Modelling a Closed-Loop Product Recovery System with Supply Uncertainty

Venkata Sundar Kamal Devu

A Thesis

in

The Department

of

Mechanical and Industrial Engineering

Presented in Partial Fulfillment of the Requirements

for the Degree of Master of Applied Science (Mechanical Engineering) at

Concordia University

Montreal, Quebec, Canada

October 2005

Your file Votre référence
ISBN: 0-494-14304-5
Our file Notre référence
ISBN: 0-494-14304-5

Abstract

Modelling a Closed-Loop Product Recovery System with Supply Uncertainty

Venkata Sundar Kamal Devu

Logistic networks for product recovery have to be implemented in an efficient manner to recover cost savings from remanufacturing. Uncertainty of the quantity and timing of product returns is a major issue in the product recovery networks. Product recovery networks require investments of high fixed costs. Hence the uncertain information has to be taken into account when the strategic network model is designed. This thesis is aimed at presenting a mathematical model for closed-loop product recovery system with uncertainty of product returns. A generic mixed integer-programming model is developed. Stochastic programming approach is implemented in the deterministic model by adding scenarios and probabilities to explicitly account for the uncertainties in the product returns. The model is programmed and solved by LINGO optimization solver. Several test problems are solved by varying the parameters: number of scenarios, probability and return rates to identify the sensitivity of the model. A statistical analysis is conducted on all the example problems by measuring the Expected Value of Perfect Information (EVPI), Value of Stochastic Solution (VSS) and the results are discussed.

Keywords: Reverse logistics, product recovery, stochastic programming, uncertainty, facility location, network design

Acknowledgements

The author is greatly indebted to Dr. Mingyuan Chen for his invaluable guidance, support and encouragement through all the phases of graduate study and thesis preparation. The author highly appreciates the financial assistance received from the Department of Mechanical and Industrial Engineering, Concordia University.

Finally the author wishes to thank his family and friends without whose support and encouragement this thesis work would not have been possible.

Table of Contents

List of Figures

List of Tables

Chapter One

Introduction to Reverse Logistics

1.1 Introduction

Reverse logistics encompasses activities of processing and transporting end-of-life products from the end user to the manufacturer. Product Recovery Management (PRM), a subset of the reverse logistics, is defined as the "management of all used and discarded products, components and materials for which a manufacturing company is legally, contractually or otherwise responsible" (Krikke et al., 1999). PRM deals with activities of end-of-life products going back to the manufacturer that are no longer required by the end-user. Recovery of used products has become a field of rapidly growing importance. Many companies are getting increasingly active in the recovery activities. In 1994, paper recycling in Europe amounted to 27.7 million tonnes with an annual growth rate of about 7%, signifying a recovery rate of about 43% in percentage of total paper consumption (Fleischmann et al., 1997). European glass recycling grew by almost 10% (in tonnes collected) in 1994 to more than 7 million tonnes, being a recycling rate of roughly 60%. In Germany, recovery goals for sales packaging materials are mandatory between 60% and 75% (Fleischmann et al., 1997). Recycling of products and materials has existed for some time. Paper recycling, deposit system for soft drink and beer bottles, recycling metal scrap, etc, all have existed. Researchers have identified the economical benefits from remanufacturing and exploiting the opportunities of recovering value from used products. Electronic products such as computers, photocopying machines, cameras, etc, can be remanufactured which result in high savings and significant reduction of solid waste disposal. Krikke et al (1999) presented a business case for designing reverse logistic network for remanufacturing photocopiers. Shih (2001) proposed a reverse logistics system planning for recycling electrical appliances and computers in Taiwan. In Europe stringent laws have been enforced to recycle carpet waste. Louwers et al. (1999) presented a facility location allocation model for reusing carpet materials. In Europe stringent laws have been passed to recycle sand from the demolition waste. Barros et al (1998) presented a two-level network, a case study for recycling sand in The Netherlands. In Europe "RevLog", an international working group on Reverse Logistics is established with the co-operation of

- Erasmus University Rotterdam, The Netherlands (Coordinating university),
- Aristoteles University of Thessaloniki, Greece
- Eindhoven University of Technology, The Netherlands,
- INSEAD business school, France,
- Otto-von-Guericke University Magdeburg, Germany,
- University of Piraeus, Greece

The main objective of RevLog is to analyse the key issues of Reverse Logistics, to order them according to their impact on various industries and society, and to build a framework linking these issues (RevLog, Europe). The group is focused more on developing integrated supply chain models or closed-loop supply chain models with traditional activities such as production, distribution, inventory control and reverse logistics activities such as collection, sorting, disassembly, remanufacturing, disposal. Figure 1.1 gives a general schematic representation of reverse logistics system.

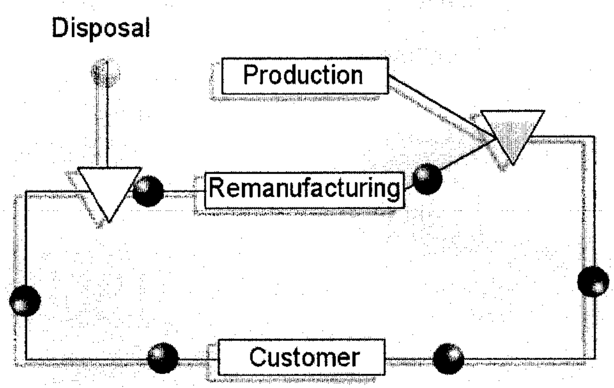


Figure 1.1 Reverse Logistics System (RevLog)

1.2 Drivers for Product Recovery

Product Recovery started in Europe in major industrial countries like The Netherlands, Germany, France, Greece, etc. Now it is picking up pace in North America too. It is motivated by three main factors.

- **Legislation**

This is the first driver for increasing recycling rate of used products. Landfills are getting depleted due to increasing disposal of solid waste. Hence waste reduction has become a major concern in many countries. As a result environmental regulations are widely extended. Apart from increasing disposal fees and landfill bans, producers have the additional responsibility of taking back their products at the end-of-life. In Europe, EU regulation enhances producer responsibility or product stewardship for several branches of industry (Krikke et al., 2001). The Original Equipment Manufacturers (OEMs) are responsible for the set-up of a take back and recovery system for products discarded by the end user. In California, laws have been introduced to reduce air pollution (Krikke et al., 2001). As a result many automobile industries, packaging industries, electronic industries are entrusted with task of collecting back their products after end-of-life. An example is Hewlett-Packard, who collects empty laser-printer cartridges from the consumers for reuse (Jayaraman et al., 2003).

- **Economic benefits**

The second driver for remanufacturing and reuse is the economical benefits. Used products provide less expensive resources from which added value and material may be recovered (Fleischmann et al., 2001). The photocopier recycling in The Netherlands, reuse of the disposal cameras by Kodak, remanufacturing of computers all serve as examples of cost savings.

IBM's business activities involve several closed-loop chains, concerning end-of-lease product returns, buy-back offers, environmental take-back and production scrap (Fleischmann, 2001). The total annual volume of these flows amounts to several ten thousand metric tons worldwide (Fleischmann, 2001). In order to recover maximum value from various "reverse" goods, IBM considers a hierarchy of reuse options at product, part, and material levels (Fleischmann, 2001). In this way, product recovery accounts for an annual financial benefits of several hundred US$ and at the same time reduces land filling and incineration to less than 4% of the volume processed (Fleischmann, 2001).

- **Green image of the manufacturer**

The third driver for reuse of the products is the green image. The reverse logistics activities can be crucial for a company's survival, because the permanent goodwill of the company is at stake. "Businesses succeed because they respond to both external and internal changes and adjust in an effective manner to remain competitive" (Jayaraman et al., 2003). To achieve its business objectives, a company must respond to increasing customer demand for "green" products, comply with strict environmental regulations, and implement environmentally responsible plans as a good corporate citizen (Jayaraman et al., 2003). This "green" image can play as a significant marketing factor.

For example, Church and Dwight Co. Inc, the owner of Arm and Hammer, estimates that the loyalty of customers who appreciate the company's clean-and-green image translates into 5-15% more revenues per year, about US $75 million (Ottoman, 1998).

1.3 Reverse Logistics Network Types

Reverse logistics networks can be classified based on three criteria. They are type of product involved, recovery process employed (remanufacturing, recycling and repair) and economic benefits. Fleischmann et al. (2000) classified product recovery networks in three types. They note that process-orientation is an important discriminating factor. Fleischmann (2001) extended this classification by including two more classes of recovery networks on the basis of driver for recovery and the owner of the recovery process. The five classes of networks have different strategies and the objectives depend on the driver namely, legislation, economics and the green image. Interested reader can refer to these two articles for more information.

- **Networks with no recapturing value**

Reverse logistic networks established for the sole purpose of product take back mandated by the legislation to protect environment from increasing solid waste fall in this category. Examples include German “green dot” system for packaging recycling, sand recycling network in The Netherlands, recycling of beverage bottles and cans, recycling scrap cars, etc. Testing and separation operations don’t exist in these networks.

- **Networks for value added recovery**

Closed-loop networks established by the OEMs for the purpose of recovering value from the used products fall in this category. Examples include OCE photocopier remanufacturing in The Netherlands, automotive parts remanufacturing, remanufacturing of electronic appliances and computers in Taiwan, cellular telephone remanufacturing and printed circuit boards recovery, recovery from single-use cameras, etc. Testing and grading operations play a significant role in these networks.

- **Dedicated remanufacturing networks**

Specialized dedicated remanufacturing networks have been around for a while. These networks are more strongly opportunity driven and concentrate more on profit maximizing rather than cost minimization. Examples include automotive remanufacturing, industrial equipment manufacturers, tire retreaders, etc. Testing and grading operations play a major role in these networks.

- **Networks for material recovery**

These networks are established to recover material value from the end-of-life products. They are termed as recycling networks, characterized by low profit margins. Examples include recycling of steel by-products, carpet recycling, paper recycling, plastic recycling, etc. Testing and grading operations is not a major concern.

- **Re-usable item networks**

This type of recovery networks can be found in systems of directly re-usable items such as re-usable containers, packaging, bottles, boxes, etc. Kroon and Vrijens (1995) made a comprehensive study on the returnable containers. All these returnable packages are termed as secondary packages that can be used more than once in the same form. In these networks the uncertainty of timing of returns is an important issue. Major cost factors include transportation and procurement of new packages.

1.4 Issues in the Reverse Logistics Network

Most of the research in the literature is concentrated on three major issues in the area of reverse logistics.

- **Network design for redistribution**

Reverse distribution is the collection and transportation of used products and packages. This process can take place through the original forward channel, through a separate reverse channel or through combinations of the forward and the reverse channel (Fleischmann et al., 1997). Designing efficient networks with cost minimization or profit maximization as the objective and subject to constraints is the important aspect of this problem. The network design is plagued by two decisive factors: determining the locations of the collection, testing and grading, remanufacturing nodes and allocation of optimal transportation flows. A major issue in reverse distribution systems is the integration of forward chain and the reverse chain. Most of the OEM networks (remanufacturing and re-use) are closed-loop networks whereas recycling can often be described as open-loop system. Supply uncertainty is a major problem when designing a reverse logistics networks due to high investment costs involved in opening disassembly centres and remanufacturing plants.

- **Inventory control**

A second key area in reverse logistics is inventory management. Appropriate control methods are required to integrate the return flow of used products into the producer's material planning. In this kind of issue, the producer meets demand for new products and receives used products returned from the market (Fleischmann et al., 1997). He has two alternatives for fulfilling the demand, either he orders the required raw materials externally and fabricates new products or he overhauls old products and brings them back to 'as new' conditions (Fleischmann et al., 1997). The objective of inventory management is to control external component orders and the internal component recovery process to guarantee a required service level and to minimize fixed and variable costs (Fleischmann et al., 1997).

- **Production planning**

The third issue in the area of reverse logistics is remanufacturing i.e. production planning with reuse of parts and materials. Planning production operations in the forward flow is fairly easy due to supply of raw materials from the suppliers with certainty and the availability of the demand data with certainty to an extent. In the reverse logistics context the production planning is difficult due to two aspects, which add complexity to this task. They are additional disassembly level and high uncertainty with respect to timing, quantity and quality of the return flow. Researchers are developing remanufacturing models to handle this kind of problem. Extended approaches are required for the scheduling of production activities related with product and material reuse (Fleischmann et al., 1997). When compared with traditional manufacturing no well-determined sequence of production steps exists in remanufacturing. This exposes planning in a remanufacturing environment to a much higher uncertainty.

1.5 Research Background

This research concentrates on the issue of reverse logistics network design. It generalizes and extends earlier results obtained by Fleischmann et al (2001). They developed a mixed integer linear program for the design of a generic product recovery network model, which integrates the forward flow with the reverse flow to form a closed-loop reverse logistic network. Their model can be best described as a discrete, static, deterministic, single product, uncapacitated, fixed linear multi-echelon cost minimization product recovery network model.

1.6 Contribution of this Thesis

- In this thesis, the generic product recovery model developed by Fleischmann et al (2001) is extended to include option for multiple product types.
- Additional capacity limitations of the plants, warehouses and disassembly centres are included to make the model more realistic.
- To handle this issue, stochastic programming model is developed by introducing scenarios with probabilities and solved. The investment costs to build plants, disassembly centres and warehouses are very high. Hence proper care should be taken to identify the optimal locations for these centres. The reverse logistics network design issue has become more complex due to the uncertainty in the supply of product returns.
- Statistical analysis has been done by estimating Value of the Stochastic Solution (VSS) and importance of the stochastic solutions over expected solutions is discussed.

1.7 Organization of the Thesis

Following the introduction to reverse logistics in chapter 1, in chapter 2 the literature for the recent and earlier work in this is reviewed,

Chapter 3 presents the problem definition and modeling of the recovery network model,

Chapter 4 presents example problems tested on the model and the analysis of the results,

In Chapter 5 conclusion is presented with directions for future research work that can be done in this area.

Chapter Two

Literature Review

Over the past few years, significant progress has been made in the area of Reverse Logistics. Researchers have developed various models for Product Recovery Network Design, Optimal Inventory, Production Planning and Control, Remanufacturing, etc. In this chapter reviews of some of the past and present papers in this area are presented. The reviews are more specific to the designing of the Product Recovery Networks. The papers have been categorized into product recovery network models, facility location models, capacitated models and stochastic models. The first two sections contain literature about the concept of reverse logistics and the various issues concerning it. Subsequent sections deal more with the modeling issues for specific kind of problem. The last section contains some interesting papers concerning different issues in the reverse logistics. The reviewed articles are summarized in Table 2.1.

Table 2.1: Categorization of Literature

Topics	Authors
Introduction to Reverse Logistics	de Brito et al. (2003), Fleischmann et al. (1997), Ginter and Starling (1978), Thierry et al. (1995)
Characteristics of Product Recovery Networks	Fleischmann et al. (2000), Fleischmann (2001)
Product Recovery Network Models	Barros et al. (1998), Fleischmann et al. (2001), Jayaraman et al. (2003), Krikke et al. (1999), Krikke et al. (2001), Listes and Dekker (2003), Louwers et al. (1999), Shih (2001), Spengler et al. (1997), Wang et al. (1995)
Capacitated Facility location models	Bloemhof-Ruwaard et al. (1996), Tragantalerngsak et al. (1997),
Other interesting papers	Alfredo and Blas (1998), de Brito (2003), Guide Jr. et al. (2000), Kroon and Vrijens (1995), Realff et al. (2000), Retzlaff-Roberts and Frolick (1997)

2.1 Introduction to Reverse Logistics

de Brito et al. (2003): In this paper, reviews and content analysis of scientific literature on reverse logistics case studies are provided. Over sixty case studies are included portraying how firms and other organizations deal with reverse logistics. The whole range of recovery options and driving forces with cases from several continents are covered. Overall statistics regarding type of industry, product and the geographic area of the cases are provided. The authors categorized the cases into five subdivisions namely, reverse logistics network structures, reverse logistics relationships, inventory management, planning & control of recovery activities and IT for reverse logistics. For each of these subdivisions, the authors discuss the present observations, propositions and research opportunities. In the appendix of the paper a table is presented with all the cases listed in their respective areas and the reasons for returns, driving force and recovery options.

Fleischmann et al. (1997): This paper surveys the field of reverse logistics. A systematic overview of the issues arising in this field is discussed. In this paper, the authors subdivides the field into three main areas, namely distribution planning, inventory control and production planning. Each of these areas has been introduced in a detailed manner. Based on practical examples for reuse activities, the logistic planning problems arising in the various contexts are discussed. Comparisons are drawn out with the traditional logistic situations. For each of these areas, the implications of the emerging reuse efforts are discussed. The mathematical models proposed in the literature are reviewed and the areas in need for future research are pointed out.

Ginter and Starling (1978): This paper examines the reverse distribution channels for recycling of solid waste. The authors study the problems associated with solid waste pollution. They provide statistics of the waste generated every year due to technological advancements, improved manufacturing techniques, packaging and marketing of consumer products. They discuss the factors that made recycling very essential. They provide the various channels available for the reverse distribution and discuss their attributes. The influence of legislation in the development of reverse channel is discussed. A schematic representation of the reverse channel is presented.

Thierry et al. (1995): This paper studies strategic production and operations management issues in product recovery management (PRM). This article also discusses the relevance of PRM to durable products manufacturers. It categorizes the PRM decisions into five product recovery options. Repair, refurbishing, remanufacturing, cannibalization and recycling are discussed in detail and a schematic representation of an integrated view of product recovery activities is provided. A case study based on the PRM system of a multinational copier manufacturer is presented to illustrate a set of specific production and operations management issues. In addition the PRM activities of pro-active manufacturers, BMW (cars) and IBM (computers) are also presented. The managerial implications of PRM are discussed and eight observations are presented.

