in solving multi-objective problems is goal programming. The basic idea of goal programming is for each objective under consideration, a goal value is to be achieved and the deviations from those goals would be minimized (Tamiz 1996). In comparison to weighing method, goal programming eliminates troublesome weighing processes, but it needs specific targeted goals from decision makers. In general, this method gives a definite solution rather than a set of non-dominating solutions.

In this research the constraint method is applied since it reduces the problem size and dismisses uncertain weights. Moreover, it is easy to implement and the results match our aim to present a set of non-dominating solutions rather than a single solution. The results present different solutions and their trade-offs.

The constraint method algorithm used in this research is similar to that discussed in Du *et al* (2008).The specific steps for solving multiple objective models are as bellow:

Step 1: Construct a trade-off table:

a) For each objective function in the model, solve the optimization model for all objective functions while removing other objectives to find their optimal solutions. Let X^1, X^2, and X^3 be the optimal solutions corresponding to the three objectives, respectively. Then $Z_1^*(X^1)$, $Z_2(X^1)$, and $Z_3(X^1)$ would be the objective function values associated with solution X^1, the optimal solution value for $Z_1(X)$. Similarly, the objective function values corresponding to X^2 and X^3 can be obtained.

b) Construct a trade-off table as shown in Table 3.2.

Table 3.2. Trade-off Table

	$Z_1(X^k)$	$Z_2(X^k)$	$Z_3(X^k)$
X^1	$Z_1^*(X^1)$	$Z_2(X^1)$	$Z_3(X^1)$
X^2	$Z_1(X^2)$	$Z_2^*(X^2)$	$Z_3(X^2)$
X^3	$Z_1(X^3)$	$Z_2(X^3)$	$Z_3^*(X^3)$

The trade-off table gives a systematic way of finding ranges for the objectives in the non-dominated set.

Step 2: Convert the multi-objective model to its corresponding constrained model as:

$$
\begin{aligned}
& Minimize\ Z_1(X) \\
& \quad s.t. \\
& \qquad X \in F_d \\
& \qquad Z_2(X) \leq L_h \\
& \qquad Z_3(X) \leq L'_h
\end{aligned}
$$

The first objective is chosen as the objective function of the single-objective model. The second and the third objectives are treated as constraints. This formulation is a single objective problem with the feasible region of F_d. The range of the second and the third objectives are L_h, L'_h respectively. In other words, the upper bound of L_h is $Z_2^*(X^2)$ and the lower bound of it is $Z_2(X^1)$. Similarly, the upper bound of L'_h is $Z_3^*(X^3)$, and the lower bound of it is $Z_3(X^1)$.

Step 3: Generate a candidate solution by arbitrarily choosing a number $\gamma_1$and γ_2 in the formulas below:

$$L_h = Z_2(X^1) + [h/(\gamma_1 - 1)] \times [Z_2^*(X^2) - Z_2(X^1)]$$

$$L'_h = Z_3(X^1) + [h/(\gamma_2 - 1)] \times [Z_3^*(X^3) - Z_3(X^1)]$$

Where $h = 0, 1, 2, \ldots, (\gamma_i - 1)$

Step 4: Solve the single objective model for every combinations of L_h and L'_h. Each of the optimal solution that is feasible will yield a non-dominating solution.

Chapter Four

Numerical Examples and Analysis

In this chapter we present a numerical example to validate and illustrate the model developed in the previous chapter. The numerical example used in this chapter is hypothetical with realistic assumptions. It is based on and extended from an example problem in the literature. Some extensions are added to the original example for more realistic considerations. The problem is solved by LINGO optimization software, version 10, on a PC platform with 2.2 GHZ and 2 GB RAM.

4.1 Example Problem

The example problem proposed in Salema (2006) for design of reverse logistics network in an European photo copier manufacturer is used in this chapter to illustrate the developed model. We use the same data in the example with some modifications for a hypothetical company. The main modifications are: 1) we consider a multi-product recovery network with three type of product or product family; 2) capacity limits are added to all facilities for each product type independently; and 3) the demand and return volumes as well as the distances between cities are changed.

We assume that the company is a domestic company with manufacturing plants, warehouses, disassembly centers, and distribution channels in Canada. The products are sold to domestic customers across Canada. Used products are collected and shipped to disassembly centers for inspection and separation. At these centers three disposition activities would be carried out. A portion of the returns that can be reused without major re-processing would be sent to warehouses directly for reuse. A portion of returns that could be restored would be shipped to plants for further re-processing. Restored products are sent back to the market as a new product. The remainder is the returns that cannot be reused and would be sent to an external party for material recycling or proper disposal.

4.2.1 Example Problem Data

We assume that the company serves customers in 30 major Canadian cities with known demands. The return volumes for each product are proportional to the demand. We restrict the possible plant locations to 7 cities, whereas warehouses and disassembly centers could be located in any of the 30 cities considered. For simplicity, we assume all relevant costs are location independent and all facilities have equal capacities for the same products.

The size of the integrated reverse logistics network in this example is summarized in table below.

Table 4.1.Example Problem Network Data

Members of the Network	**Total**
Plants	7
Warehouses	30
Disassembly Centers	30
Customers	30
Products	3
Forward supply Chain Arcs	3330
Reverse Supply Chain Arcs	6120

The problem is defined as:

Given

- Customers' demand and return;
- Minimum disposal fraction;
- Maximum reusable return fraction;
- Unit costs of demand and return;
- Unit cost of disposal;
- Penalty cost for non-satisfied demand;
- Fixed costs to open plants, warehouses, and disassembly centers;

Generate a set of non-dominating solutions for three objectives: total cost minimization, total collected returns maximization, and total recovered returns maximization.

Other data used in this example are shown in Table 4.2.

Table 4.2.Example Problem Data

Description	**Parameter**	**Value**
Fixed cost per factory	f^p	\$5,000,000
Fixed cost per warehouse	f^w	\$1,500,000
Fixed cost per disassembly center	f^d	\$500,000
Transportation cost per Km and product		
Factory-warehouse	C^{pw}	\$0.0045
Warehouse- costumer	C^{wc}	\$0.01
Costumer-disassembly center	C^{cr}	\$0.005
Disassembly center- factory	C^{rp}	\$0.003
Disassembly center- warehouse	C^{rw}	\$0.0025
Return rate	$\gamma = {}^{r}/_{d}$	0.6
Minimum disposal fraction	α	0.2
Maximum reusable return fraction	β	0.2
Disposal cost per product	C^d	\$2.5
Not-satisfied demand penalty	C^u	\$100

The unit variable costs are calculated as: $C^{f_1}_{mij} = C^{pw}_m t_{ij}$, $C^{f_2}_{mjk} = C^{wc}_m t_{jk}$, $C^{r_1}_{mkl} = C^{cr}_m t_{kl}$, $C^{r_2}_{mli} = C^{rp}_m t_{li}$, $C^{r_3}_{mlj} = C^{rw}_m t_{lj}$, where t_{ab} is the distance between nodes a and b. The distances between the cities in this example are shown in Appendix A.

4.2 Solution Analysis

We develop the reverse logistics network design model as a multi-objective, multi-product, capacitated mixed integer linear program. The model is coded and solved in LINGO software version 10. The data are managed by Microsoft Excel and linked to the model in LINGO. The data worksheet and LINGO codes are presented in Appendix B.

As discussed in the previous chapter, the model was solved by Constraint Method. The detailed procedure taken to solve the example problem is given next.

4.2.1. Constraint Method

The constraint method algorithm based on the one discussed in Du *et al* (2008) for the tri-objective model in this research is as follows:

Step 1: Construct a trade-off table:

a) Solve the optimization model for each of the three objective functions while relaxing other objectives to find the optimal solution for each one of them. Let X^1, X^2, and X^3 denote optimal solutions of the three objectives, respectively. Then $Z_1^*(X^1)$, $Z_2(X^1)$, and $Z_3(X^1)$ would be the objective function values associated with solution X^1, the optimal solution value for $Z_1(X)$. By the same approach the objective function values corresponding to X^2 and X^3 can be achieved.

b) The trade-off table for this example problem is given in Table 4.3.

Table 4.3.Objective Functions' Trade-off Table

	$Z_1(X^k)$	$Z_2(X^k)$	$Z_3(X^k)$
X^1	47252890	0	0
X^2	49599200	1	3117877
X^3	50052700	1	3117877

The trade-off table gives a systematic way of finding the ranges of the objectives in the non-dominating set.

The example problem has 67 binary variables, 9787 continuous variables and 786 constraints.

Step 2: Convert the multi-objective model to its corresponding constrained model:

$Minimize\ Z_1(X)$

$s.t.$

$X \in F_d$

$Z_2(X) \leq L_h$

$Z_3(X) \leq L'_h$

The first objective is chosen as the objective function of the single-objective model. The second and the third objectives are modeled as constraints. This formulation is a single objective problem with the feasible region of F_d. The upper bound of L_h is 1 and the lower bound of it is zero. Similarly, the upper bound of L'_h is 3117877, and the lower bound of it is zero.

Step 3: Generate a non-dominating solution set by arbitrarily choosing the values of γ_1 and γ_2 in the formula below:

$$L_h = Z_2(X^1) + [h/(\gamma_1 - 1)] \times [Z_2^*(X^2) - Z_2(X^1)]$$

$$L'_h = Z_3(X^1) + [h/(\gamma_2 - 1)] \times [Z_3^*(X^3) - Z_3(X^1)]$$

where $h = 0, 1, 2, \ldots, (\gamma_i - 1)$;

Higher values of γ_i will lead to more candidate solution and require more computational effort. We set $\gamma_1 = 11$ and $\gamma_2 = 6$ in solving this example problem.

Step 4: Solve the single objective model for the 66 combinations of L_h and L'_h. Each of the candidate solution that is feasible will yield a non-dominating solution.

4.2.2. Numerical Results

Table 4.4 shows the feasible non-dominating solutions for the example problem and their trade-offs. The table presents the three objective values and the solutions for the facility arrangements.

Table 4.4.Trade-off Solutions

	Z_1	Z_2	Z_3	**Number of Plants**	**Number of warehouses**	**Number of disassembly Centers**
1	50052700	1	3117877	3	9	9
2	50004600	1	2494302	3	9	9
3	51402460	1	1870726	3	9	9
4	52936190	1	1247151	3	9	9
5	55149650	1	623575	3	9	9
6	64189740	1	0	4	9	9
7	48472500	0.9	2494302	3	9	7
8	49787460	0.9	1870726	3	9	7

Table 4.5.Trade-off Solutions (Continued)

	Z_1	Z_2	Z_3	**Number of Plants**	**Number of warehouses**	**Number of disassembly Centers**
9	51309810	0.9	1247151	3	9	7
10	53215680	0.9	623575	3	9	7
11	61872260	0.9	0	4	9	7
12	47392220	0.8	2494302	3	9	6
13	48675690	0.8	1870726	3	9	6
14	50182610	0.8	1247151	3	9	6
15	51741550	0.8	623575	3	9	6
16	59974960	0.8	0	4	9	6
17	48053330	0.7	1870726	3	9	6
18	49541350	0.7	1247151	3	9	6
19	51100290	0.7	623575	3	9	6
20	58336290	0.7	0	4	9	6
21	48720670	0.6	1870726	4	9	4
22	50124630	0.6	1247151	4	9	4
23	51683570	0.6	623575	4	9	4
24	56701520	0.6	0	4	9	4
25	49149720	0.5	1247151	4	9	3
26	50702320	0.5	623575	4	9	3
27	55209040	0.5	0	4	9	3
28	48693800	0.4	1247151	4	9	3
29	50212890	0.4	623575	4	9	3
30	54121120	0.4	0	4	9	3
31	49267240	0.3	623575	4	9	2
32	52627580	0.3	0	4	9	2
33	48867260	0.2	623575	4	9	2
34	51648000	0.2	0	4	9	2
35	50173660	0.1	0	4	9	1
36	48699320	0	0	4	9	0

There are several points in the above table require more attention. First, the total cost reaches its maximum of 64189740 when 100% of product returns have been collected and all of those went through disposal. This happens because all the product returns are exiting the system so there are no recovery cost savings. Second, as we can observe, the number of disassembly centers is proportional to the amount of collected returns and has a descending trend as the return collection rate decreases. Third, the model decides to open an extra plant whenever there are not sufficient capacities for reusable returns between disassembly centers and warehouses to meet the demand in the forward channel. This happens when the third objective equals to zero and in all cases that the return collection rate is equal or less than 60%. Fourth, the minimum total cost of 47392220 is achieved when 80% of the returns are collected and a total of 2494302 product returns are recovered in the system. Finally, in the last solution, there are no product return collections and no reverse flow in the network. This may not be desirable since the goal of this study is to design an integrated reverse logistics network.

Figure 4.1 illustrates the relationship between the three competing objectives. Each curve represents a return collection rate. The top point of each curve corresponds to the highest disposal amount. The bottom points represent the minimum cost at each collected returns level. In the figure, the impact of return recovery on the overall cost is clearly illustrated. It can be observed from each curve that for a given return collection rate the amount of recovered returns is negatively related to the total cost. On each curve, the top points denote the highest total costs corresponding to the situation when the system has zero return recovery and all the collected returns are disposed. The curves have descending trend as more returns recovered in the reverse chain of the network. They indicate that, less cost occurs when more product returns recovered and reused in the system.