2.2 Characteristics of Product Recovery Networks

Fleischmann et al. (2000): In this paper the authors investigate the design of reverse logistic networks. At first they understand the product recovery network design in current practice by reviewing and analyzing the recent case studies on logistics network design for product recovery in different industries. They identify the general characteristics of product recovery networks: the commonalities, the processes and compare them with the traditional logistics structures. They give a brief overview about the modeling aspects of the networks by analyzing the MILP models presented in various papers. It is understood that only deterministic facility location models have been presented for product recovery networks. They classify the networks and identify the main differences in the networks such as degree of centralization, number of echelons, links with other networks, open vs closed loop structure, degree of branch co-operation.

Fleischmann (2001): In this paper the focus is mainly on the logistics network structures for the particular case of closed-loop supply chains. The key issues that companies are facing when deciding upon the logistics implementation of a product recovery initiative are highlighted. In particular, the differences and analogies with logistics network design for traditional "forward" supply chains are pointed out. The strategic fit between the specific context of a closed-loop chain and the logistics network structure are discussed. The author distinguishes classes of reverse logistics networks on the basis of two context variables, the driver for the product recovery (economics versus legislation) and the owner of the recovery process (OEM versus third party). The issues concerning the quantitative analysis of the reverse logistic networks are presented. The author identifies that most of the available mathematical models rely on MILP. The continuous network design model in which the demand varies as a continuous geographic density function, as opposed to the discrete demand locations assumed by traditional MILP approaches is highlighted.

2.3 Product Recovery Network Models

Barros et al. (1998): In this paper a MILP model is presented to determine an optimal network for the recycling of sand. In this case, sieved case is an important subproduct of recycling construction waste. The sand comes from sorting and crushing facilities as a result of their recycling process. The sand is delivered at a regional depot, where it is sorted and classified into three quality classes: clean, half-clean and polluted. The first two classes of sand can be reused and are stored at the regional depot. The polluted sand is cleaned at a treatment facility, where it is also subsequently stored as clean sand. The clean and half-clean sand are reused in new projects, which represent the sinks. Since no information is available about the location of the projects, 10 strategic sites are selected as the potential demand points. Supply of the three classes of sand and the demand of the two classes are fixed at these locations. The crux of the problem is to determine at which of these locations regional and treatment centres must be opened. It is also necessary to determine the transportation links within the system and the required capacities of the facilities. The capacities of both these facilities are fixed. Opening a facility incurs a fixed cost and variable processing cost. Transportation costs are linear. The model developed is a multi-echelon capacitated warehouse location model. Heuristic procedures are developed to solve the model.

Fleischmann et al. (2001): In this paper the authors developed a general quantitative model for product recovery network design that can be implemented on most of the problems with recovery network design issues. The topological aspect of their research concerns more on the impact of product recovery on the physical network structure. In the model, three intermediate levels of facilities are considered, namely disassembly centres where inspection and separation is carried out, factories for manufacturing and remanufacturing and distribution warehouses. The quantitative model developed is a multi-echelon, single product type, uncapacitated, closed-loop cost minimization recovery network model. Penalty costs have been considered for the demands of the customers, which are not met, and for the returns from the customers which are not collected. The issue of uncertainty in the product returns, a major determinant factor for fixing the location variables is not considered. To model is validated by testing it on two examples, *Copier Remanufacturing* and *Paper Recycling*. Significant cost savings are shown. Issues concerning the integrating forward and reverse flows, selecting recovery processing technologies, value of information concerning quality of returns, end of life management are discussed.

Jayaraman et al. (2003): In this paper a discussion is carried out about the issues involved in designing a network for reverse distribution. A mathematical programming model is proposed. The model finds an efficient strategy to return the defective products from a set of origination sites to specific collection sites, which in turn will ship them to refurbishing sites for remanufacturing or disposal. The model allows shipping from origination site to refurbishing site directly, but with higher variable cost. The retailer/wholesaler is considered as the initial collection point. The model is adaptable for end-of-life commercial returns, recycling, remanufacturing, re-use. Since the proposed model is very complex, a heuristic solution methodology is introduced for solving this NP-hard problem. The solution methodology with a heuristic procedure solves the subproblems with reduced sets of decision variables are iteratively. Based on the solutions from the subproblems, a final concentration set of potential facility sites is constructed. The model is solved to optimality with the help of AMPL as front-end interface and CPLEX as the solver for the subproblems.

Krikke et al. (1999): In this paper, discussion is based on a business case study carried out at Oce, a copier firm in The Netherlands. It concerns the installation of a remanufacturing process of the copy machines. The return process is divided into two stages. In the first stage, customers return a machine to the local operating company. The operating company is allowed to refurbish the machine and put it back into the market. If the operating companies themselves are not interested in refurbishing, they return the machine to a recovery location of Oce, for which they receive a fee. In the second stage, there exist three recovery strategies: Revision strategy where the recovered machines are sold as secondary machine, Factory Produced New Model strategy where the recovered machines are sold as new machine, Scrap strategy. The recovery strategies applied to return flows is represented by a processing graph for each product. Available logistic systems that can potentially be used in the reverse logistic network is represented in a transportation graph. The processing graph and the transportation graph are combined in a network graph. The network graph reflects the maximal reverse logistic network that can be realized. The final design is a sub-graph of the network graph with lowest overall costs providing sufficient capacity. A two-echelon optimization model is constructed and it is solved with the solver LINDO. The solution from the model is compared with three given managerial solutions before taking a decision.

Krikke et al. (2001): This paper discusses the issue of a product and the corresponding design of a closed-loop supply chain for a refrigerator of a Japanese manufacturer. The authors develop a quantitative modeling to support an optimal design structure of a product, i.e. modularity, repairability, recyclability, as well as the optimal locations and goods flows allocation in the logistics system. The aim of the paper is twofold:

1) To develop a closed-loop supply chain network based on MILP with options for multiple product design, multiple product recovery as well as multiple objective optimization.

2) To provide an illustrative case study, analyzing mutual interaction between product design and network design as well as their relative importance in specific situations and to test the robustness of solutions found for varying recovery feasibility, rate of return and recovery targets imposed by environmental legislation.

The objective function of the MILP model is minimization of cost, energy, and waste subject to deviational equations, balance equations in the forward chain (pull) and balance equations in the reverse chain (push). The model is solved to optimality and comparisons are made between centralized versus decentralized supply chain network, three alternative product designs with centralized supply chain network. Sensitivity analysis is conducted to test the robustness of management solutions on varying rate of return, recovery feasibility and recovery targets.

Listes and Dekker (2003): In this paper the authors present a stochastic programming based approach by which a large scale deterministic location model for product recovery network design may be extended to explicitly account for uncertainties. They apply the stochastic models to a case study concerning the recycling of sand from demolition waste, which was handled by *Barros et al. (1998)*. Previously this kind of cases was handled by scenario analysis only. The aim of the authors is to develop insights for problems with real-world dimension, the construction of the stochastic models deliberately follows a rather simple technique, which may be potentially used to extend in a reasonable manner any large location model in which uncertainty is an issue and a relatively small set of realistic scenarios can be identified. The objective function of the MILP model is to maximize the net revenue (revenue – costs) subject to constraints. There is uncertainty in the supply data of the unclean sand, the authors considered two cases: high supply case, low supply case. They solved the model for location uncertainty of demand and additional uncertainty of supply. The stochastic model is solved in two stages. In the first stage the location variables are fixed and then in the second stage the model is solved for the optimal flows of the material. The model is programmed in GAMS modeling language and the mixed integer solver CPLEX 6.5 is used to solve the model for all the variants of the problem.

Louwers et al. (1999): In this paper a facility location-allocation model for the collection, preprocessing and redistribution of carpet waste is presented. The paper focuses on the design of the logistic structure of the reuse network, i.e. the physical locations, the capacities of the facilities for storing and preprocessing, the allocation of disposed carpet waste and the transportation mode. The MILP model differs from other mathematical models for supporting the design of the logistic structure or reuse networks. Here, it gives a completely free choice for the locations of the preprocessing centres and the explicit inclusion of depreciation costs. The objective function of the MILP model is to minimize the total costs in the network with respect to the constraints on costs and transportation. The model is tested by implementing it on two actual applications.

Shih (2001): In this paper, the issue of recycling end-of-life home appliances such as electrical appliances and computers is discussed. The Environmental Protection Administration (EPA) of Taiwan has announced a Scrap Home Appliances and Computers Recycling Regulation that mandate manufactures and importers to take-back their products. The author proposed a mixed integer programming model to optimize the design and flow of the reverse network. The model attempts to maximize the revenue from the reclaimed materials at the same time taking care of transportation cost, operating cost, fixed cost for opening new facilities, final disposal cost and landfill cost. The nodes considered in the reverse network are: Collecting points, Storage sites, Disassembly and Recycling plants, Secondary material markets, final treatment and landfill. Integer variables are incorporated for site selection for storage and treatment facilities. The optimal physical flow of EOL products going through collection points, storage points, recycling plants and the final disposition sites are obtained by solving the model. The system does not include the option for repair or remanufacturing. Several scenarios for different take-back rates and operating conditions are simulated through the model. Comparison of the results from all the scenarios indicates that a reduction of storage sites is possible. Results also indicate the benefits of sharing storage facilities.

Spengler et al. (1997): In this paper the authors develop a MILP model for the recycling of industrial by-products in German steel industry. The model is based on a multi-level warehouse location problem. It has to be determined which locations will be opened and how flows are routed from the sources through the intermediate facilities to the sinks. The model is multi-stage and multi-product, while it is allowed to transfer substreams of interim products from one intermediate facility to another in various ways, before delivering it at a sink. A sink can be either a reuse or a disposal location. Facilities can be installed at a set of potential locations and at different capacity levels, with corresponding fixed and variable processing costs. The type of processes to be installed at the intermediate facilities also have to be determined, hence the processing graph is not given in advance. Maximum facility capacities are restricted and transportation costs between locations are linear. While the amount of waste generated at the sources is fixed, the demand at the sinks is flexible within a range. This range is set by the minimum required throughput and the maximum capacity of the sink.

Wang et al. (1995): In this paper, the authors examine the possibility of installing intermediate processing stations between sellers and buyers for recycling of paper. A mixed integer linear programming model for transportation of recovered paper is developed. The modes of transportation to recycled markets available for the study are semi-trailer truck and rail. The objective function of the MILP model is to minimize the transportation of recovered materials from suppliers to demand centres through the use of intermediate processing stations. Constraints include supply of materials, capacity of processing stations, output of processing stations and modes of transportation.

2.4 Capacitated Facility Location Models

Tragantalerngsak et al. (1997): In this paper the authors are concerned with a particular type of facility location problem in which there exist two echelons of facilities, single source and capacitated. They deal with the problem of simultaneously locating facilities in the first and the second echelons, where each facility in the second echelon has a limited capacity and can be supplied by only one facility in the first echelon. Each customer is serviced by only one facility in the second echelon. This problem is an extension of a problem solved by another author, in which there are potentially multiple warehouses or depots from which the vehicles can operate. The model developed by the authors can determine the number of depots and vehicles needed, the location of the open depots, which vehicles should operate from which open depots and which customers each vehicles should service. They present a mathematical model for the problem and consider six heuristics based on Lagrangian relaxation. They present numerical results for these heuristics, and compare their performance on a set of test problems. The quality of the solutions is compared with the optimal solutions found by using branch and bound method.

Bloemhof-Ruwaard et al. (1996): In this paper the authors study the problem of simultaneous design of a distribution network with plants and waste disposal units, and the coordination of product flows and waste flows within this network. They consider plants and waste disposal units (WDUs) to be located at selected sites. In addition, there are restrictions on production capacity at the plants and disposal capacity at WDUs. The objective is to minimize the sum of fixed costs (from opening plants and WDUs), and variable costs (product and waste flows). This problem is a generalization of several other NP-hard problems: one-level capacitated plant location problem, two-level capacitated facility location problem, two-level uncapacitated distribution and waste disposal problem solved by other authors. Heuristic procedures are developed for obtaining feasible solutions.

2.5 Other Interesting Papers

Alfredo and Blas (1998): In this paper, the authors analyze a new plant location problem, in which either a previously known part of a product requested by customers, or a proportional amount of a second product, is sent back to the plants supplying the product. In both cases, each plant receives an amount of the second product which is in proportion to the demand it satisfies. This problem is referred to as the Return Plant Location Problem (RPLP). This is a cost minimization problem of fixed costs and transportation. The model determines the plants to be opened, the amount of primary product required by each customer that has to be supplied from each plant and the amount of the secondary product that is returned from each customer. The MILP model is solved by Lagrangian decomposition based heuristics and exact solution methods. These methods are applied to test problems with different structures and compared with classical subgradient optimization approach.

de Brito (2003): This article gives an exploratory study about the promising areas for future research on reverse logistics. REVLOG, an inter-university EU sponsored project for European Research on Reverse Logistics organized a meeting to discuss the advancements in this area for the last 5 years. The 15 member committee underwent brainstorming sessions to identify the future research opportunities and rate these areas on a 0-10 rating scale. The members identify that the coordination of supply and return networks, quantitative modeling under uncertainty, cost accounting of reverse logistics, Strategic + International Issues (mapping, decision paths) form the crux for future research. The committee anticipates the development of the field in the direction of integrated reverse logistics or extended reverse logistics.

Guide Jr. et al. (2000): In this paper the authors discuss the issues related to the supply-chain management for product recovery manufacturing systems. The authors present seven major characteristics that complicate the management, planning and control of recoverable manufacturing systems. A comparison of the recoverable manufacturing environment and traditional manufacturing environment by area of the responsibility is presented. The table shows that managers should consider the inherent uncertainties in the timing and quality of returns, materials recovery in the reverse chains.

Kroon and Vrijens (1995): In this paper the authors study a practical application of reverse logistics in the area of physical distribution: the reuse of secondary packaging material. The authors are motivated to solve the problem after considering the impact of secondary packaging material on environment pollution and legislative laws implemented by the Dutch Government. They follow the reverse logistics design system which distinguishes it into three types: switch pool systems, systems with return logistics and systems without return logistics. The sender chooses the type of return system depending on the type, the weight, the structure of the goods and also on the quantities involved. The model is tested on a case study carried out for a large logistics service organization in the The Netherlands. The case is related to the design of a return logistics for returnable containers. The authors develop a MILP model for minimizing the total logistic costs (distribution, collection, relocation and fixed costs of the container depots). This model is a special case of the classical plant location model.

Realff et al. (2000): In this paper the authors present the concepts and issues concerning the reverse production system design and an initial formulation to address some of the questions about its implementation. They develop a mathematical programming model to aid in the strategic design of these reverse production systems. This framework poses the objective as the minimization of the maximum deviation of the performance of the network from the optimal performance under a number of different scenarios. The authors illustrate the framework with the example of carpet recycling.

Retzlaff-Roberts and Frolick (1997): The reverse logistics studied in this paper involves a three-link supply chain for microcomputer products, in which products are returned to a supplier from an end user, and then from the supplier to a wholesaler. This study examines this reverse logistics process by mapping the current process, determining current cycle time, identifying obstacles that adversely affect cycle time performance and exploring opportunities for cycle time reduction. The authors identify the causes for returns which are delay of hand-off time, customers not following correct return procedure and tracking problems. They provide measures for reduction of these returns. The approach proposed by the authors can be applied to other reverse logistic processes too.

Chapter Three

Problem Description and Modeling

This chapter will explain, in detail, the characteristics of a generic product recovery network model. It further includes

1) Explanation of the general characteristics and various processes in product recovery network design and their relationship to each other.
2) Explanation of various entities/facilities considered in the network.
3) Framework of the product recovery system is presented.
4) Detailed discussion about the issues in the product recovery network design.
5) The modeling aspects of the problem and the strategy to solve the uncertainty issue of the return products are discussed.
6) The mixed integer linear programming model is presented.

3.1 Problem Introduction

The implementation of product recovery requires setting up an appropriate logistics infrastructure for the flows of used and recovered products. In conventional supply chains, logistics network design is commonly recognized as a strategic issue of prime importance. The location of production facilities, storage concepts and transportation strategies are major determinants of supply chain performance. They convey the used products from their former users to a producer and to future markets again. Analogously, setting up an appropriate logistics network has a fundamental impact on the economic viability of a closed-loop supply chain. In order to successfully exploit the opportunities of recovering value from used products, it is necessary to design a logistics structure that facilitates the arising goods flows in an optimal way. Most of the research developed in the literature in product recovery network models is more specific to the type of industry it is dealing with. The European recycling network for carpet waste, recycling of sieved sand in The Netherlands, remanufacturing of copier machines have similar basic concept of recycling end of life products to recover value from them. The generic product recovery network model developed in this research has many required features for remanufacturing/ recycling.

3.1.1 General Characteristics of Product Recovery Networks

Analyzing the cases presented in the literature, a general characterization of logistics networks for product recovery is derived. Initially common features such as operations of the networks and the nodes in the networks are identified. Subsequently, issues in the recovery network design are identified.

- **Activities in the product recovery network**

The first unifying factor of all the product recovery examples concerns the activities carried out within the logistics network. All networks considered span from a market of used products to another market with demand for recovered products.

The following processes are identified which appear to be recurrent in all the product recovery networks.

- Acquisition/ Collection
- Testing/ Grading
- Reprocessing
- Disposal
- Redistribution

Transportation costs are involved between the centres where these processes are carried out. Each of these steps is briefly explained below.

Collection

Collection refers to activities concerning the used products which are readily available and moved to some points where further treatment is carried out. Collection of the polluted sand from the construction waste, collection of empty beer bottles and cans, collection of used carpets from the carpet dealers, collection of used copier machines from the customers are typical examples of this activity. In general collection can include purchasing, transportation and storage activities. Sometimes collection of used products is imposed by legislation on the manufacturers to reduce environmental pollution.

Testing

Testing and grading comprises all operations to determine whether a given product is in fact re-usable. The location of testing and grading operations in the network has an important impact on the arising goods flows. It is only after this stage the individual products can be assigned to an appropriate recovery option and hence to a geographical destination. The trade-off between transportation and investment costs is observed at this stage. Testing collected products early in the channel may minimize total transportation distance since graded products can directly be sent to the corresponding recovery operation. In particular, unnecessary transportation can be avoided by separating reusable items from unrecoverable scrap. On the other hand, expensive test equipment and the need for skilled labour may be drivers for centralizing the test and grade operations. In the thesis, three options have been considered after the testing and grading operations depending on the quality of the returned products. If the returned products can be recovered with minimal costs and less repair, then they are sent to the plant. If they require excessive repair, then they are sold to raw material suppliers. If the returned products are completely worn out, then they are disposed.