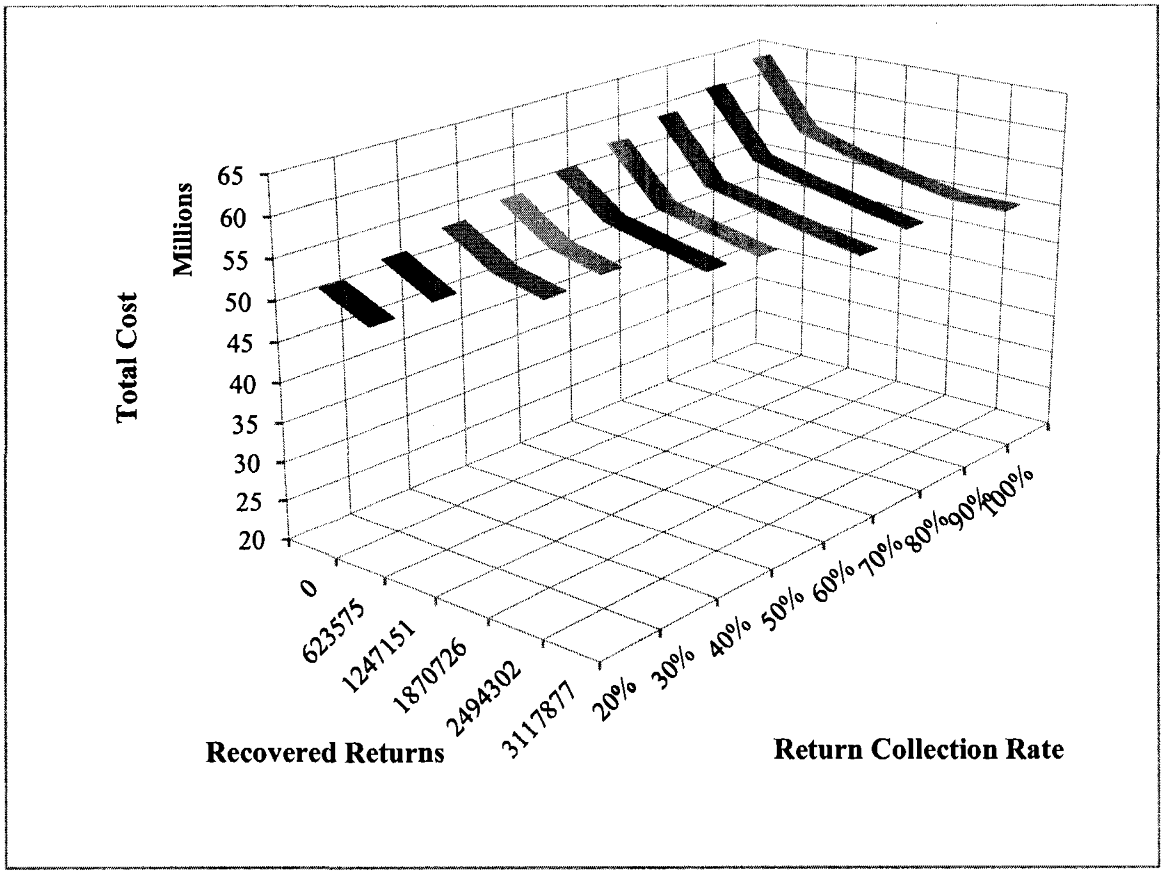

Figure 4.1.The Relationship of Three Objectives

The relationship of return collection rate and total cost is shown in Figure 4.2. Each curve represents a different recovered return amount level. The recovered return amount increases from left to right. The curves show that for the same recovered return level, the total cost increases as the collection rate increases. It can be seen that the minimum total cost occurs when 2494302 returns recovered in the system with 80% of return collection rate which corresponds to point in Figure 4.2.

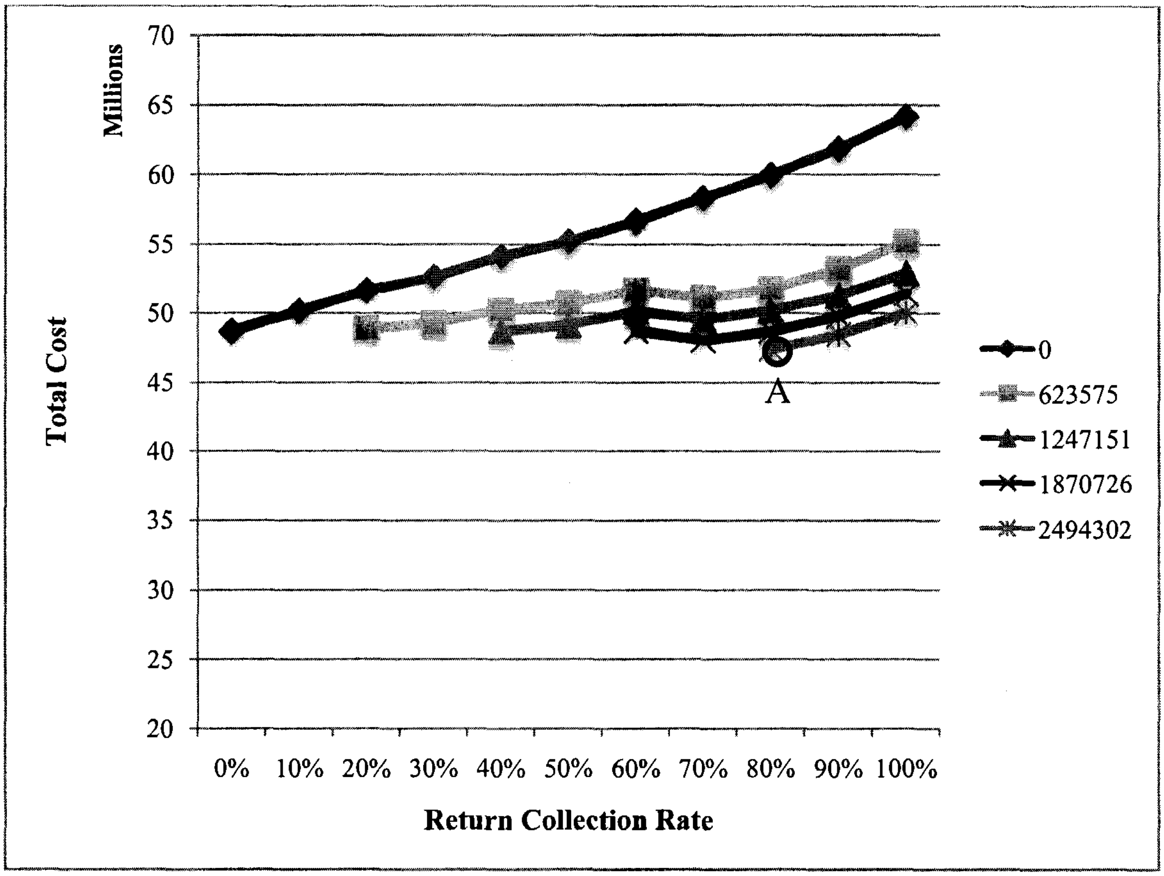

Figure 4.2.Return Collection Rate vs. Total Cost

4.3 Sensitivity Analysis

In the example problem, we conducted some sensitivity analysis on variable costs and maximum direct reusable return fraction to investigate the effects of these parameters on the objective values and the non-dominating solution set.