Reprocessing

This stage comprises all the operations of transformation of a used product into a usable product again. The transformation may include different operations such as recycling, repair and remanufacturing. The reprocessing stage often requires the highest investments within the reverse logistics network. The cost for specialized manufacturing or recycling equipment largely influences the economic viability of the entire chain. In many cases, high investment costs at the reprocessing stage call for high processing volumes to be profitable. If the closed-loop chain is managed by the original equipment manufacturer (OEM) designing the reprocessing stage may involve a trade-off between integration and dedication. In this case, partly integrating product recovery operations with the original manufacturing process may offer economies of scale. Integration may concern shared locations, workforce or even manufacturing lines.

Disposal

At this stage, the products that cannot be reused for technical or economical reasons are disposed. This applies to products rejected at the separation level due to excessive repair requirements and also to products without satisfactory market potential, e.g., outdating. Disposal may include transportation, land filling and incineration steps.

Redistribution

Redistribution refers to directing re-usable products to a potential market and to physically moving them to future users. The design of the redistribution stage resembles a traditional distribution network. In particular, we find the conventional trade-off between consolidation and responsiveness in transportation.

Figure 3.1 depicts the flow of materials through the closed-loop system and the various operations that take place.

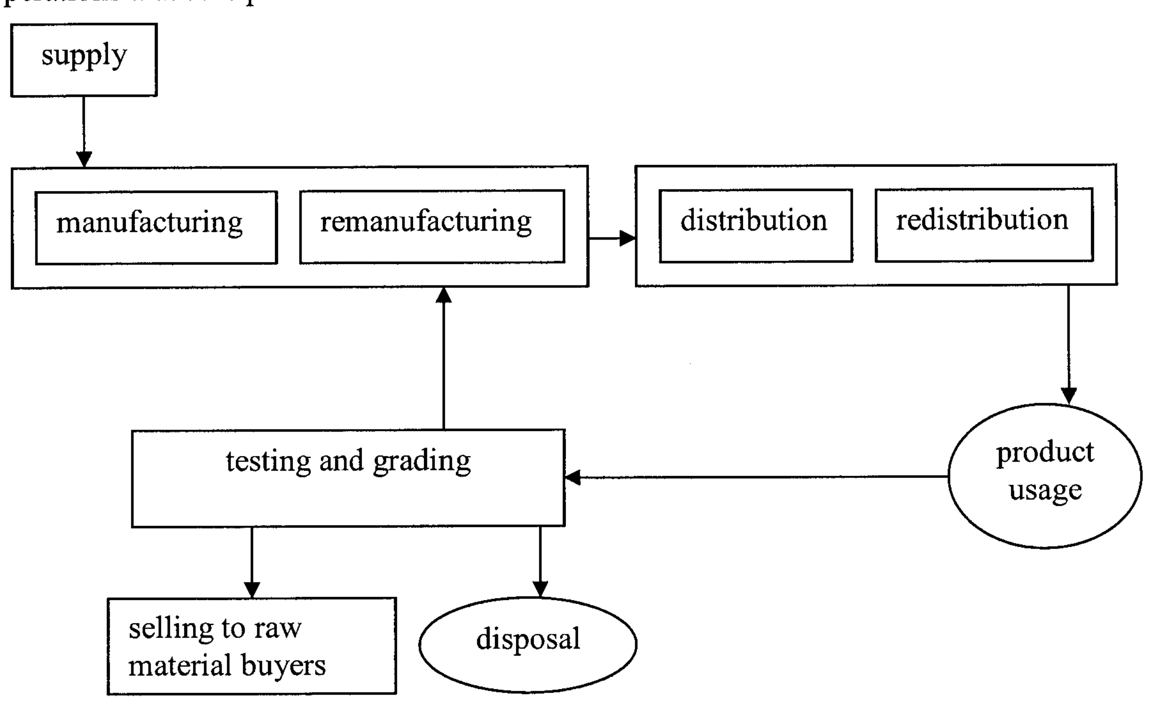


Figure 3.1 Operations in the closed loop supply chain

- **Nodes in the network**

Plants

The product cycle starts at the plant. After receiving the raw material from the suppliers, the product is manufactured. The remanufacturing of the returned products may also be processed at this node by sharing the resources such as labour, manufacturing lines and locations. Once the final product is produced, it is sent to a warehouse.

The costs involved are

- Manufacturing costs
- Handling costs
- Transportation Costs
- Fixed costs to install machinery to manufacture the products
- Fixed costs of the plant itself

The capacity limitation of the plant should be shared between both the manufacturing and remanufacturing operations.

Warehouses

These form intermediaries between plants and customers. The final products sent to the warehouse are stored, sorted and distributed to the customers as per their order requirement.

The costs involved are

- Handling and storage costs
- Transportation costs
- Fixed costs of the warehouse

The capacity limitation of the warehouse is for processing the distribution of the forward flow only.

Customers

They form the end nodes of the forward flow supply chain. They include retail outlets and wholesalers. The products after undergoing the usage of their useful life are sent to the disassembly centres as returns.

The model developed in the thesis has multi product options, i.e. customers can order multiple product types with different order quantities.

The costs involved are

- Transportation costs for sending returns to the disassembly centre

Disassembly centre

At this node the testing and grading operations are carried out. Testing operation may encompass disassembly, shredding, testing and sorting. The returns after the processing are sent to plants or raw material suppliers or even disposed depending on their quality. In some case studies of the product recovery network, warehouses act as the disassembly centres too.

The Costs involved are

- Disassembly costs
- Testing costs
- Transportation Costs
- Fixed costs to install machinery to disassemble the products

- Fixed costs of the disassembly centres

The capacity limitation of the disassembly centre is for processing the returns of the reverse flow only.

Non-recoverable material buyers

This node is situated at the end node of the reverse flow. This is one of the available options after the testing and grading operations carried out at the disassembly centre. The returns, which involve high costs and require excessive repair are not reprocessed. They can be sold to the non-recoverable material buyers.

There are no costs involved but selling the returns generates revenue.

Disposal

At this node, the returns from which no material value can be recovered are disposed. This is the last option after the testing and grading operations.

The costs involved are:

- Land filling costs
- Incineration costs

Figure 3.2 depicts the framework of the closed-loop product recovery network model considered in the thesis. All the nodes discussed in this section are presented in the framework. In the figure solid lines indicate the forward flow and the dashed lines indicate the return flow.

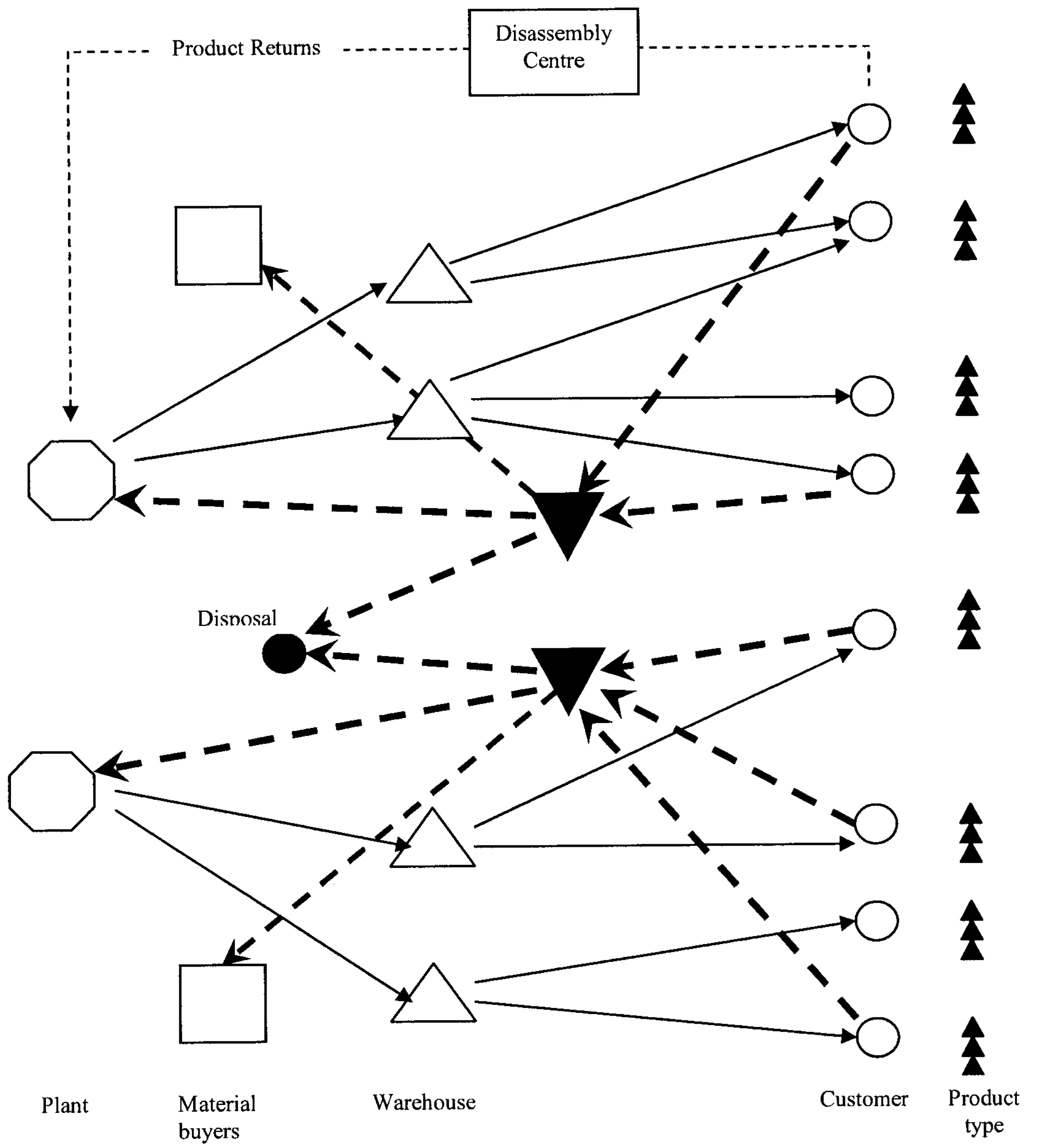
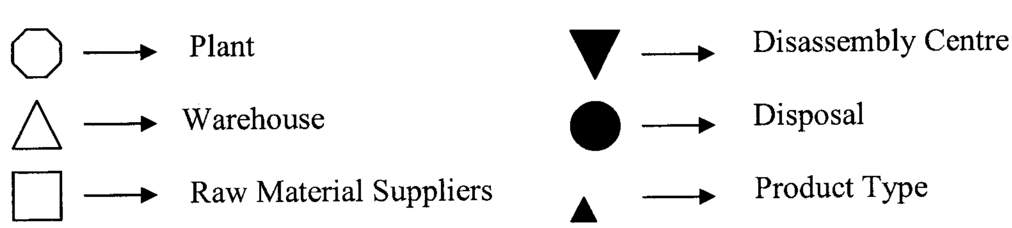


Figure 3.2 Framework of the Product Recovery Network Model



3.1.2 Issues in Product Recovery Network Design

After analyzing the cases in the literature, three main issues that distinguish the design of product recovery networks from traditional distribution networks are identified. They are

- Centralizing of testing and grading
- Uncertainty and lack of supply control
- Integration of forward and reverse flows

Centralizing of testing and grading

Reviewing the literature, it is understood that the fixing locations of testing and grading operations has major consequences for the product flows in a closed-loop supply chain. Only after this stage the product destinations can be assigned. In a traditional supply chain with forward flow only, product routings are known before hand.

Uncertainty and lack of supply control

Reviewing the literature, it is understood that reverse logistics environments are characterized by high level of supply uncertainty. In traditional supply chains, demand is typically perceived as the main unknown factor. Here, it is the supply of the returns that contributes significantly to additional uncertainty. Used products are a much less homogenous input resource than conventional "virgin" raw materials. Quantity and quality of the used products is uncertain and difficult to influence. It is very challenging to match demand and supply in the closed loop supply chains. Consequently, the robustness of the logistics network design with respect to the variations in demand and supply is a major issue in product recovery.

Integration of forward and reverse flows

Implementations of closed loop supply chains may offer several opportunities for exploiting the synergies between different product flows. While traditional distribution networks are typically perceived as one-way flow (forward flow), closed loop supply chains naturally involve multiple inbound and outbound flows of different orientation. Hence there is an opportunity for integrating transportation and facilities. In many cases, reverse logistic networks are not designed from the scratch, but are added on top of the existing logistics structures.

3.2 Generic Stochastic Product Recovery Network Model

This section presents a general quantitative model for stochastic product recovery network design. This model is an extension of the model presented by Fleishmann et al (2001). They present a basic model capturing the major aspects of logistics network design in a product recovery network context. From a facility location point of view, their model can be characterized as a discrete, static, deterministic, single product and uncapacitated cost minimization problem. Recovery network models are similar to each other, most of them being MILP models similar to classical warehouse location models (Fleischmann et al., 2001). In this thesis the model is extended to handle multiple product types in a capacitated network. Moreover, uncertainty in the recovery of product returns is considered. Deterministic equivalent of the stochastic model is incorporated with scenarios and probabilities. Many papers in the literature provide the basis for developing the mathematical model. Caruso et al. (1993), Sridharan (1995), Hinjosa et al. (2000), Mazzola and Neebe (1999) presented similar but different model formulation.

We first specify the number of facility levels in model formulation. Three intermediate levels of facilities are considered, namely

a) Factories/plants where manufacturing and remanufacturing activities are carried out
b) Warehouses for distribution of the manufactured products
c) Disassembly centres where the inspection and separation functions are carried out

Moreover three dispositions for the collected goods are considered, namely recovery, selling to Raw Material Suppliers and disposal.

3.2.1 Model Assumptions

1) The capacities of the plant, warehouse and disassembly centres are specified in labour hours.
2) Customer returns of the used products can go to any plant, irrespective of which plant manufactures and supplies them.
3) Recovery is feasible only for a certain fraction of the collected goods.
4) Since the quality of returns of certain fraction of products is intermediate between disposal and remanufacturing, they are disassembled and are sold to the material buyers as secondary materials.
5) Returns of a customer are always less than the demand.
6) For every scenario, return rates of each product type from every customer are assumed constant.
7) Penalty costs are assigned for unsatisfied demands and uncollected returns.

8) Existence of only one disposal centre and one raw material buyer is assumed to reduce the complexity of the model.

3.2.2 Modeling Approach

Developing a mathematical model for this kind of problem and requires the identification of issues to be tackled, costs involved and the constraints to be handled. In this section, a deterministic model of the problem is developed. The objective of the mixed integer product recovery model is to minimize the total costs in the system subject to the constraints. It is a closed-loop supply chain model, in which the product returns from the customer are remanufactured at the plants itself. No separate remanufacturing plants are located. In the next section stochastic modeling is dealt. The required modeling to eliminate the problem of uncertainty of the product returns is incorporated in the model.

The costs in the objective function

Production, transportation and handling costs: Operations involving manufacturing, remanufacturing, disposal and selling disassembled parts to material buyers involve these costs. These costs apply both on forward path and reverse path between plants, warehouses, disassembly centres, material buyers and disposal centres.

Penalty costs: These costs apply on the fraction of unsatisfied demands of the customer and the fraction of uncollected returns from the customer. Since the objective function is a cost-minimizing problem, the model tends to keep the costs as low as possible by not supplying the demand for manufactured products from the customer or by not collecting returns from the customer. Hence including high penalty costs will force the model to satisfy the demand and collect the returns.

Fixed costs: These costs are required for opening new facility locations for manufacturing and remanufacturing plants, warehouses for distribution and redistribution, disassembly centres for testing and grading operations. High costs are involved in opening these facilities.

Setup costs: These costs are required for installing machinery at plants for manufacturing and remanufacturing operations and at disassembly centres for disassembling products for testing and grading operations.

Revenue in the objective function

Material buyers: This function corresponds to the revenue from the disassembled parts, which are sold to the materials buyers minus transportation costs and handling costs.

Hence, the objective function is minimization of the total costs minus the revenue from the materials buyers.

Constraints

Logical constraints: These constraints are required to ensure that demands of all the customers and the returns from all the customers of each product type is taken into account.

Product flow constraints: These constraints are required to ensure that of each product type, no plant receives more returned products than it produces and also no customer returns more products than he receives.

Minimum disposal and maximum selling constraints: In the model it is incorporated to have three options for the returned products remanufacturing, selling to material buyers and disposal. In reality all the returned products cannot be remanufactured because of the quality of the returns. There is always an uncertainty in the quality of returns. Hence it is enforced to dispose a fraction of the returns and sell a certain fraction of the returns to material buyers.

Capacity constraints: These constraints are required to include capacity limitation of plants, warehouses and the disassembly centres.

Machinery installation constraints: These constraints are required for installing machinery at plants for manufacturing or remanufacturing operations and at disassembly centres for testing and grading operations of each product type. If a plant is not producing a specific product type, then the required machinery to manufacture it is not installed. Similarly is the case with disassembly centre.

Non-negativity and integer constraints: Decision variables for determining facility locations and installing machinery are assigned as binary variables. Other decision variables are assigned as non-negative variables.

3.2.3 Stochastic Modeling of the Problem

Designing a closed-loop product recovery system faces the uncertainty of timing and quantity of product returns. This thesis concentrates on solving this issue. Most of the research in the literature discusses models for product recovery network for deterministic cases only.

As seen in Figure 3.3 there are many possible scenarios with different return rates and probability of occurrences of the scenarios. Each scenario may correspond to a set of locations of the facility centres best suited for that scenario. Stochastic programming, a well established optimization method can be used to reach an overall best solution considering the uncertainty of the problem.

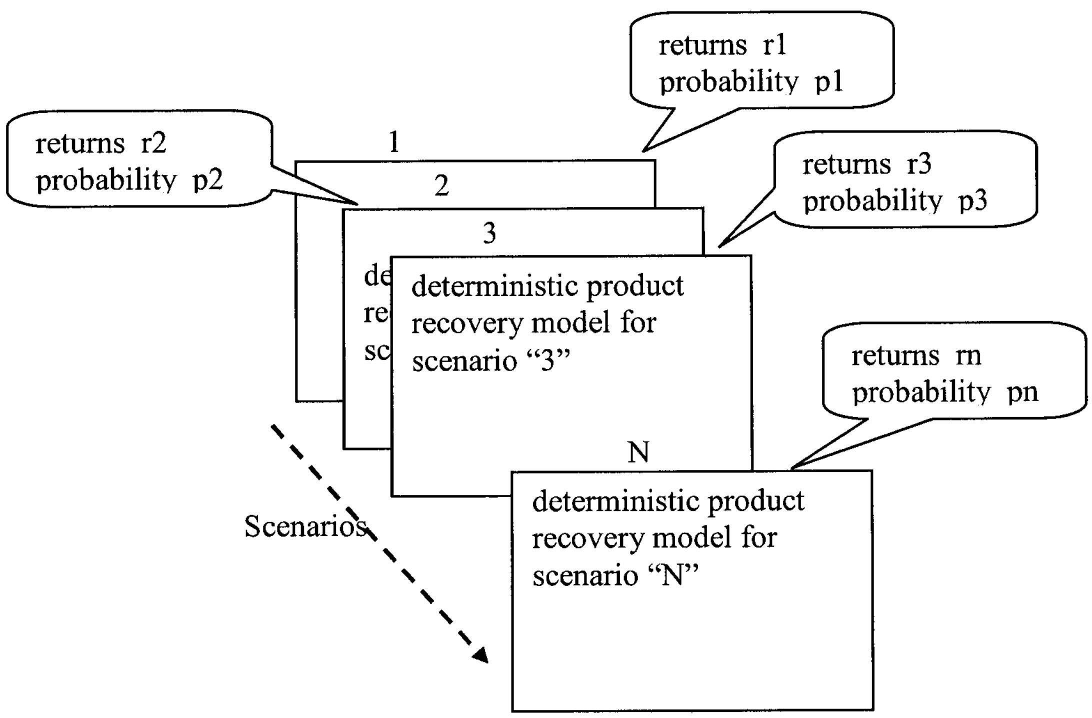


Figure 3.3 Scenario representation of the system

Stochastic programming extends the deterministic version of the model by introducing an additional dimension in the model i.e. scenarios. Each scenario is identified by its characteristic property of probability of the occurrence. The stochastic solution can be analyzed by measuring two parameters.

Expected Value of Perfect Information (EVPI): It measures how much more one can expect to win if perfect information about the stochastic components of the problem is available. In other words, EVPI measures the cost or value of knowing the future with certainty. This is therefore the maximum amount that should be spent in gathering information about the uncertain world

Value of Stochastic Solution (VSS): It measures the value of a stochastic over a deterministic model. It can also be termed as the cost of ignoring uncertainty in choosing a decision.

General introduction and detailed discussions on stochastic programming modeling and solution methods can be found in Birge and Louveaux (1997). In solving the problem discussed in Section 3.1 of this chapter, each scenario is a deterministic product recovery system whose objective is to minimize the total costs of the system with respect to the constraints. The transportation costs, penalty costs and demand data are different for every scenario. Fixed costs and the setup costs are not influenced by the occurrence of any scenario. All the constraints are influenced by the variations of the scenario occurrence. Hence every constraint includes an additional dimension of the probability in the model. The number of variables and the constraints are increased by the number of times the scenarios in the stochastic model. The mixed integer model solves for all the scenarios with different return rates simultaneously finding the total cost and an optimal solution of the locations best suitable for the combinations of the scenario. This solution incorporates the effect of uncertainty. The actual mathematical model is presented in the subsequent section with an explanation to the cost and the constraint functions.

3.2.4 MILP Model Formulation

The following subsection will present the mathematical model developed in the study. We first introduce the notations used for denoting the scenarios, location centres, customers and the product types. Then we explain decision variables, cost coefficients and parameters. Finally the mathematical model is presented.

Index Sets

S = Total number of scenarios considered in the model

I = Total number of potential plant locations

J = Total number of potential warehouse locations

L = Total number of potential disassembly locations

K = Total number of customer locations

P = Total number of product types

O = Disposal centre (only one is considered in the model)

B = Material buyer (only one is considered in the model)

Decision variables

x^{c}_{sijkp} = fraction of demand of product p of customer k served from plant i through warehouse j in scenario s; $s=1,...,S, i=1,...,I, j=1,...,J, k=1,...,K, p=1,...,P$

x^{r}_{spkli} = fraction of returns of product p from customer k to be returned via disassembly centre l to plant i in scenario s; $s=1,...,S, p=1,...,P, k=1,...,K, l=1,...,L, i=1,...,I$

x^{d}_{spklo} = fraction of returns of product p from customer k to be disposed via disassembly centre l in scenario s; $s=1,\dots,S, p=1,\dots,P, k=1,\dots,K, l=1,\dots,L, o=O$

x^{b}_{spklb} = fraction of returns of product p from customer k to be sold to material buyers r via disassembly centre l in scenario s; $s=1,\dots,S, p=1,\dots,P, k=1,\dots,K, l=1,\dots,L, b=B$

u_{spk} = unsatisfied fraction of demand of product p of customer k in scenario s; $s=1,\dots,S, p=1,\dots,P, k=1,\dots,K$

w_{spk} = uncollected fraction of return of product p from customer k in scenario s; $s=1,\dots,S, p=1,\dots,P, k=1,\dots,K$

y_i^P = location variable for selection of plant i; $i=1,\dots,I$

y_j^W = location variable for selection of warehouse j; $j=1,\dots,J$

y_l^D = location variable for selection of disassembly centre l; $l=1,\dots,L$

v_{ip} = decision variable for setting up of machinery to manufacture product p at plant i; $i=1,\dots,I, p=1,\dots,P$

z_{lp} = decision variable for setting up of machinery to disassemble product p at the disassembly centre l; $l=1,\dots,L, p=1,\dots,P$

Costs coefficients

C^{c}_{sijkp} = unit variable cost of serving demand of product p of customer k from plant i through warehouse j in scenario s, including transportation, production and handling cost; $s=1,\dots,S, i=1,\dots,I, j=1,\dots,J, k=1,\dots,K, p=1,\dots,P$

C^{r}_{spkli} = unit variable cost of collecting returns of product p from customer k via disassembly centre l to plant i in scenario s, including transportation, production and handling cost minus production savings at plant i; $s = 1,...,S, p = 1,...,P, k = 1,...,K, l = 1,...,L, i = 1,...,I$

C^{d}_{spklo} = unit variable cost of disposing returns of product p from customer k through disassembly centre l at the disposal centre o in scenario s, including collection, transportation, handling and disposal cost; $s = 1,...,S, p = 1,...,P, k = 1,...,K, l = 1,...,L$

P^{b}_{spklr} = unit variable revenue from selling returns of product p from customer k through disassembly centre l to material buyers b in scenario s minus collection, transportation, handling costs; $s = 1,...,S, p = 1,...,P, k = 1,...,K, l = 1,...,L, b = B$

G_{ip} = setup cost for installing machinery to manufacture product p at plant i; $i = 1,...,I, p = 1,...,P$

H_{lp} = setup cost for installing machinery to disassemble product p at disassembly centre l; $l = 1,...,L, p = 1,...,P$

P_{spk} = unit penalty cost for not serving demand of product p of customer k in scenario s; $s = 1,...,S, p = 1,...,P, k = 1,...,K$

Q_{spk} = unit penalty cost for not collecting returns of product p from customer k in scenario s; $s = 1,...,S, p = 1,...,P, k = 1,...,K$

F_{i} = fixed cost for opening plant i for manufacturing and remanufacturing; $i = 1,...,I$

F_{j} = fixed cost for opening warehouse j; $j = 1,...,J$

F_{l} = fixed cost for opening disassembly centre l; $l = 1,...,L$

d_{spk} = demand of product p of customer k in scenario s; $s = 1,...,S, p = 1,...,P, k = 1,...,K$

r_{spk} = returns of product p from customer k in scenario s; $s = 1,...,S, p = 1,...,P, k = 1,...,K$

S_i^P = capacity of plant i in labor hours; $i = 1,...,I$

S_j^W = capacity of warehouse j in labor hours; $j = 1,...,J$

S_l^D = capacity of disassembly centre l in labor hours; $l = 1,...,L$

Parameters

α_1 = minimum disposal fraction

α_2 = fraction of returns sold to material buyers

β_p = number of labor hours required for manufacturing/ remanufacturing 1 unit of product p; $p = 1,...,P$

γ_p = number of labor hours required for handling 1 unit of product p at warehouse; $p = 1,...,P$

τ_p = number of labor hours required for disassembling 1 unit of product p at disassembly centre; $p = 1,...,P$

P_s = probability of the occurrence of scenario s; $s = 1,...,S$

Mathematical model

The primary task in building up of the model is to define the objective function. In the present model the objective functions is to minimize the total cost. The objective function includes of costs for production, transportation and handling costs at the plants, warehouses, disassembly centres, penalty costs for unsatisfied demands and uncollected returns, fixed costs for the location centres and the setup costs for the machinery at the plants and the disassembly centres. In the later part of this section constraint equations are defined.

Objective function

- **Production, transportation and handling costs**

Forward flow: The total production, transportation and handling (PTH) costs incurred at all the plants in satisfying the demands of all the customers of every product type.

$$PTHFF = \sum_{s=1}^{S} P_s \times \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{p=1}^{P} C_{sijkp}^{c} \times x_{sijkp}^{c} \times d_{spk} \qquad \ldots\ldots (3.1)$$

Return flow to the plant: The total PTH costs minus production cost savings at all the plants obtained in collecting the returns from all the customers of every product type.

$$PTHRF = \sum_{s=1}^{S} P_s \times \sum_{p=1}^{P} \sum_{k=1}^{K} \sum_{l=1}^{L} \sum_{i=1}^{I} C_{spkli}^{r} \times x_{spkli}^{r} \times r_{spk} \qquad \ldots\ldots (3.2)$$

Disposal costs: The total PTH costs incurred in disposing the returns from all the customers of every product type.

$$PTHD = \sum_{s=1}^{S} P_s \times \sum_{p=1}^{P} \sum_{k=1}^{K} \sum_{l=1}^{L} C_{spklo}^{d} \times x_{spklo}^{d} \times r_{spk} \qquad \ldots\ldots (3.3)$$

- **Penalty costs**

Unsatisfied demands: The total penalty costs incurred on all the unsatisfied demands of all the customers of every product type.

$$PCUD = \sum_{s=1}^{S} P_s \times \sum_{p=1}^{P} \sum_{k=1}^{K} P_{spk} \times d_{spk} \times u_{spk} \qquad \ldots\ldots (3.4)$$

Uncollected returns: The total penalty costs incurred on all the uncollected returns from all the customers of every product type.

$$PCUR = \sum_{s=1}^{S} P_s \times \sum_{p=1}^{P} \sum_{k=1}^{K} Q_{spk} \times r_{spk} \times w_{spk} \qquad \ldots\ldots (3.5)$$

- **Fixed costs**

Plant: The total cost incurred in fixing the selected sites for manufacturing/ remanufacturing activities.

$$FCP = \sum_{i=1}^{I} F_i \times y_i^P \qquad \ldots\ldots (3.6)$$

Warehouse: The total cost incurred in fixing the selected sites for warehouse handling activities.

$$FCW = \sum_{j=1}^{J} F_j \times y_j^W \qquad \ldots\ldots (3.7)$$

Disassembly centre: The total cost incurred in fixing selected sites for disassembling activities of the returns.

$$FCD = \sum_{l=1}^{L} F_l \times y_l^D \qquad \ldots\ldots (3.8)$$

- **Setup costs**

Plant: The total cost incurred in installing machinery for manufacturing/ remanufacturing of every product type at all the selected manufacturing sites

$$SCP = \sum_{i=1}^{I} \sum_{p=1}^{P} G_{ip} \times v_{ip} \qquad \text{...... (3.9)}$$

Disassembly centre: The total cost incurred in installing machinery for disassembling the returns of every product type at all the selected disassembly centres.

$$SCD = \sum_{l=1}^{L} \sum_{p=1}^{P} H_{lp} \times z_{lp} \qquad \text{...... (3.10)}$$

- **Revenue**

Revenue from material buyers: The total revenue from selling returns to material buyers minus PTH costs.

$$RMB = \sum_{s=1}^{S} P_s \times \sum_{p=1}^{P} \sum_{k=1}^{K} \sum_{l=1}^{L} P^{b}_{spklb} \times x^{b}_{spklb} \times r_{spk} \qquad \text{...... (3.11)}$$

Putting equations (3.1) to (3.11) together, we have the total cost equation as follows

$$\text{TOTAL COST } = Z = \begin{matrix} PTHFF + PTHRF + PTHD + PCUD + PCUR + FCP + \\ FCW + FCD + SCP + SCD - RMB \end{matrix}$$

Hence, the Objective function is written as

Minimize Total Cost Z

Constraints

- **Logical constraints**

Forward flow: Constraints ensuring that demands of all the customers of each product type are taken into account, i.e. sum of the fraction of satisfied demands and unsatisfied demands equals unity.

$$\sum_{i=1}^{I}\sum_{j=1}^{J} x_{sijkp}^{c} + u_{spk} = 1 \qquad \forall s,k,p \qquad \ldots\ldots (3.12)$$

Return flow: Constraints ensuring that returns from all the customers of each product type are taken into account i.e. sum of the fraction of collected returns going to plant, fraction of collected returns going for disposal and uncollected fraction equals unity.

$$\sum_{l=1}^{L}\left\{\sum_{i=1}^{I} x_{spkli}^{r} + \left(x_{spklo}^{d} + x_{spklb}^{b}\right)\right\} + w_{spk} = 1 \quad \forall o,b,s,k,p \qquad \ldots\ldots (3.13)$$

- **Product flow constraints**

(a) The total outgoing flow at each plant of every product type should be atleast as big as the total incoming flow from all the customers

$$r_{spk} \times \sum_{k=1}^{K}\sum_{l=1}^{L} x_{spkli}^{r} \le d_{spk} \times \sum_{j=1}^{J}\sum_{k=1}^{K} x_{sijkp}^{c} \qquad \forall s,i,p \qquad \ldots\ldots (3.14)$$

(b) The total outgoing flow from every customer of every product type should be atmost the total incoming flow from all the plants.

$$r_{spk} \times \left\{ \sum_{l=1}^{L}\sum_{i=1}^{I} x^{r}_{spkli} + \sum_{l=1}^{L} x^{d}_{spklo} + \sum_{l=1}^{L} x^{b}_{spklb} \right\} \le d_{spk} \times \sum_{i=1}^{I}\sum_{j=1}^{J} x^{c}_{sijkp} \quad \forall o,b,s,k,p$$

...... (3.15)

- **Minimum disposal and maximum selling**

(a) This constraint enforces a minimum disposal fraction "α_1" for the returns of every product from every customer, to comply with the technical infeasibility/feasibility of reuse

$$\alpha_1 \times \left\{ \sum_{i=1}^{I} x^{r}_{spkli} + \left(x^{d}_{spklo} + x^{b}_{sfklb} \right) \right\} \le x^{d}_{spklo} \qquad \forall o,b,s,l,k,p \qquad \text{...... (3.16)}$$

(b) This constraint enforces a maximum fraction of "α_2" of the returns to be sold to the material buyers

$$\alpha_2 \times \left\{ \sum_{i=1}^{I} x^{r}_{spkli} + \left(x^{d}_{spklo} + x^{b}_{sfklb} \right) \right\} \le x^{b}_{spklb} \qquad \forall o,b,s,l,k,p \qquad \text{...... (3.17)}$$

- **Capacity constraints**

(a) **Plant**: The total manufacturing/ remanufacturing activities at every selected plant should be operated below its capacity. These activities can be carried out at the plant location *i* subject to its selection.

$$\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{p=1}^{P} x_{sijkp}^{c} \times d_{spk} \times \beta_p + \sum_{p=1}^{P}\sum_{k=1}^{K}\sum_{l=1}^{L} x_{spkli}^{r} \times \beta_p \times r_{spk} \le S_i^P \times y_i^P$$

$$\forall s,i \qquad \text{...... (3.18)}$$

(b) **Warehouse**: The total warehouse handling activities at every selected warehouse should be operated below its capacity. These activities can be carried out at the warehouse location j subject to its selection.

$$\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{p=1}^{P} x_{sijkp}^{c} \times d_{spk} \times \gamma_p \le S_j^W \times y_j^W \qquad \forall s,j \qquad \text{...... (3.19)}$$

(c) **Disassembly centre**: The total disassembly activities at every selected disassembly centres should be operated below its capacity. These activities can be carried out at the disassembly centre j subject to its selection.

$$\sum_{p=1}^{P}\sum_{k=1}^{K} \tau_p \times r_{spk} \times \left\{ \sum_{i=1}^{I} x_{spkli}^{r} + \left(x_{spklo}^{d} + x_{spklb}^{b} \right) \right\} \le S_l^D \times y_l^D \qquad \forall o,b,s,l$$

$$\text{...... (3.20)}$$

- **Machinery installation constraints**

(a) **Plant:** The product type p is manufactured/ remanufactured at the plant i only if the required machinery is installed at that plant.

$$\sum_{i=1}^{I} x_{sijkp}^{c} \le v_{ip} \qquad \forall s,j,k,p \qquad \text{...... (3.21)}$$

(b) **Disassembly centre:** The returns of the product type p are processed at the disassembly centre l only if the required machinery is installed at that disassembly centre.

$$\sum_{i=1}^{I} x^{r}_{spkli} + \left(x^{d}_{spklo} + x^{b}_{spklb}\right) \leq z_{lp} \qquad \forall o, b, s, k, p, l \qquad \text{...... (3.22)}$$

3.2.5 Summary Model Representation

Putting the objective function (equations 3.1 to 3.11) and the constraints (equations 3.12 to 3.22) together, we get the complete MILP Product Recovery Model as follows.