4.3.1 The Effects of Variable Costs

Variable costs in this example problem are formed as a sum of transportation and operational costs. These costs can vary due to various reasons such as fuel cost. This variation can affect the objective values and the non-dominating solution set. Figure 4.3

illustrates the effect of multiplying variable costs by two on the objective functions' values. It can be seen from the figure that there is a cost increase for each return collection rate.

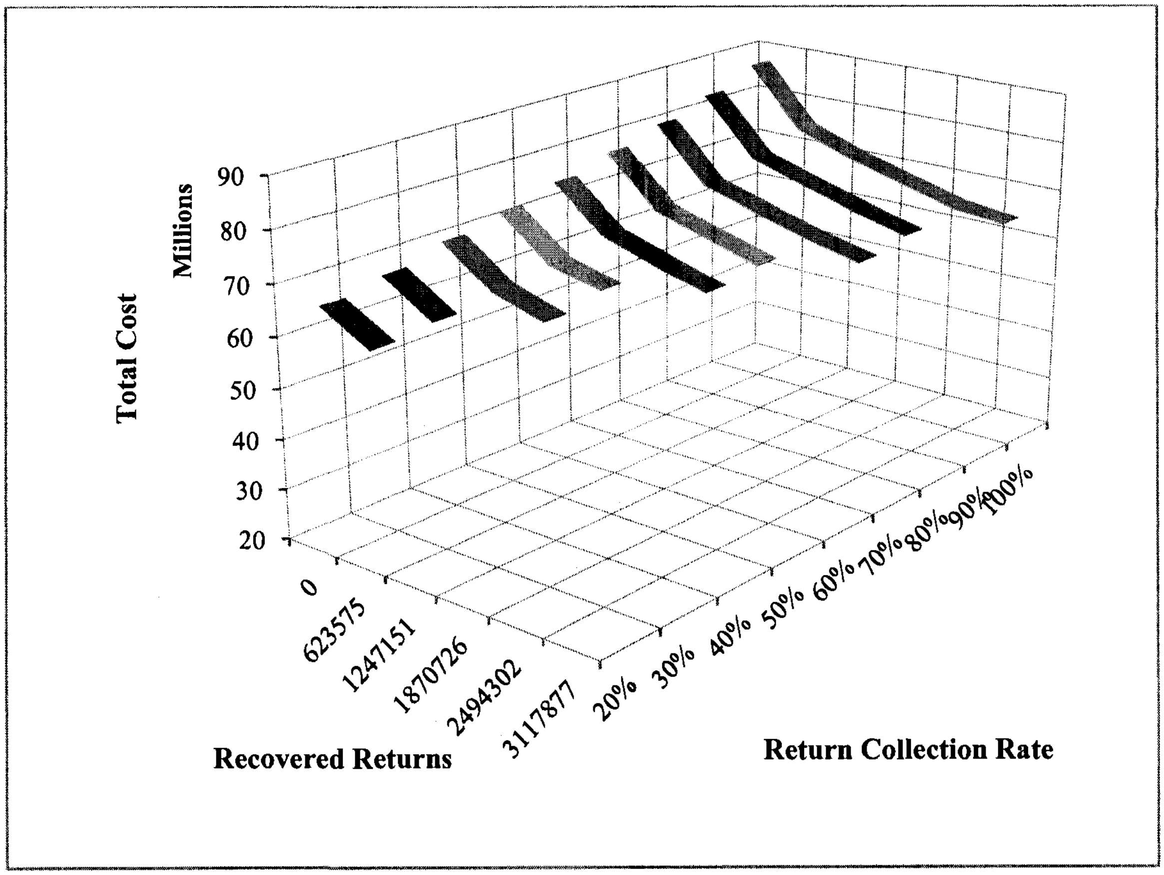

Figure 4.3.The Relationship of Three Objectives

Another effect of variable costs increase on the objective values is that the minimum cost occurs while the return collection rate is 40% and the return recovery amount is 1247151. This value corresponds to point in Figure 4.4.