Minimize Total Cost (Z) =

$$\sum_{s=1}^{S} P_s \times \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{p=1}^{P} C^{c}_{sijkp} \times x^{c}_{sijkp} \times d_{spk} + \sum_{s=1}^{S} P_s \times \sum_{p=1}^{P}\sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{i=1}^{I} C^{r}_{spkli} \times x^{r}_{spkli} \times r_{spk}$$

$$\sum_{s=1}^{S} P_s \times \sum_{p=1}^{P}\sum_{k=1}^{K}\sum_{l=1}^{L} C^{d}_{spklo} \times x^{d}_{spklo} \times r_{spk} - \sum_{s=1}^{S} P_s \times \sum_{p=1}^{P}\sum_{k=1}^{K}\sum_{l=1}^{L} P^{b}_{spklb} \times x^{b}_{spklb} \times r_{spk}$$

$$\sum_{s=1}^{S} P_s \times \sum_{p=1}^{P}\sum_{k=1}^{K} P_{spk} \times d_{spk} \times u_{spk} + \sum_{s=1}^{S} P_s \times \sum_{p=1}^{P}\sum_{k=1}^{K} Q_{spk} \times r_{spk} \times w_{spk}$$

$$\sum_{i=1}^{I} F_i \times y^{P}_{i} + \sum_{j=1}^{J} F_j \times y^{W}_{j} + \sum_{l=1}^{L} F_l \times y^{D}_{l} + \sum_{i=1}^{I}\sum_{p=1}^{P} G_{ip} \times v_{ip} + \sum_{l=1}^{L}\sum_{p=1}^{P} H_{lp} \times z_{lp}$$

Subject to constraints:

$$\sum_{i=1}^{I}\sum_{j=1}^{J} x^{c}_{sijkp} + u_{spk} = 1 \qquad \forall s, k, p$$

$$\sum_{l=1}^{L}\left\{\sum_{i=1}^{I} x^{r}_{spkli} + \left(x^{d}_{spklo} + x^{b}_{spklb}\right)\right\} + w_{spk} = 1 \qquad \forall o, b, s, k, p$$

$$r_{spk} \times \sum_{k=1}^{K} \sum_{l=1}^{L} x^{r}_{spkli} \leq d_{spk} \times \sum_{j=1}^{J} \sum_{k=1}^{K} x^{c}_{sijkp} \qquad \forall s, i, p$$

$$r_{spk} \times \left\{ \sum_{l=1}^{L} \sum_{i=1}^{I} x^{r}_{spkli} + \sum_{l=1}^{L} x^{d}_{spklo} + \sum_{l=1}^{L} x^{b}_{spklb} \right\} \leq d_{spk} \times \sum_{i=1}^{I} \sum_{j=1}^{J} x^{c}_{sijkp} \qquad \forall o, b, s, k, p$$

$$\alpha_1 \times \left\{ \sum_{i=1}^{I} x^{r}_{spkli} + \left(x^{d}_{spklo} + x^{b}_{sfklb} \right) \right\} \leq x^{d}_{spklo} \qquad \forall o, b, s, l, k, p$$

$$\alpha_2 \times \left\{ \sum_{i=1}^{I} x^{r}_{spkli} + \left(x^{d}_{spklo} + x^{b}_{sfklb} \right) \right\} \leq x^{b}_{spklb} \qquad \forall o, b, s, l, k, p$$

$$\sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{p=1}^{P} x^{c}_{sijkp} \times d_{spk} \times \beta_p + \sum_{p=1}^{P} \sum_{k=1}^{K} \sum_{l=1}^{L} x^{r}_{spkli} \times \beta_p \times r_{spk} \leq S^{P}_{i} \times y^{P}_{i} \qquad \forall s, i$$

$$\sum_{i=1}^{I} \sum_{k=1}^{K} \sum_{p=1}^{P} x^{c}_{sijkp} \times d_{spk} \times \gamma_p \leq S^{W}_{j} \times y^{W}_{j} \qquad \forall s, j$$

$$\sum_{p=1}^{P} \sum_{k=1}^{K} \tau_p \times r_{spk} \times \left\{ \sum_{i=1}^{I} x^{r}_{spkli} + \left(x^{d}_{spklo} + x^{b}_{spklb} \right) \right\} \leq S^{D}_{l} \times y^{D}_{l} \qquad \forall o, b, s, l$$

$$\sum_{i=1}^{I} x^{c}_{sijkp} \leq v_{ip} \qquad \forall s, j, k, p$$

$$\sum_{i=1}^{I} x^{r}_{spkli} + \left(x^{d}_{spklo} + x^{b}_{spklb} \right) \leq z_{lp} \qquad \forall o, b, s, k, p, l$$

Binary Variables

$$y_i, y_j, y_l, v_{ip}, z_{lp} \in \{0,1\}$$

Continuous Variables

$$0 \le x^c_{sijkp}, x^r_{spkli}, x^d_{spklo}, u_{spk}, w_{spk} \le 1$$

Chapter Four

Numerical Examples and Analysis

This chapter presents numerical analysis of the problem of the model introduced in the previous chapters. The model developed has been tested for various instances of the problem. Parametric analysis has been conducted by varying the number of scenarios, probabilities and return rate, then observing its influence on the total costs, location variables of the facilities and transportation links of the model. Probabilities of the scenarios are maintained constant when the return rate of the scenarios is varied.

Expected Value of Perfect Information (EVPI) and Value of Stochastic Solution (VSS) are the two statistical tools for stochastic optimization problems. They are calculated for the problem instances to understand the influence of the varying return rates, number of scenarios and the probabilities.

In the problem instances where return rates and probabilities are varied, the numbers of available plants, warehouses and disassembly centres, customers and product types are fixed. The optimization solver LINGO selects the optimum facility locations. First four examples are solved with variation in the number of scenarios. Later sets of examples consider the variation of return rates. The production, transportation and handling costs, fixed costs, setup costs, penalty costs, demands, capacity limitations of the facility centres and other relevant data for one scenario is provided in Appendix 1. The LINGO programming model is presented in Appendix 3.

The example problems solved in the chapter do not comprise a comprehensive analysis of the model. The main purpose of this thesis research is to develop the mathematical model for reverse supply chain analysis. The computational results of the example problems presented in this chapter validate the model and identify the sensitive parameters of the model. Extensive investigations of the model can be conducted in our future research by varying the return rates and probabilities of scenarios in combination with number of scenarios.

4.1 Example Problems

- **Example 1**

We first solve an example problem with the basic data given in Tables 4.1 and 4.2. The solutions will be discussed to illustrate different features of the developed model.

Table 4.1 Example 1: facilities, customers & products

Number of plants (P)	3
Number of warehouse (W)	9
Number of disassembly centres (L)	6
Number of raw material buyers (R)	1
Number of disposal centres (D)	1
Number of customers (K)	12
Number of product types (F)	3

As shown in Table 4.2, there are 3 possible scenarios with different return rates and probabilities. Other data used in this example are given in the Appendix 1.

Table 4.2 Example 1: parameter values

Scenario	Return rates	Probabilities
1	0.3	0.1
2	0.6	0.3
3	0.9	0.6

The data used in this example are realistic but hypothetical. The model is programmed and solved by LINGO optimization software, version 7, for the optimal solution. The number of variables and constraints determines the size of the problem. For this example, we have 15418 constraints and a total of 6417 variables including 45 integers.

To solve the model the software took a runtime of about 3 hours and 36 minutes for the optimal solution on a PC computer with Pentium 4 processor. The total cost obtained after solving the deterministic equivalent of the stochastic model is 11942880. Plants, warehouse and disassembly centre selections are shown in Table 4.3

Table 4.3 Example 1: stochastic solution

Plant	1,1,0
Warehouse	0,1,1,0,0,0,0,0,0
Disassembly Centre	1,0,0,0,1,0

Statistical analysis

For stochastic optimization problems, we compute two statistics that quantify the importance of randomness. They are

1) Expected Value of Perfect Information
2) Value of Stochastic Solution

Expected Value of Perfect Information

The Expected Value of Perfect Information, EVPI, is the difference between Expected Outcome with Perfect Information and the Expected Outcome without Perfect Information.

The Expected Value With Perfect Information is the expected or average return, in the long run, if we have perfect information before a decision has to be made. To calculate this value, we choose the best alternative for each state of nature and multiply its payoff times the probability of occurrence of that state of nature.

Expected Value with Perfect Information (E1)

$B_1, B_2, B_3, \ldots, B_n$ denote the best outcomes of scenarios $1,2,3,\ldots,n$

$P_1, P_2, P_3, \ldots, P_n$ denote the probabilities of scenarios $1,2,3,\ldots,n$

Then,

$$E1 = (B_1 \times P_1) + (B_2 \times P_2) + (B_3 \times P_3) + \ldots + (B_n \times P_n)$$

Expected Value without Perfect Information (E2)

Without perfect information the minimum expected total cost could be obtained only by solving the recourse problem. The recourse problem is the deterministic equivalent of the stochastic model. Here, the probabilities of their respective scenarios are implemented in the mathematical model.

Hence from the above definitions, we have

Expected Value of Perfect Information, EVPI = E2 – E1

For example 1, we compute EVPI using Table 4.4 which presents the optimal total cost from the individual scenarios and compare it with the deterministic equivalent of the stochastic solution.

$E1 = (11485750 \times 0.1) + (11285020 \times 0.3) + (11309650 \times 0.6) = 11319871$

From the Stochastic Solution, we have

$E2 = 11942880$

$EVPI = E2 - E1 = 623009$

EVPI is 5.21% better than the stochastic solution.

Table 4.4 Example 1: EVPI, scenario solution

Scenario	Best outcome of the Individual Scenario in ($\times 10^7$)
1	1.148575
2	1.128502
3	1.130965

Value of Stochastic Solution

Value of Stochastic Solution, VSS, is the difference between the objective value for the stochastic problem (stochastic solution) and the objective value for the deterministic problem computed with stochastic variables replaced by their expectations (expected value solution).

Wait and See Solution

Wait and See (WS) problems assume that the decision-maker waits until the uncertainty is resolved before implementing the optimal decisions. This approach therefore relies upon perfect information about the future. Wait and see models are often used to analyze the probability distribution of the objective value, and consist of a family of LP models, each associated with an individual scenario.

Finding the wait-and-see solution or equivalently solving the distribution problem may not be possible if perfect information is not available. The wait-and-see solution approach delivers a set of solutions instead of one solution that would be implementable. It is much easier to solve a simpler problem with all random variables replaced by their expected values. It is called then expected value problem or mean value problem.

Expectation of the expected value, EEV, is the quantity that measures how $\bar{x}\left(\bar{\xi}\right)$ performs, allowing second stage decisions to be chosen optimally as functions of $\bar{x}\left(\bar{\xi}\right)$ and ξ.

where $\bar{\xi} = E(\xi)$ denotes the expectation of the random variable "ξ". The Value of the Stochastic Solution is the statistical tool that measures how good or bad a decision $\bar{x}\left(\bar{\xi}\right)$ is in terms of the deterministic equivalent of the stochastic program(SS).

Hence it is defined as

$VSS = EEV - SS$

For example 1, we compute VSS for all the scenarios and compare them with the deterministic equivalent of the stochastic solution. Figure 4.1 presents the comparison of the individual scenario solutions with the deterministic equivalent of stochastic solution.

As a first step the optimal first stage solution is obtained, which is presented in Table 4.5. Then, the first stage decision variables (i.e. location variables) for the first scenario are fixed and the total costs (which include transportation costs, fixed costs and machinery costs) for every scenario is obtained. These results are presented in Table 4.6.

Expectation of the expected cost (EEV) is the expectation of these total costs with their respective probabilities. This quantity measures the impact of the first stage decision variables on the second stage decision variables by optimally allocating the transportation links.

$$EEV = TC_{11} \times P_1 + TC_{12} \times P_2 + TC_{13} \times P_3$$

where TC_{11} = Total cost of scenario 1 when the optimal first stage decision variables of scenario 1 is set.

TC_{12} = Total cost of scenario 2 when the optimal first stage decision variables of scenario 1 is set.

TC_{13} = Total cost of scenario 3 when the optimal first stage decision variables of scenario 1 is set.

P_1, P_2 and P_3 are probabilities of scenarios 1, 2 and 3 respectively.

EEV = 11485750 × 0.1 + 12302160 × 0.3 + 14014070 × 0.6 = 13247665

Deterministic equivalent of Stochastic Solution (SS) = 11942880

Value of Stochastic Solution (VSS) = EEV – SS = 13247665 – 11942880 = 1304785

The difference between stochastic solution and the EEV is 9.85%.

Table 4.5 Example 1: VSS, expected solution of individual scenarios

Scenario	Total Cost ($\times 10^7$)	Plants	Warehouse	Disassembly Centre
1	1.148575	1,0,0	0,0,0,0,0,1,1,0,0	0,0,0,0,0,1
2	1.128502	1,0,0	0,0,0,1,1,0,0,0,0	0,1,0,0,0,0
3	1.130965	1,1,0	0,1,1,0,0,0,0,0,0	1,0,0,0,1,0

Table 4.6 Example 1: VSS, fixing scen1

Scenario	Total Cost ($\times 10^7$)
1	1.148575
2	1.230216
3	1.401407

Similarly, the first stage decision variables of the second scenario are fixed and the total costs for every scenario is obtained which is presented in Table 4.7.

EEV = 12733030 × 0.1 + 11285020 × 0.3 + 13567050 × 0.6 = 12799039

Deterministic equivalent of Stochastic Solution (SS) = 11942880

VSS = EEV – SS = 856159

The difference between stochastic solution and the EEV is 6.69%.

Table 4.7 Example 1: VSS, fixing scen2

Scenario	Total Cost ($\times 10^7$)
1	1.273303
2	1.128502
3	1.356705

Finally, the first stage decision variables of the third scenario are fixed and the total costs of every scenario are obtained which is presented in Table 4.8.

EEV = 13579580 × 0.1 + 12663780 × 0.3 + 11309650 × 0.6 = 11942882

Deterministic equivalent of Stochastic Solution (SS) = 11942880

VSS = EEV – SS = 2

Table 4.8 Example 1: VSS, fixing scen3

Scenario	Total Cost ($\times 10^7$)
1	1.357958
2	1.266378
3	1.130965

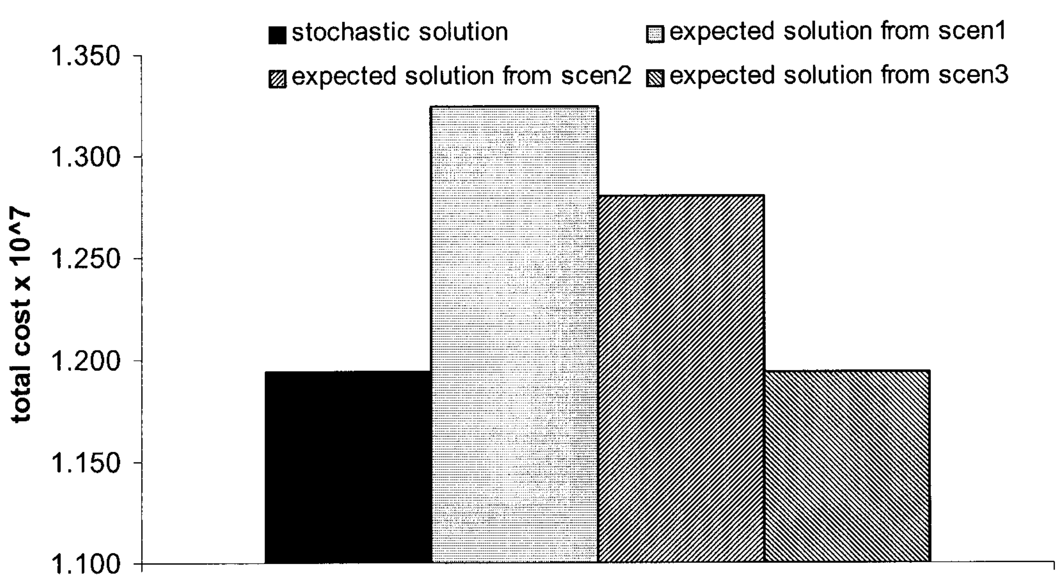


Figure 4.1 Example1: stochastic solution vs individual scenario solutions

- **Example 2**

In this example the number of scenarios has been reduced to two. The main purpose of solving this example is to investigate the variation of total cost and the selection of location variables with the variation of number of scenarios. The number of available plants, warehouses, disassembly centres, customers and the product types remain constant, which is presented in Table 4.9. Table 4.10 presents the probability and return rate data. Other data used in the problem is provided in Appendix 1. This example problem has 10279 constraints and total variables of 4293, including 45 integers.

To solve the model, the software took a runtime of about 3 hours and 25 minutes for the optimal solution. The total cost obtained after solving the deterministic equivalent of the stochastic model is 11978080. Selections of location variables is presented in Table 4.11

Table 4.9 Example 2: facilities, customers & products

Number of plants (P)	3
Number of warehouse (W)	9
Number of Disassembly Centres (L)	6
Number of Raw Material Buyers (R)	1
Number of Disposal Centres (D)	1
Number of Customers (K)	12
Number of Product Types (F)	3

Table 4.10 Example 2: parameter values

Scenario	Return rates	Probabilities
1	0.4	0.3
2	0.8	0.7

Table 4.11 Example 2: stochastic solution

Plant	1,1,0
Warehouse	0,0,0,0,0,0,1,1,0
Disassembly Centre	0,0,0,0,1,1

EVPI is calculated using the total optimal costs of the individual scenarios presented in Table 4.12.

E1 = (11192920 × 0.3) + (11574320 × 0.7) = 11459900

E2 = 11978080

EVPI = E2 – E1 = 518180

Expected Value with Perfect Information is 4.32 % better than the stochastic solution.

Table 4.12 Example 2: EVPI, scenario solution

Scenario	Best outcome of the Individual Scenario ($\times 10^7$)
1	1.119292
2	1.157432

VSS for all the scenarios is computed in the same way as in Example 1. The optimal first stage location decision variable for both scenarios is computed which is presented in Table 4.13.

The first stage decision variables of the first scenario are fixed and the total cost of both the scenarios is obtained. These results are presented in Table 4.14.

Hence

EEV = 11192920 × 0.3 + 12942670 × 0.7 = 12417745

Deterministic equivalent of Stochastic Solution (SS) = 11978080

VSS = EEV – SS = 439665

The difference between stochastic solution and the EEV is 3.54%.

Table 4.13 Example 2: VSS, expected solution of individual scenarios

Scenario	Total Cost ($\times 10^7$)	Plants	Warehouse	Disassembly Centre
1	1.119292	1,0,0	0,0,0,0,0,1,1,0,0	0,0,0,0,0,1
2	1.157432	1,0,0	0,0,0,1,1,0,0,0,0	1,0,0,0,1,0

Table 4.14 Example 2: VSS, fixing scen1

Scenario	Total Cost ($\times 10^7$)
1	1.119292
2	1.294267

After fixing the first stage decision variables of the second scenario, the total cost of both the scenarios is obtained which is presented in Table 4.15.

EEV = 13092470 × 0.3 + 11574320 × 0.7 = 12029765

Deterministic equivalent of Stochastic Solution (SS) = 11978080

VSS = EEV – SS = 51685

The difference between stochastic solution and the EEV is 0.42%.

The VSS is very low in this case, because the probability of the scenario is 0.8

Table 4.15 Example 2: VSS, fixing scen2

Scenario	Total Cost ($\times 10^7$)
1	1.309247
2	1.157432

- **Example 3**

In this example the number of scenarios is four. The number of available plants, customers and the product types remain constant. The number of warehouses is reduced to 7 and disassembly centres are reduced to 4. This is done to accommodate the model within the capacity limits of the solver. Return rates and probabilities are presented in Table 4.16.

The model is solved to optimality and the total cost obtained after solving the deterministic equivalent of the stochastic model is 12661650. The selection of location variables of the stochastic model is presented in Table 4.17. EVPI is calculated and it is found to be 978053. Results of total costs of individual scenarios are presented in Table 4.18. Total cost from expected solution for this example is 7.72 % better than the stochastic solution, nevertheless it is an expected solution. VSS for all the scenarios is computed and presented in Table 4.19.

Table 4.16 Example 3: parameter values

Scenario	Return rates	Probabilities
1	0.2	0.1
2	0.4	0.2
3	0.6	0.3
4	0.9	0.4

Table 4.17 Example 3: stochastic solution

Plant	1,1,0
Warehouse	0,1,0,0,0,0,1
Disassembly Centre	1,0,1,0

Table 4.18 Example 3: EVPI, scenario solution

Scenario	Best outcome of the Individual Scenario ($\times 10^7$)
1	1.180228
2	1.159764
3	1.163227
4	1.173540

Table 4.19 Example 3: VSS of all scenarios

Location variables of scenario which is set	Expected Solution from respective scenarios	Stochastic solution	VSS	% Change
1	13251278	12661650	589628	4.45
2	13206849	12661650	545199	4.13
3	12921592	12661650	259942	2.01
4	12866867	12661650	205217	1.59

- **Example 4**

In this example the number of scenarios is five. The number of customers and the product types remain constant. The number of plants is reduced to 2, warehouses and disassembly centres are remain the same at 7 and 4 respectively to comply with the solver capability. Probabilities and return rates are presented in Table 4.20.

The model is solved to optimality and the total cost obtained after solving the deterministic equivalent of the stochastic model is 12505430. The selection of location variables of stochastic solution is presented in Table 4.21. EVPI is calculated and it is found to be 901110. Results of total costs of individual scenarios are presented in Table 4.22. Total cost from expected solution for this example is 7.21 % better than the stochastic solution. VSS for all the scenarios is computed and presented in Table 4.23.

Table 4.20 Example 4: parameter values

Scenario	Return rates	Probabilities
1	0.1	0.2
2	0.3	0.1
3	0.5	0.1
4	0.7	0.2
5	0.9	0.4

Table 4.21 Example 4: stochastic solution

Plant	1,1
Warehouse	0,0,1,1,0,0,0
Disassembly Centre	1,0,1,0

Table 4.22 Example 4: EVPI, scenario solution

Scenario	Best outcome of the Individual Scenario ($\times 10^7$)
1	1.208315
2	1.184675
3	1.151575
4	1.175002
5	1.125359

Table 4.23 Example 4: VSS of all scenarios

Location variables of scenario which is set	Expected Solution from respective scenarios	Stochastic solution	VSS	% Change
1	12930518	12505430	425088	3.29
2	12679638	12505430	174208	1.37
3	12805452	12505430	300022	2.34
4	12716894	12505430	211464	1.66
5	12505393	12505430	-37	0.00

4.2 Comparison of Total Cost, EVPI and VSS of the Example Problems

Figures 4.3, 4.4 and 4.5 compares total costs, EVPI, VSS of all the 4 examples. The differences between the probabilities of individual scenarios decrease as the number scenarios increase. As a result each scenario will have equally likely chance of occurrence. Thus, the total cost from stochastic solution increases to reduce the uncertainty of the scenario occurrence with different return rates. Hence the total savings, i.e. VSS, from the implementation of stochastic solution decreases as the number of scenarios increase. Nevertheless the solution from the stochastic model is always efficient over the expected solution. Optimal costs of individual scenarios are always lower than the stochastic cost, because uncertainty is never an issue within them. As a result expected costs are always lower than stochastic costs. Since total costs increase with the increase in the number of scenarios, EVPI also increases.

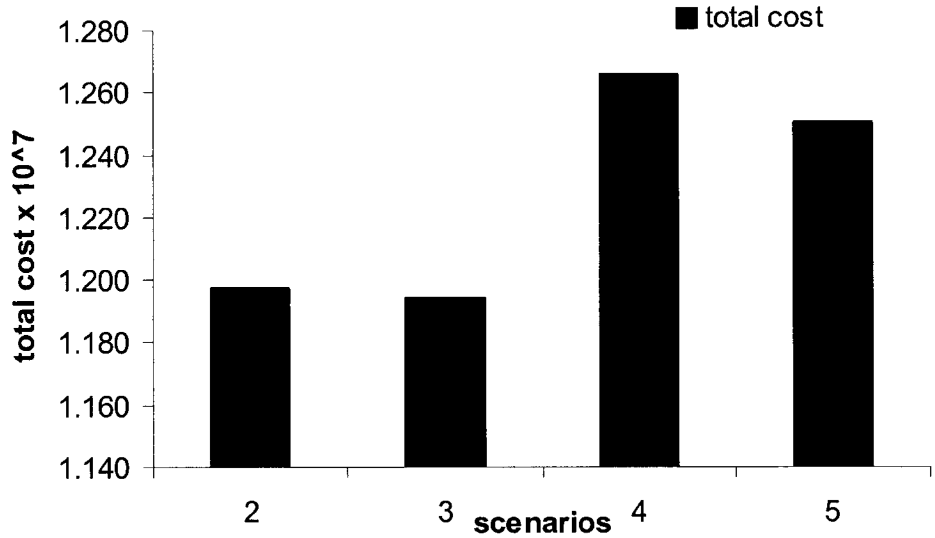


Figure 4.2 Comparison of stochastic solution of all the examples

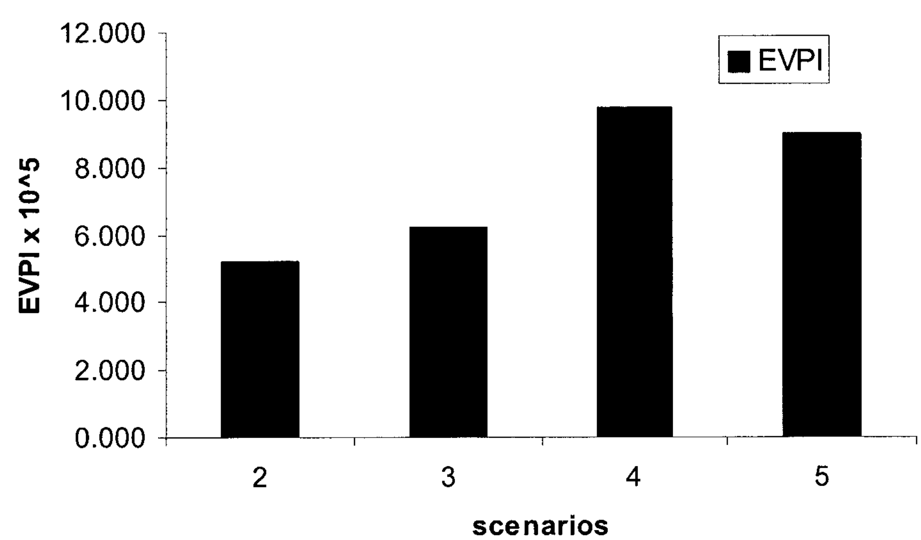


Figure 4.3 Comparison of EVPI of all the examples

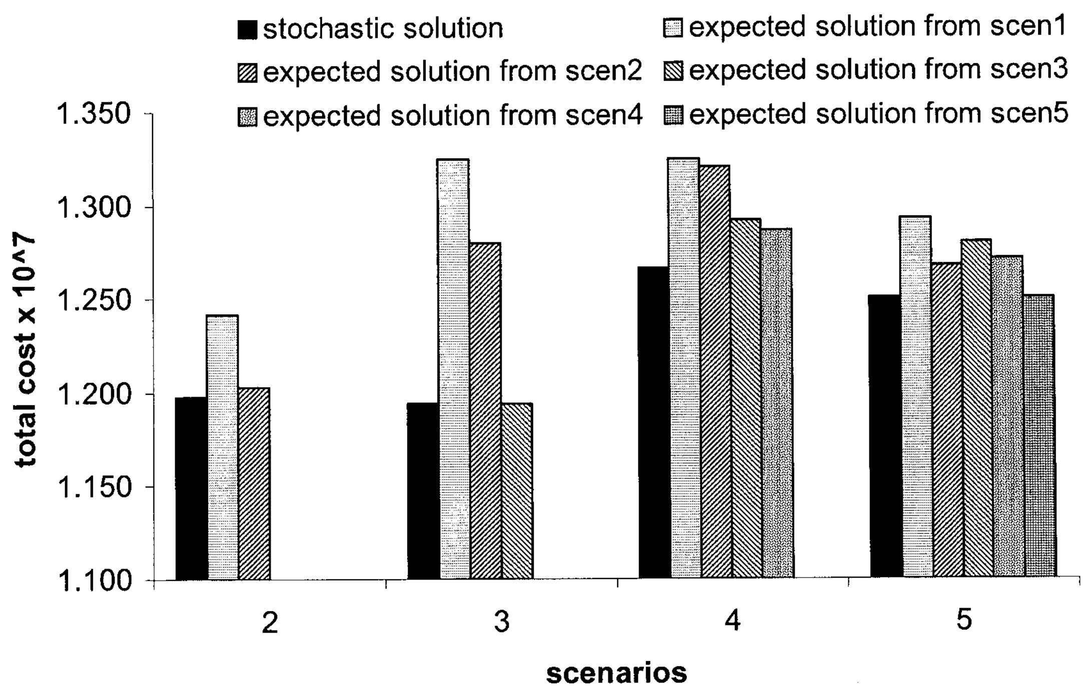


Figure 4.4 Comparison of VSS of all the examples

4.3 Variation of the Probabilities of the Scenarios

In this section, the probabilities of the individual scenarios are varied to see the effects on the stochastic solution, EVPI and VSS. Two cases are considered:

(a) Low Probability Variation (LPV) between the scenarios

(b) High Probability Variation (HPV) between the scenarios

Problem data presented in Example 1 is considered. Variation of probabilities of the three scenarios for the two cases is shown in Tables 4.24 and 4.25. Solutions for the two cases are presented in Tables 4.26 and 4.27 respectively.

Table 4.24 LPV parameters

Scenario	Probability
1	0.3
2	0.3
3	0.4

Table 4.25 HPV parameters

Scenario	Probability
1	0.7
2	0.2
3	0.1

Table 4.26 Results of LPV between scenarios

Stochastic Solution	12345960	
EVPI	990869	
VSS	Scenario1	396041.00
	Scenario2	286275.00
	Scenario3	50908.00

Table 4.27 Results of HPV between scenarios

Stochastic Solution	11820690	
EVPI	392696	
VSS	Scenario1	81174
	Scenario2	706140
	Scenario3	1348737

Figures 4.5, 4.6 and 4.7 compare the total cost, EVPI and VSS for the probability variations. It is observed that the total cost from stochastic solution is more when there is low probability variation between the scenarios. This is because of the equally likely

chance of occurrence of each scenario. As a result the total savings (VSS) from the stochastic solution over the individual scenario solution is less when there is low probability variation, but the solution reduces the uncertainty of the occurrence of scenario more efficiently.

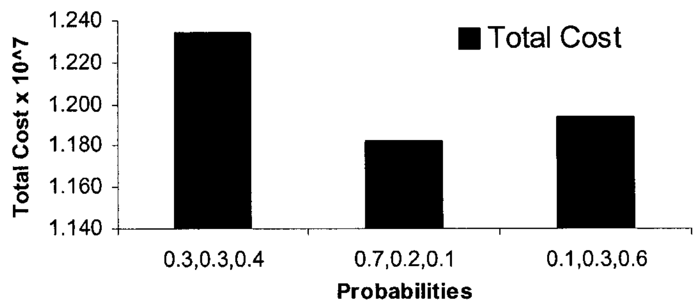


Figure 4.5 Comparison of total cost with varying probability

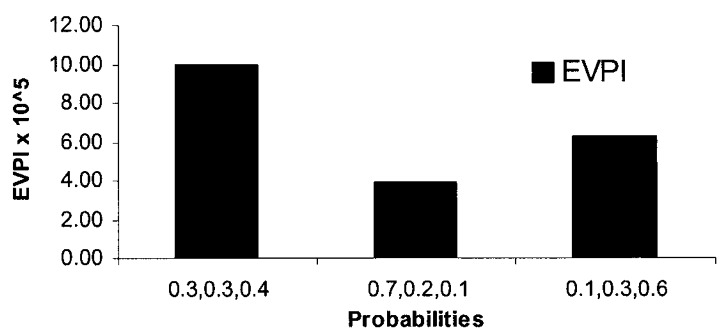


Figure 4.6 Comparison of EVPI with varying probability

for both the cases for all variations. Hence, the problem size in all these cases remains the same.

4.4.1 Total cost vs Return rate

In this section, the effects of the variation of the return rates on the total cost are observed. The two cases can be divided into four types of variations that are described below.

(a) Variation of total cost from stochastic solution with increasing return rates of scenarios 1, 2, 3. Total cost and the selection of the location variables are presented in Table 4.28. Comparisons of total costs for all the examples of this type are presented in Figure 4.8.

Table 4.28 Total cost: return rate variation of all scenarios simultaneously

Return Rate	Total Cost	Plant Location	Warehouse Location	Disassembly Centre Location
0.1, 0.1, 0.1	12685990.00	0,1,0	0,0,1,1,0,0,0,0,0	0,0,0,0,1,0
0.2, 0.2, 0.2	12386950.00	0,1,0	0,0,1,1,0,0,0,0,0	0,0,0,0,1,0
0.3, 0.3, 0.3	12122960.00	0,1,0	0,0,1,1,0,0,0,0,0	0,0,0,0,1,0
0.4, 0.4, 0.4	11934180.00	0,1,0	0,0,1,1,0,0,0,0,0	0,0,0,0,1,0
0.5, 0.5, 0.5	11724940.00	1,0,0	1,1,0,0,0,0,0,0,0	1,0,0,0,0,0
0.6, 0.6, 0.6	11709280.00	1,0,0	1,1,0,0,0,0,0,0,0	0,0,1,0,0,0
0.7, 0.7, 0.7	11977530.00	1,0,0	0,1,1,0,0,0,0,0,0	0,0,1,0,0,0
0.8, 0.8, 0.8	11797600.00	1,1,0	0,1,1,0,0,0,0,0,0	1,0,0,0,1,0
0.9, 0.9, 0.9	11467990.00	1,1,0	0,1,1,0,0,0,0,0,0	1,0,0,0,1,0

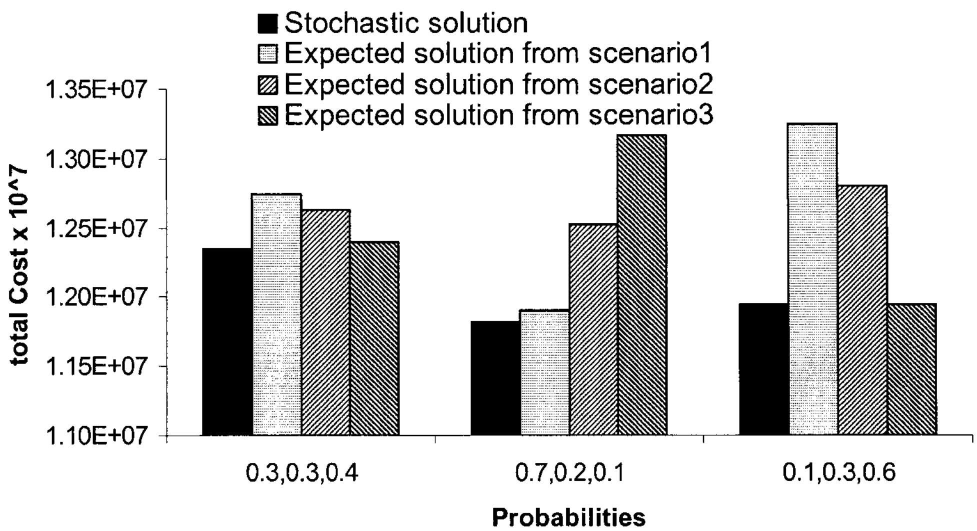


Figure 4.7 Comparison of VSS with varying probability

4.4 Variation of the Return Rates

The designing of the product recovery network models can be mainly hindered by the uncertainty of the return rates of the products after their end of life. It mainly affects the first stage decision variables. One cannot firmly decide the locations of plants, warehouses and disassembly centres which involve high cost investments. This has a direct effect on the total costs of the closed loop product recovery network. Hence, the return rates have been varied to observe its effect on total costs, EVPI and VSS. Two cases are considered:

- Variation of the return rates of all the scenarios simultaneously
- Variation of the return rate of one scenario and maintaining other scenarios constant.