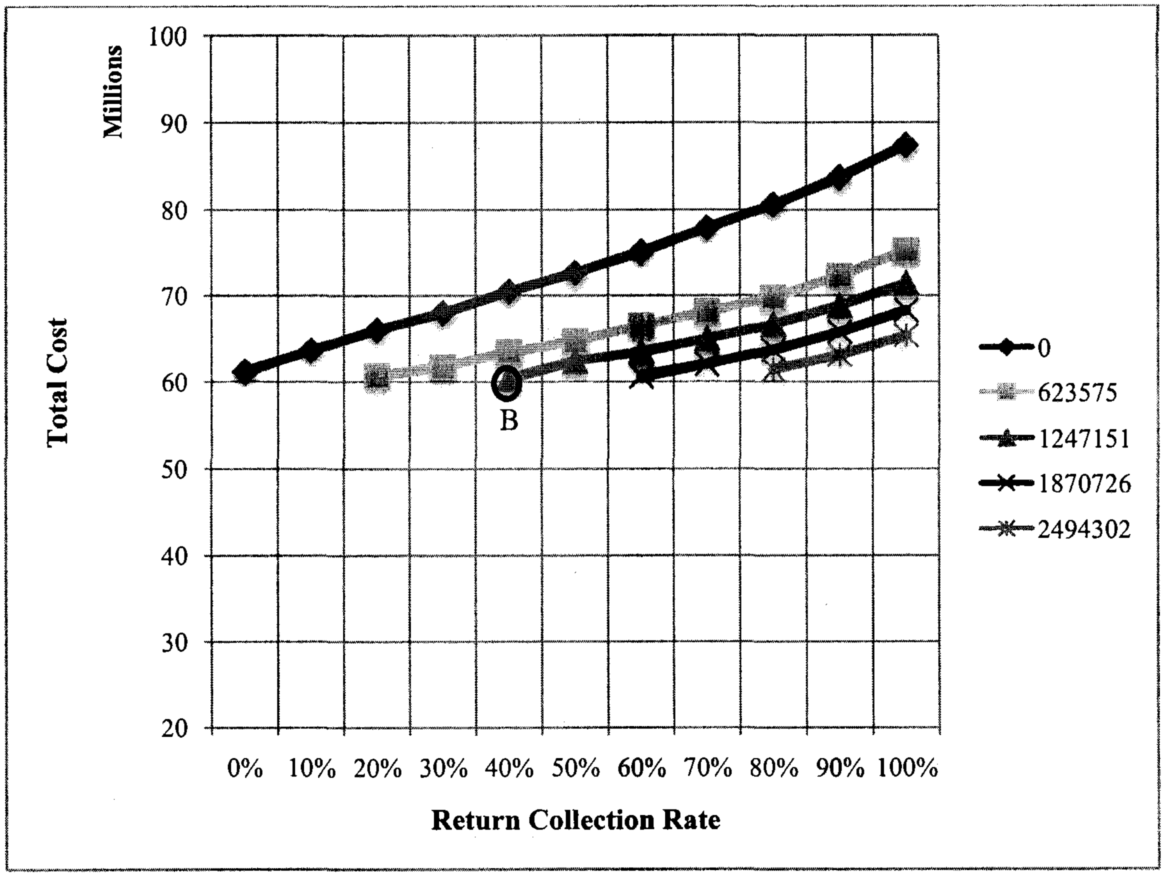

Figure 4.4.The Relationship of Three Objectives

4.3.2 The Effect of Maximum Reusable Return Fraction

The effect of the maximum reusable return fraction can be translated into the technical and technological proficiency of the system to recover the returned goods at disassembly centers. We investigate the effect of this issue on the recovery network design by varying the maximum reusable return fraction. Figures 4.5 and 4.6 illustrate the effects of setting the fraction value to zero and 40%, respectively. Comparing the two graphs, it can be seen that the curves corresponding to each return collection rate have sharper negative slope when 40% of the returns are recovered at disassembly centers because of savings in both fixed and operational costs.

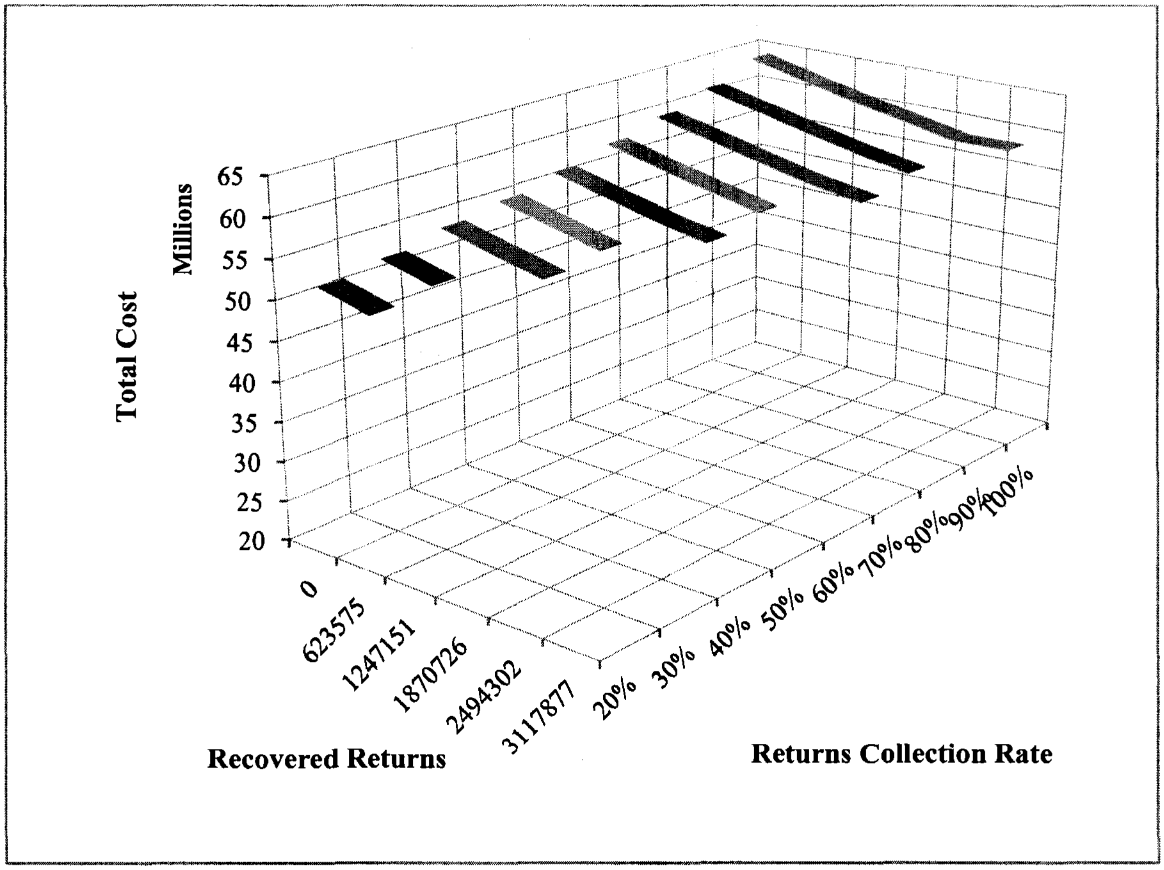

Figure 4.5.The Relationship of Three Objectives

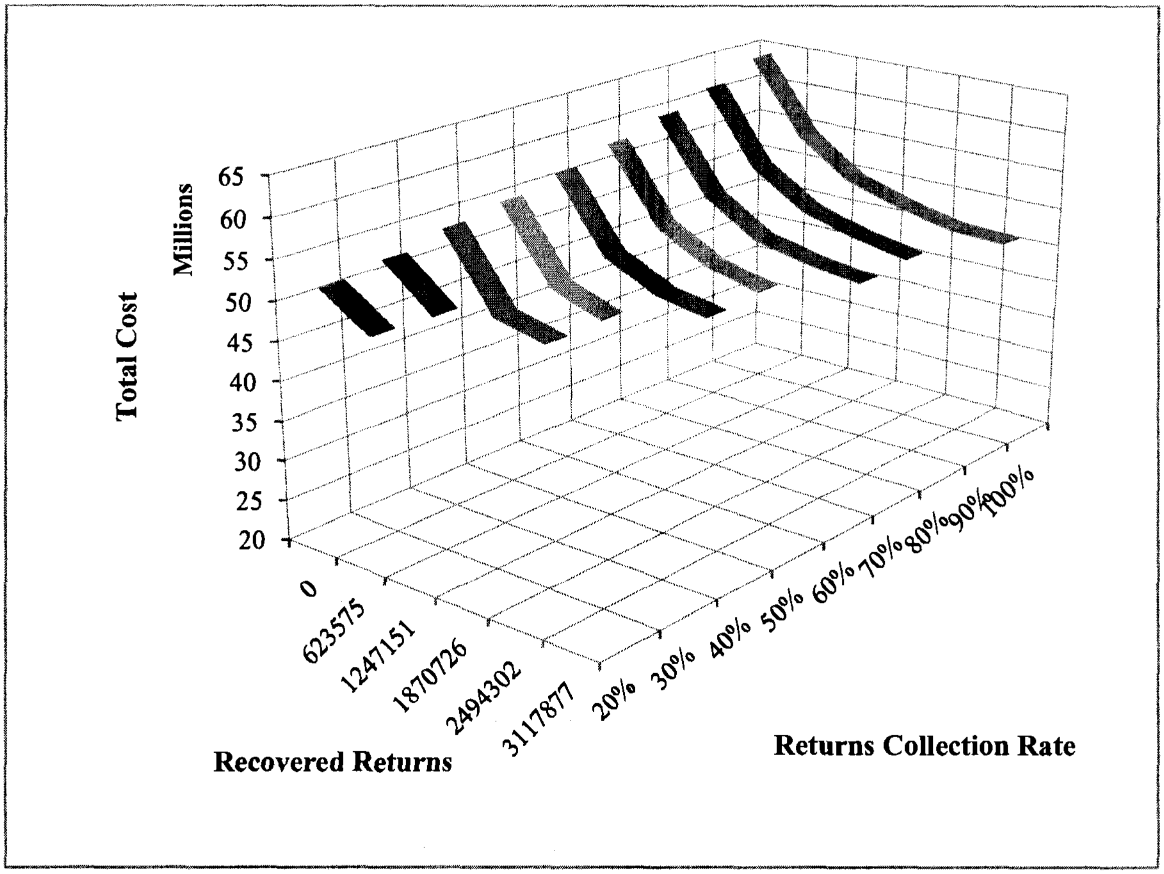

Figure 4.6.The Relationship of Three Objectives

The effect of maximum reusable return fraction on total cost for different values of this fraction can be seen in Figure 4.7. In this figure, minimum costs corresponding to different recovered return amounts and return collection rates are presented. It can be seen that in the case of zero direct reusable return fraction the total cost increases constantly with the increase in return collection rate. However, with 20% direct reusable returns, the total cost fluctuates with the increase in return collection. The minimum cost occurs when the collection rate is 80%, as discussed before. In the case of 40% reusable return fraction, there is a significant cost saving in the system. It can be seen that the curve has a sharp downward slope in total cost before it reaches its minimum at 40% of return collection. It starts to increase gradually thereafter.

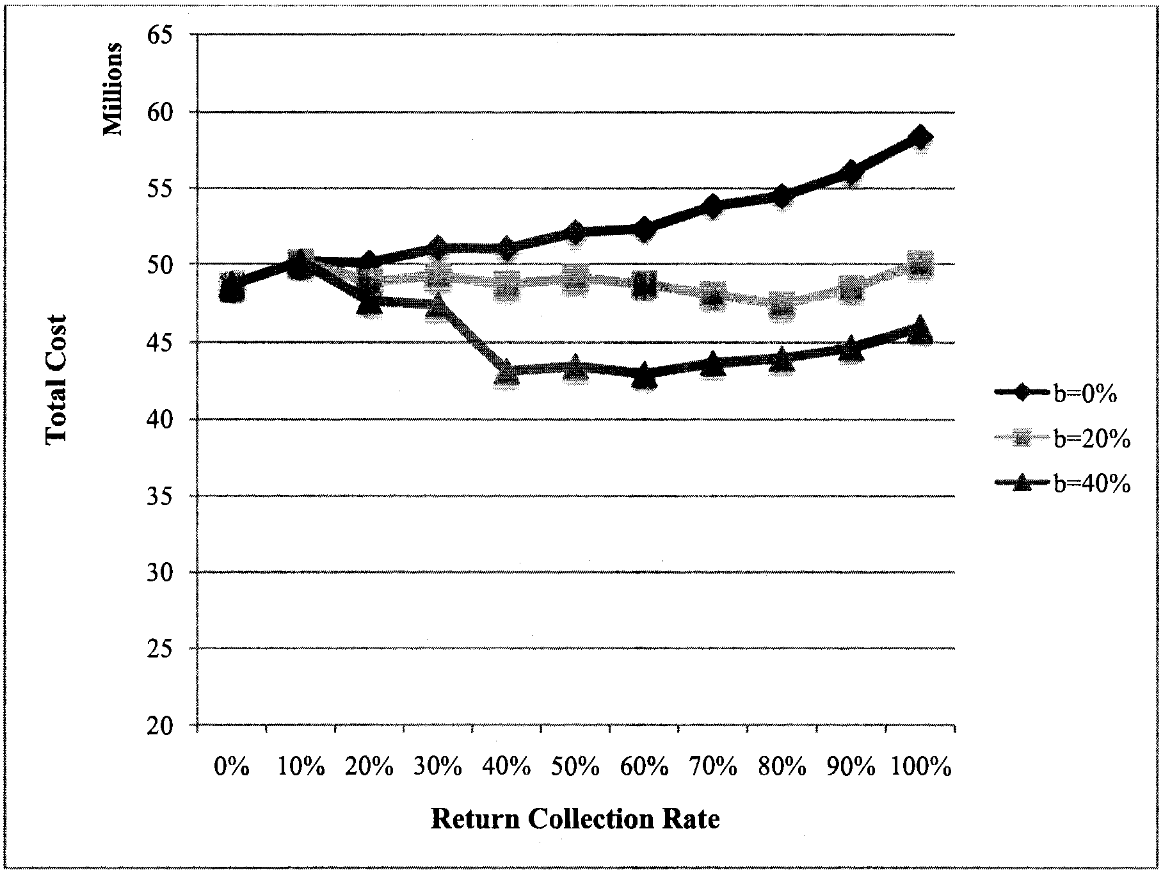

Figure 4.7.The Relationship of Three Objectives

4.4Summery

A numerical example problem is presented based on hypothetical data. The Constraint method is used to transform the multi-objective problem into single objective. The numerical results demonstrate the trade-off table for different solutions sets. The interactions between the three objectives are studied and the location of the facilities can be any of the trade-off solutions for the three objectives. Sensitivity analysis is conducted to study the impact of variable costs as well as reusable return fraction on the network design. The results show that with higher variable costs, the minimum total cost occurs when less product returns are to be collected and recovered. In the second sensitivity test, the problem is tested for three values of reusable return fraction. The result show that with more reusable returns, the total cost decreases due to savings in fixed costs.