Problem data presented in Example 1 is considered. Variations of the return rates of the three scenarios for the two cases are done. Probabilities of the scenarios remain the same

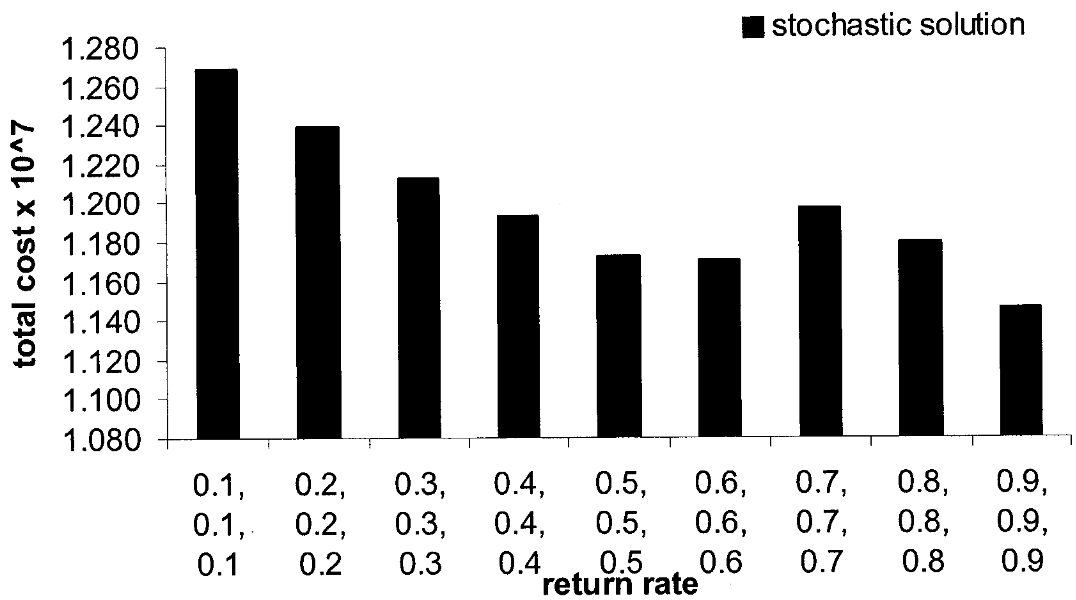


Figure 4.8 Stochastic solution w.r.t varying return rates of all scenarios simultaneously

(b) Variation of total cost from stochastic solution with increasing return rate of scenario 1 where as return rates of scenarios 2, 3 remaining constant. Table 4.29 present the total costs obtained. In this type of variation, the first stage location variables of plants, warehouses and the disassembly centres remained the same throughout. The selection of these variables is presented in Table 4.30. Comparison of total costs for all examples of this type is presented in Figure 4.9.

Table 4.29 Total cost: return rate variation of scenario 1 only

Return Rate	Total Cost
0.1, 0.6, 0.9	12005180.00
0.2, 0.6, 0.9	11974030.00
0.3, 0.6, 0.9	11942880.00
0.4, 0.6, 0.9	11911740.00
0.5, 0.6, 0.9	11880590.00
0.6, 0.6, 0.9	11849440.00
0.7, 0.6, 0.9	11818290.00
0.8, 0.6, 0.9	11787170.00
0.9, 0.6, 0.9	11756150.00

Table 4.30 Location selection: return rate variation of scenario 1 only

Plant	1,1,0
Warehouse	0,1,1,0,0,0,0,0,0
Disassembly Centre	1,0,0,0,1,0

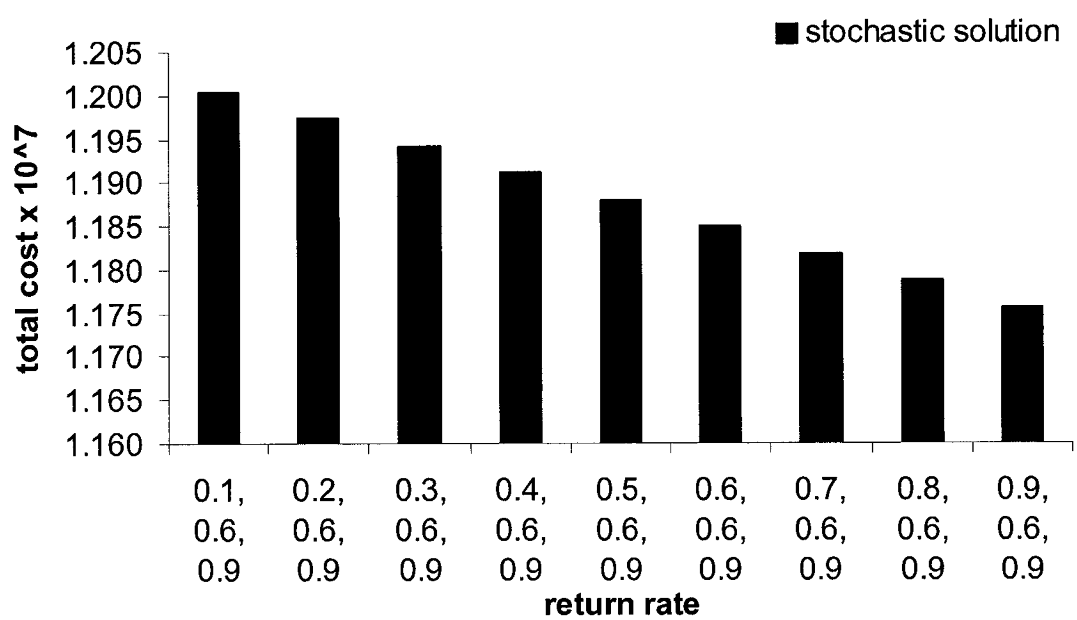


Figure 4.9 Stochastic solution w.r.t varying return rates of scenario 1

(c) Variation of total cost from stochastic solution with increasing return rate of scenario 2 where as return rates of scenarios 1 and 3 remaining constant. Table 4.31 present the total costs obtained. In this type of variation, the first stage location variables of plants, warehouses and the disassembly centres remained the same throughout. The selection of these variables is presented in Table 4.32. Comparison of total costs for all examples of this type is presented in Figure 4.10.

Table 4.31 Total cost: return rate variation of scenario 2 only

Return Rate	Total Cost
0.3, 0.1, 0.9	12424770.00
0.3, 0.2, 0.9	12328390.00
0.3, 0.3, 0.9	12232020.00
0.3, 0.4, 0.9	12135640.00
0.3, 0.5, 0.9	12039260.00
0.3, 0.6, 0.9	11942880.00
0.3, 0.7, 0.9	11846710.00
0.3, 0.8, 0.9	11750580.00
0.3, 0.9, 0.9	11654720.00

Table 4.32 Location selection: return rate variation of scenario 2 only

Plant	1,1,0
Warehouse	0,1,1,0,0,0,0,0,0
Disassembly Centre	1,0,0,0,1,0

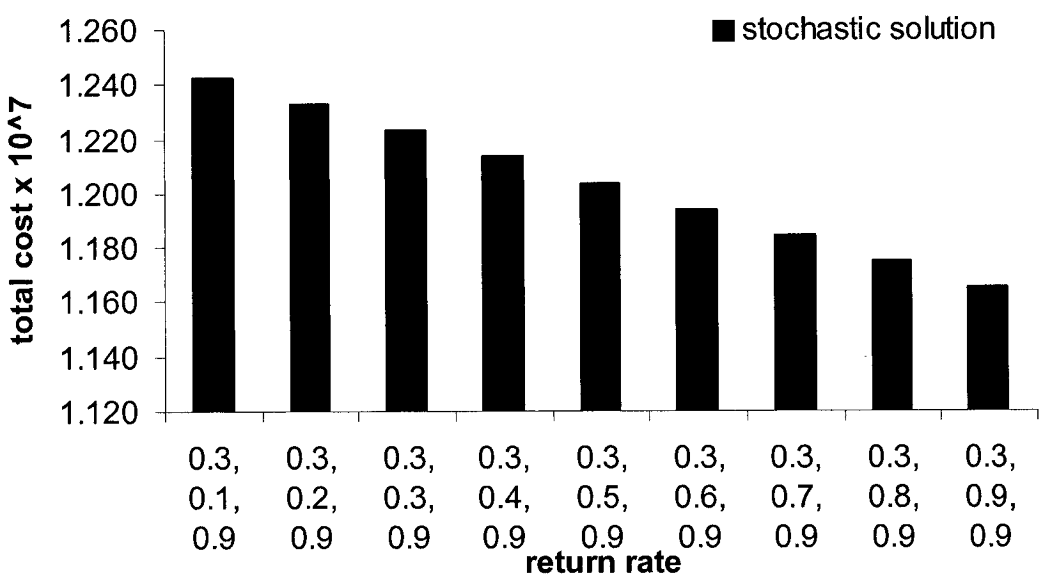


Figure 4.10 Stochastic solution w.r.t varying return rates of scenario2

(d) Variation of Total cost from stochastic solution with increasing return rate of scenario 3 where as return rates of scenarios 1 and 2 remaining constant. Table 4.33 presents the total cost and the selection of the location variables. Comparison of total costs for all the examples of this type is presented in Figure 4.11.

Table 4.33 Total cost: return rate variation of scenario3 only

Return Rate	Total Cost	Plant Location	Warehouse Location	Disassembly Centre Location
0.3, 0.6, 0.1	12385490.00	0,1,0	0,0,1,1,0,0,0,0,0	1,0,0,0,0,0
0.3, 0.6, 0.2	12197370.00	0,1,0	0,0,1,1,0,0,0,0,0	0,0,1,0,0,0
0.3, 0.6, 0.3	12041940.00	0,1,0	0,0,1,1,0,0,0,0,0	0,0,1,0,0,0
0.3, 0.6, 0.4	11932280.00	1,0,0	1,1,0,0,0,0,0,0,0	0,0,1,0,0,0
0.3, 0.6, 0.5	11763040.00	1,0,0	1,1,0,0,0,0,0,0,0	0,0,1,0,0,0
0.3, 0.6, 0.6	11782880.00	1,0,0	1,1,0,0,0,0,0,0,0	0,0,1,0,0,0
0.3, 0.6, 0.7	11955050.00	1,0,0	0,1,1,0,0,0,0,0,0	0,0,1,0,0,0
0.3, 0.6, 0.8	12145630.00	1,1,0	0,1,1,0,0,0,0,0,0	1,0,0,0,1,0
0.3, 0.6, 0.9	11942880.00	1,1,0	0,1,1,0,0,0,0,0,0	1,0,0,0,1,0

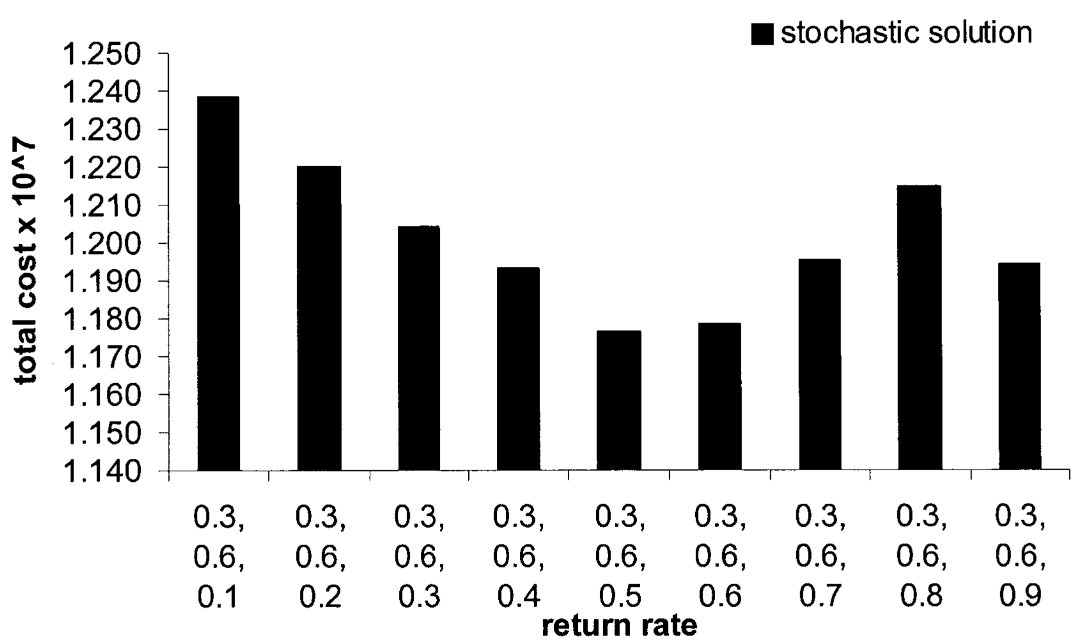


Figure 4.11 Stochastic solution w.r.t varying return rates of scenario3

In all the four return rate variations it is observed that the total costs decrease with the increase in the return rates. This is because as the return rates increase more and more costs savings can be achieved by remanufacturing. Also the facility centres are used efficiently to their full capacity. In the first case there is a small bump at the return rate of 0.7. This is because as the return rate keeps on increasing, fixed costs increase to open more facility centres to handle the increasing returns and avoid the penalty costs. For the second type where return rate of scenario 1 is increasing and the third type where the return rates of scenario 2 is increasing, the total cost decreases in a linear fashion. This is because the probability of occurrence of that specific scenario coupled with the increasing return rate would not be able to make a significant impact on the fixed costs. Fourth type of variation shows a similar pattern as in the first type, which can be attributed to the high probability of occurrence of scenario 3.

4.4.2 EVPI vs Return rates

In this section, the effects of the variation of the return rates on EVPI are observed. Results of EVPI of the four types of variations are given in Appendix 2. Figures 4.12 to 4.15 compares the variations of EVPI with the variation in the return rate of all the examples for the four types.

(a) Variation of EVPI with increasing return rates of scenarios 1, 2, 3

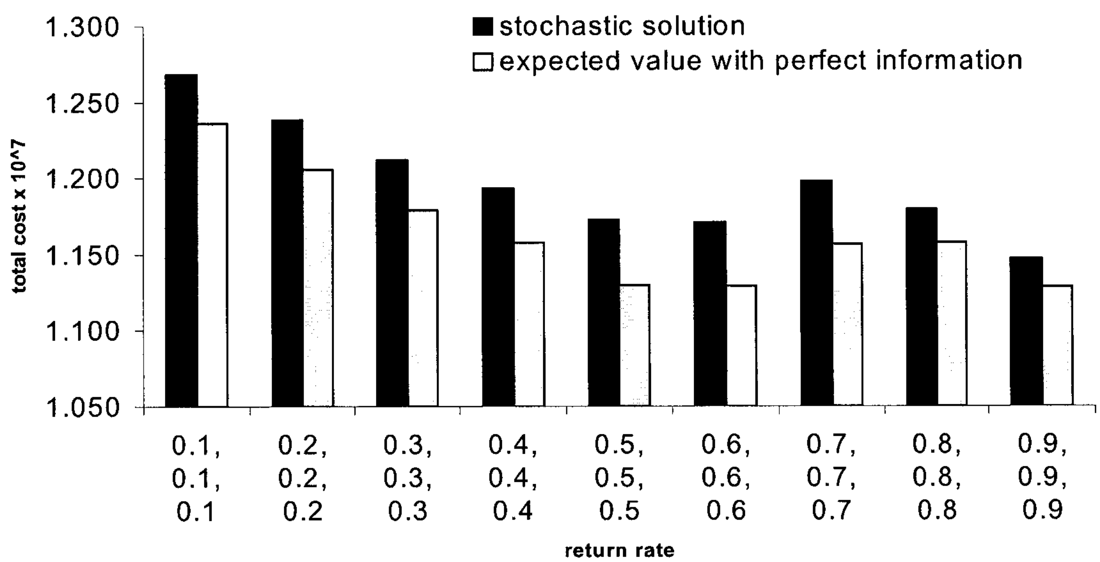


Figure 4.12 EVPI w.r.t varying return rates of all scenarios simultaneously

(b) Variation of EVPI with increasing return rate of scenario 1 where as return rates of scenarios 2, 3 remaining constant

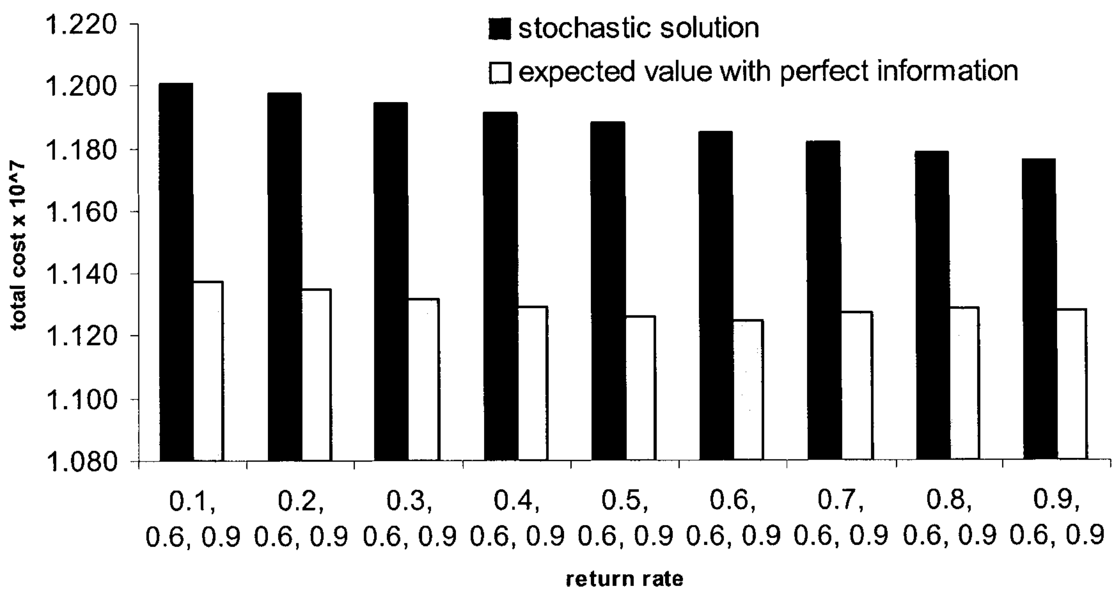


Figure 4.13 EVPI w.r.t varying return rates of scenario1

(c) Variation of EVPI with increasing return rate of scenario 2 where as return rates of scenarios 1, 3 remaining constant