Chapter Five

Conclusions and Future Research

In this chapter we present a summary of the research carried out in this thesis. It also includes several concluding remarks based on the problem modeling. Future research directions in this area are also discussed.

5.1 Conclusion

This research extends the work of Fleischmann (2001) and Salema *et al* (2007). They proposed integer programming formulations for designing integrated reverse logistics and recovery networks. In this study we developed a multi-objective mixed integer linear programming model with three objective functions considering total cost minimization as well as return collection rate and product recovery amount maximization. The model is similar to multi-level warehouse location and allocation model which allows simultaneous determination of manufacturing, recovery, and distribution facility selection and allocation, production quantities, forward transportation flows, and used product collection. It also decides disassembly center selection and allocation and reverse transportation flows.

We consider a network with forward and reverse supply chains. In the forward supply chain products are either manufactured or recovered in plants and shipped to warehouses for distribution to customers. Used products are collected and shipped to disassembly centers for inspection and separation. A portion of the collected used products that can be reused directly or with minor recovery function is shipped to warehouses for reuse. Others are shipped to plants for further restoration or to disposed sites.

The developed multi objective linear programming model is flexible to allow new constraints to be added for different implementations. There are some limitations concerning the model formulation that need to be noted. The proposed model is purely deterministic and does not capture the uncertainties which are of the nature of many product recovery systems. Another limitation of the model is the inadequate distinction between new and recovered products. In other words, both product categories are considered as perfect substitutes.

The multi-objective model is solved using the constraint method. The trade-off solutions of total cost, return collection rate, and product recovery amount provide decision makers with a set of non-dominating solutions which assist them in making more balanced decisions considering different and important factors.

The main contributions of this research are three features in modeling the problem. First, a multi-objective model formulation is developed for a general integrated reverse logistics and recovery network design. Thus, the applications are not limited to a specific industry. Second, a new material flow is added to the model to consider the returned products that can be used directly in forward supply chain without a major recovery operation. This feature adds more flexibility to the model implementation. Third, for each product in the system, there is a capacity limit at each facility which makes the model more realistic.

5.2 Future Research

There are several options to extend the model framework presented in this thesis. Our suggestions for future research in this area could be:

- Considering multiple time periods in the model to reflect long-term effects of variables on the network design.
- Incorporating supply and demand uncertainties in the model.
- Considering a separate recovered product market.
- Developing heuristic methods to decrease computational requirement in solving large size problems.

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Appendix A

Nodes' Distances Table

	Toronto	Montreal	Calgary	Ottawa	Edmonton	Mississauga	Winnipeg	Vancouver	Hamilton	Quebec City	Brampton
Toronto	0	545	3486	453	3470	27	2224	4371	66	799	42
Montreal		0	4016	199	4000	564	2754	4901	607	252	569
Calgary			0	3923	298	3466	1328	970	3420	4268	3459
Ottawa				0	3909	473	2171	4810	515	447	477
Edmonton					0	3448	1351	1158	3402	4250	3441
Mississauga						0	2204	4351	46	818	15
Winnipeg							0	2292	2158	3006	2197
Vancouver								0	4305	5154	4345
Hamilton									0	861	60
Quebec City										0	822
Brampton											0
Surrey											
Halifax											
Laval											
London											
Markham											
Gatineau											
Vaughan											
Longueuil											
Windsor											
Kitchener											
Burnaby											
Saskatoon											
Regina											
Richmond											
Oakville											
Burlington											
Richmond Hill											
Greater Sudbury											
Sherbrooke											

Nodes' Distances Table (Continued)

	Surrey	Halifax	Laval	London	Markham	Gatineau	Vaughan	Longueuil	Windsor	Kitchener	Burnaby
Toronto	4338	1790	550	192	31	452	44	566	369	107	4364
Montreal	4868	1244	24	722	533	201	551	9	899	634	4894
Calgary	947	5260	4019	3295	3496	3922	3487	4036	3106	3402	959
Ottawa	4777	1438	198	630	442	3	460	214	808	542	4803
Edmonton	1134	5242	4002	3277	3479	3904	3469	4018	3088	3384	1147
Mississauga	4318	1810	569	171	49	472	40	586	349	83	4344
Winnipeg	2268	3998	2757	2033	2234	2168	2225	2774	1844	2140	2281
Vancouver	35	6145	4905	4181	4382	4807	4373	4921	3992	4287	12
Hamilton	4273	1852	612	127	97	514	83	628	304	63	4299
Quebec City	5121	1022	266	975	486	449	805	244	1152	887	5147
Brampton	4313	1813	573	167	46	475	37	589	344	79	4339
Surrey	0	6111	4866	4147	4348	4773	4339	4887	3958	4254	28
Halifax		0	1257	1966	1778	1440	1796	1235	2144	1878	6139
Laval			0	720	531	194	550	35	897	632	4892
London				0	203	628	194	742	193	109	4175
Markham					0	445	21	559	383	117	4377
Gatineau						0	460	217	807	542	4802
Vaughan							0	571	372	106	4356
Longueuil								0	915	650	4910
Windsor									0	286	3984
Kitchener										0	4283
Burnaby											0
Saskatoon											
Regina											
Richmond											
Oakville											
Burlington											
Richmond Hill											
Greater Sudbury											
Sherbrooke											

Nodes' Distances Table (Continued)

	Saskatoon	Regina	Richmond	Oakville	Burlington	Richmond Hill	Greater Sudbury	Sherbrooke
Toronto	2946	2688	4364	37	56	29	387	695
Montreal	3476	3278	4893	578	597	536	681	157
Calgary	616	760	978	3449	3434	3493	3167	4165
Ottawa	3385	3126	4802	487	506	445	486	349
Edmonton	524	782	1165	3431	3416	3475	3043	4147
Mississauga	2926	2667	4343	21	39	48	391	714
Winnipeg	829	572	2299	2187	2172	2231	1682	2902
Vancouver	1675	1726	13	4334	4319	43	4053	5050
Hamilton	2881	2623	4299	30	15	91	433	757
Quebec City	3729	3471	5147	831	850	790	928	233
Brampton	2921	2663	4339	34	53	43	387	718
Surrey	1652	1703	34	4301	4286	4353	4019	5016
Halifax	4721	4462	6138	1823	1824	1781	1920	1049
Laval	3474	3216	4892	576	595	535	673	176
London	2757	2499	4175	156	141	200	544	871
Markham	2960	2701	4337	64	83	3	383	688
Gatineau	3385	3126	4802	487	505	445	486	352
Vaughan	3143	2884	4366	54	73	15	358	700
Longueuil	3492	3233	4909	594	616	552	697	160
Windsor	2566	2308	3983	333	318	377	721	1048
Kitchener	2865	2606	4282	77	70	112	457	784
Burnaby	1665	1715	26	4324	4309	4368	4043	5040
Saskatoon	0	259	1683	2909	2893	2952	2520	3624
Regina		0	1732	2651	2636	2695	2263	3366
Richmond			0	4327	4312	4371	4045	5043
Oakville				0	20	61	404	728
Burlington					0	81	424	748
Richmond Hill						0	378	686
Greater Sudbury							0	831
Sherbrooke								0

Appendix B

Lingo Code of Integrated Reverse Logistics Network Design

```
SETS:

PLANT/P1..P7/: FP, YP;                 !I;
DISPOSAL/DIS/;                         !I0;
WAREHOUSE/W1..W30/: FW, YW;            !J;
CUSTOMER/C1..C30/;                     !K;
DISASSEMBLY/D1..D30/: FD, YD;          !L;
PRODUCT/G1..G3/;                       !M;

ARC_F1 (PRODUCT, PLANT, WAREHOUSE):CF1, XF1;
ARC_F2 (PRODUCT, WAREHOUSE, CUSTOMER):CF2, XF2;
ARC_R1 (PRODUCT, CUSTOMER, DISASSEMBLY):CR1, XR1;
ARC_R2 (PRODUCT, DISASSEMBLY, PLANT):CR2, XR2;
ARC_RS (PRODUCT, DISASSEMBLY,DISPOSAL):CRS,XRS;
ARC_R3 (PRODUCT, DISASSEMBLY, WAREHOUSE):CR3, XR3;
ARC_MI (PRODUCT, PLANT):GP;
ARC_MK (PRODUCT, CUSTOMER): D, R, CU, CW, U, W;
ARC_MJ (PRODUCT, WAREHOUSE): GW;
ARC_ML (PRODUCT, DISASSEMBLY): GD;
ARC_MD (PRODUCT, DISPOSAL);
ARC_KL (CUSTOMER, DISASSEMBLY);
ARC_JK (WAREHOUSE, CUSTOMER);
ARC_LJ (DISASSEMBLY, WAREHOUSE);


ENDSETS

!********************************* Data ********************************;

DATA:

M=100000000000000;
a=0.2;
B=0.2;

ENDDATA
```

```
!******************Objective Function #1 - Cost Minimization *****************;

!Z1;

MIN= @SUM (PLANT(I):FP(I)*YP(I))+@SUM(WAREHOUSE(J):FW(J)*YW(J))
        +@SUM(DISASSEMBLY(L):FD(L)*YD(L))
        +@SUM(ARC_F1(M,I,J):CF1(M,I,J)*XF1(M,I,J))
        +@SUM(ARC_F2(M,J,K):CF2(M,J,K)*XF2(M,J,K))
        +@SUM(ARC_R1(M,K,L):CR1(M,K,L)*XR1(M,K,L))
        +@SUM(ARC_R2(M,L,I):CR2(M,L,I)*XR2(M,L,I))
        +@SUM(ARC_R3(M,L,J):CR3(M,L,J)*XR3(M,L,J))
        +@SUM(ARC_RS(M,L,D):CRS(M,L,1)*XRS(M,L,1))
        +@SUM (ARC_MK (M, K):CU (M, K)*U (M, K));

! ********** Objective Function #2 - Return Collection Maximization *************;

!Z2;

MAX=@SUM(ARC_R1(M,K,L):XR1(M,K,L))/@SUM(ARC_MK(M,K):R(M,K));


!********** Objective Function #3 - Product Return Recovery Maximization ********;

!Z3;

MAX=@SUM(ARC_R1(M,L,K):XR1(M,L,K))-
@SUM(ARC_RS(M,L,D):XRS(M,L,1));


!************************** **** Contraints ******************************;

! SUBJECT TO;

!1;
@FOR(ARC_MK(M,K):@SUM(WAREHOUSE(J):XF2(M,J,K))+U(M,K)=D(M,K));

!2;
@FOR(ARC_MK(M,K):@SUM(DISASSEMBLY(L):XR1(M,K,L))<=R(M,K));

!3;
@FOR(ARC_ML(M,L):a*@SUM(CUSTOMER(K):XR1(M,K,L))<=XRS(M,L,1));
```

```
!4;
@FOR (ARC_ML (M, L) :
        @SUM(WAREHOUSE(J):XR3(M,L,J))<=B*@SUM(CUSTOMER(K):XR1(M,
K,L)));

!5;
@FOR (ARC_MJ (M, J) :
        @SUM (PLANT (I):XF1 (M, I, J))
        +@SUM(DISASSEMBLY(L):XR3(M,L,J))
        =@SUM(CUSTOMER(K):XF2(M,J,K)));

!6;
@FOR (ARC_ML (M, L) :
        @SUM(PLANT(I):XR2(M,L,I))+@SUM(WAREHOUSE(J):XR3(M,L,J))
        +@SUM(DISPOSAL(D):XRS(M,L,D))
        =@SUM(CUSTOMER(K):XR1(M,K,L)));

!7;
@FOR (PRODUCT (M) :
        @SUM(ARC_KL(K,L):XR1(M,K,L))<=@SUM(ARC_JK(J,K):XF2(M,J,K)));

!8;
@FOR(PLANT(I):@SUM(ARC_ML(M,L):XR2(M,L,I))<=M*YP(I));

!9;
@FOR(WAREHOUSE(J):@SUM(ARC_ML(M,L):XR3(M,L,J))<=M*YW(J));

!10;
@FOR(ARC_MI(M,I):@SUM(WAREHOUSE(J):XF1(M,I,J))<=GP(M,I)*YP(I));

!11;
@FOR(ARC_MJ(M,J):@SUM(CUSTOMER(K):XF2(M,J,K))<=GW(M,J)*YW(J));

!12;
@FOR(ARC_ML(M,L):@SUM(CUSTOMER(K):XR1(M,K,L))<=GD(M,L)*YD(L));


!12;
@FOR (PLANT (I):@BIN (YP (I))) ;

!13;
@FOR (WAREHOUSE (J):@BIN (YW (J))) ;

!14;
@FOR (DISASSEMBLY (L):@BIN (YD (L))) ;
```