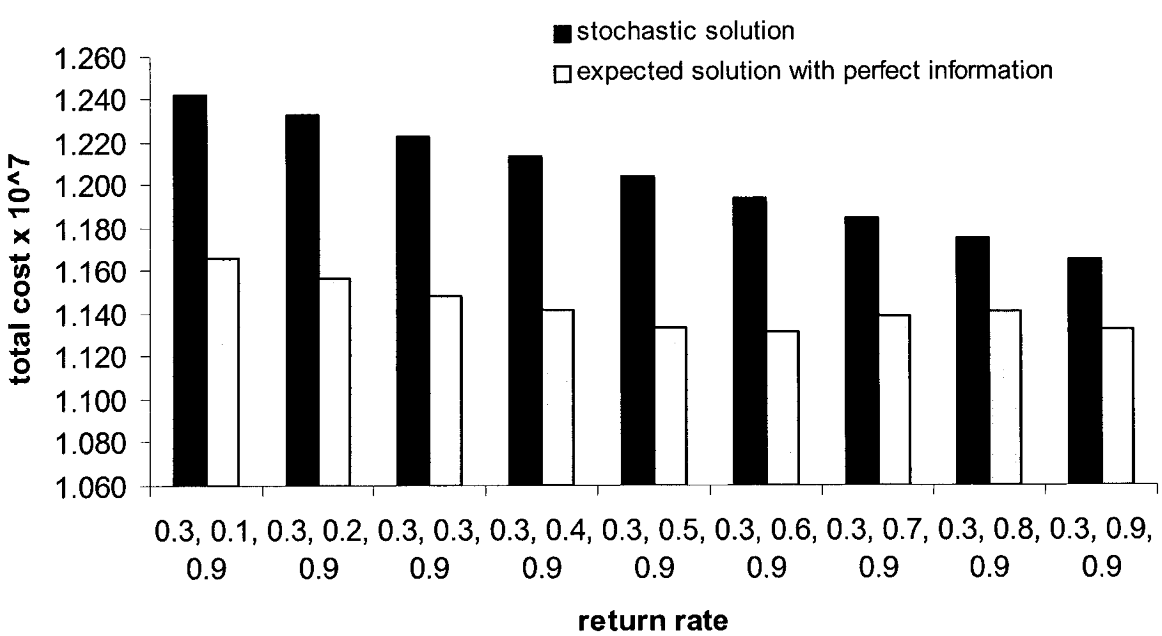


Figure 4.14 EVPI w.r.t varying return rates of scenario2

(d) Variation of EVPI with increasing return rate of scenario 3 where as return rates of scenarios 1, 2 remaining constant

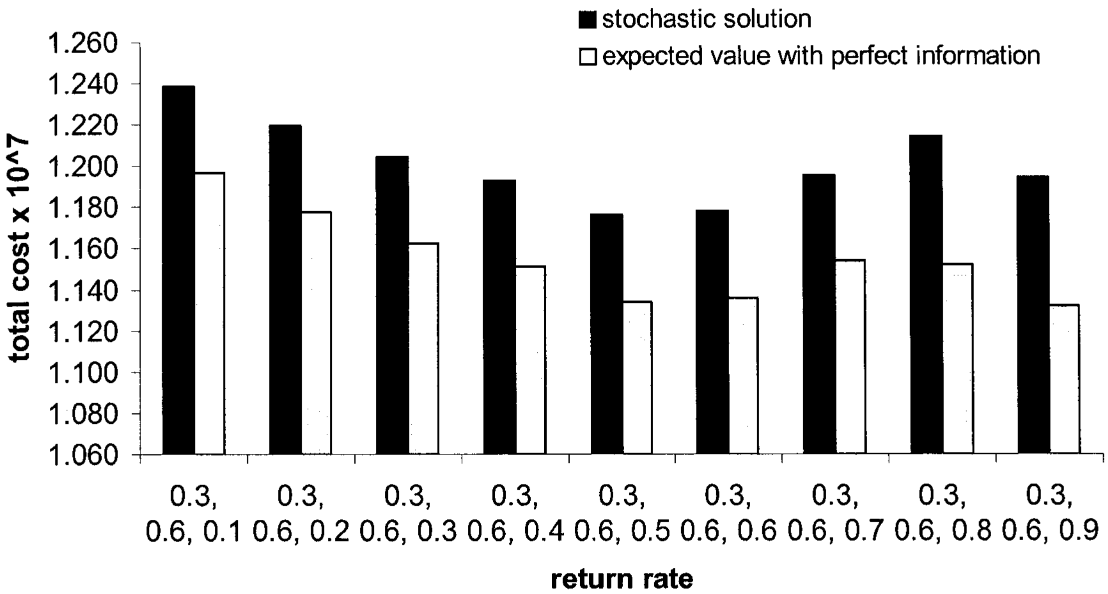


Figure 4.15 EVPI w.r.t varying return rates of scenario3

In all the four return rate variations, EVPI more or less remains constant as the return rates increase. EVPI is difference between expected total costs and stochastic total costs. As the return rates increase stochastic total costs decrease. The optimal total costs of the individual scenarios also decrease, resulting in the decrease of the expected total costs. Hence EVPI almost remains constant. The expected cost follows the same pattern as that of stochastic total cost as return rates increase. Expected costs do not consider the issue of uncertainty factor of the scenario occurrence where as stochastic solutions eliminates it giving robust solutions for better implementation of the product recovery system. More over as the return rates increase, the situation gets more worsened if one persists with the expected total costs. This is because of the high investment for fixed costs and setup costs. Hence stochastic solution is always preferred over the expected solution.

4.4.3 VSS vs Return rates

In this section, the effects of the variation of the return rates on VSS are observed. Results of VSS of the four types of variations are given in Appendix 2. Figures 4.16 to 4.19 compares the variations of VSS with the variation in the return rate of all the examples for the four types.

(a) Variation of VSS with increasing return rates of scenarios 1, 2, 3

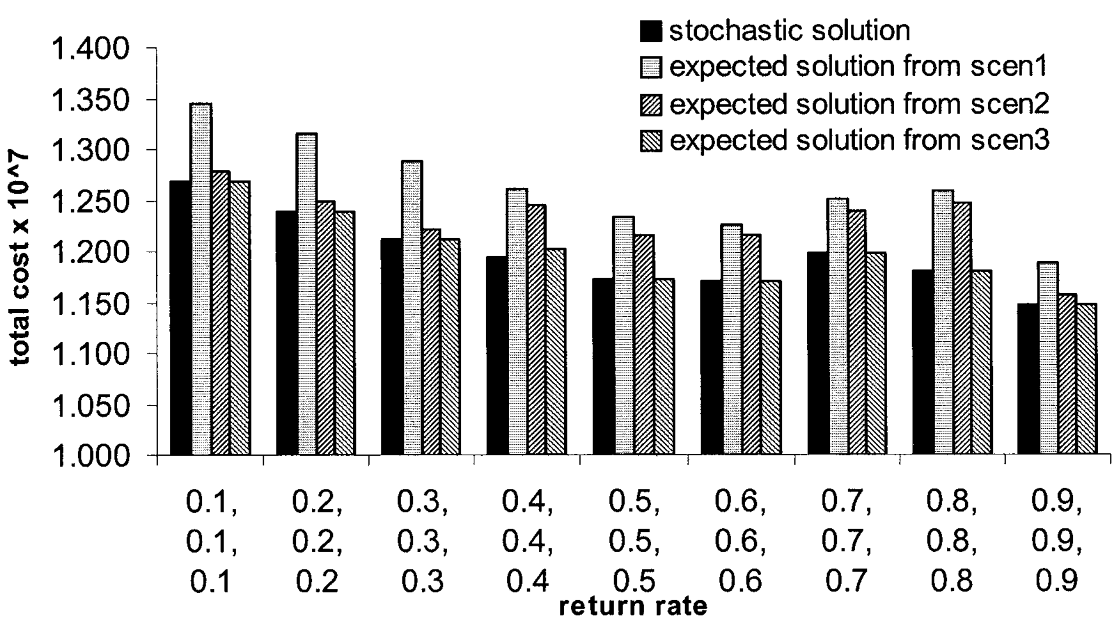


Figure 4.16 VSS w.r.t varying return rates of all scenarios simultaneously

(b) Variation of VSS with increasing return rate of scenario 1 where as return rates of scenarios 2, 3 remaining constant

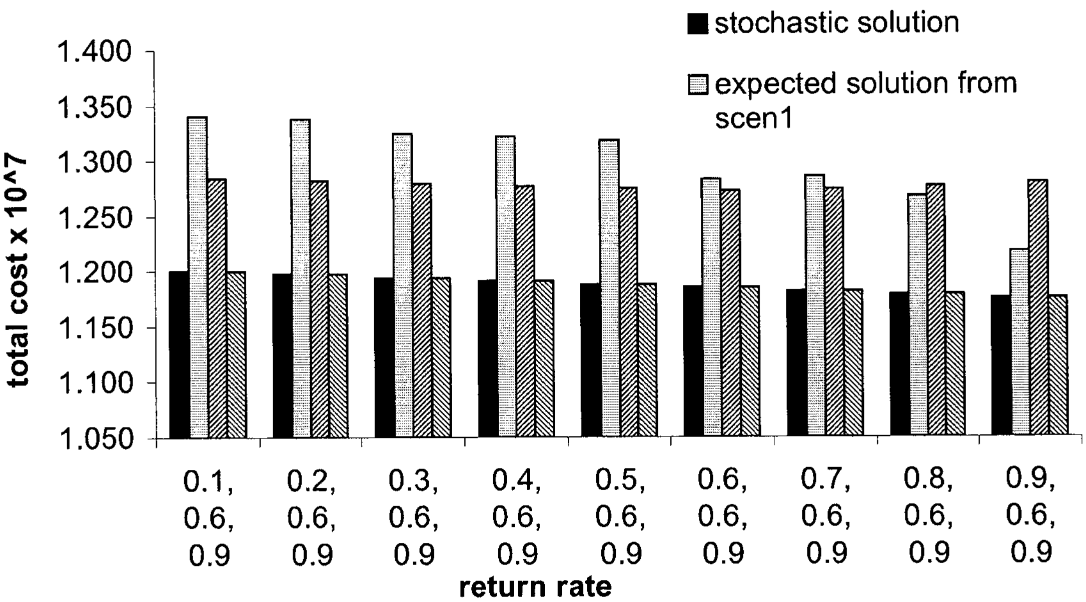


Figure 4.17 VSS w.r.t varying return rates of scenario1

(c) Variation of VSS with increasing return rate of scenario 2 and return rates of scenarios 1, 3 remaining constant

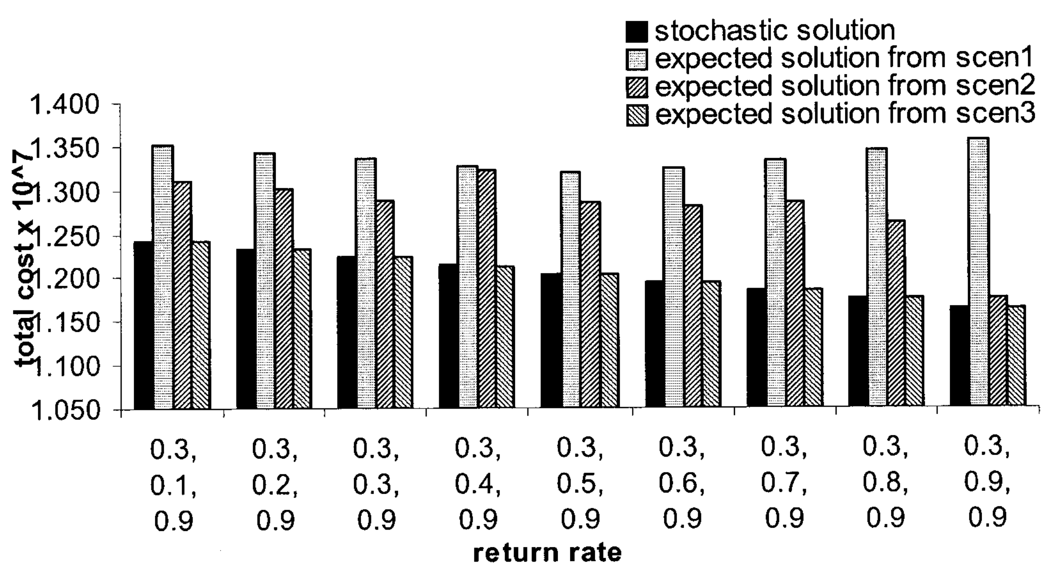


Figure 4.18 VSS w.r.t varying return rates of scenario2

(d) Variation of VSS with increasing return rate of scenario 3 where as return rates of scenarios 1, 2 remaining constant

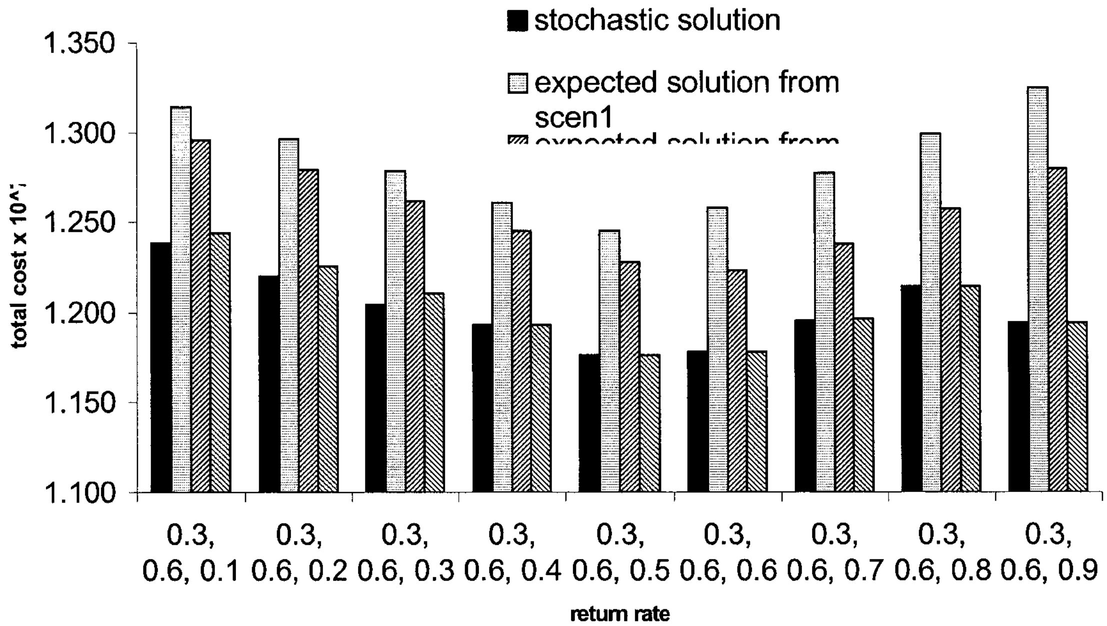


Figure 4.19 VSS w.r.t varying return rates of scenario3

In all the four return rate variations, it is shown that the total cost from the stochastic solution is less than the expected solutions from the scenarios. Hence stochastic solutions are preferred over the deterministic solution to eliminate the uncertainty factor of the return rate and scenario occurrence. As the return rates increase, VSS decrease by small amount. This is because as the return rates increase the optimal costs of individual scenarios decrease which results in decrease of EEV costs. Since the stochastic total costs also decrease, VSS decreases by only small amount. In case 1, VSS decreases for all the scenarios, because the return rates of all the scenarios are increasing. In the remaining cases, the VSS decreases corresponding to the scenario that is increasing. It should be noted that in all the cases, scenario 3 does not show much cost savings. This is because of the high probability of occurrence of scenario 3.

4.5 Summary

Uncertainty of the return rates of the end-of-life products play a major role in determining optimal locations of facility centres and in building efficient closed loop supply chain networks. The other parameters which have influence in determining the total costs and optimal locations are the number of scenarios and their probabilities. Return rates variations are tested step by step at an increasing rate with all scenarios changing simultaneously as well as by increasing one scenario at a time and maintaining other scenarios at a constant rate. The results from the example problems are summarized below.

(a) Variation of number of scenarios

Total cost increases with increase of number of scenarios.

EVPI increases with the increase of number of scenarios.

VSS decreases with the increase of number of scenarios.

(b) Variation of probability of scenarios with constant return rates and number of scenarios

Total cost decreases with the increase in variation of probability between scenarios.

EVPI decreases with the increase in variation of probability between scenarios.

VSS increases with the increase in variation of probability between scenarios.

(c) Variation of return rates of scenarios without varying number of scenarios and their probabilities

- **Return rates of all the three scenarios increase simultaneously**

Total costs from the stochastic solution are decreasing at a constant rate. EVPI remains almost constant through all the variations. VSS shows significant savings for scenarios 1 and 2 when stochastic solution is implemented, but not much savings for scenario 3.

- **When the return rate of scenario 1 is increasing, maintaining scenario 2 and 3 constant**

Total costs from the stochastic solution are decreasing at a constant rate. EVPI remains almost constant through all the variations. VSS shows high savings for scenarios 1 and 2 when stochastic solution is implemented, but savings from scenario 3 remains insignificant.

- **When the return rate of scenario 2 is increasing, maintaining scenario 1 and 3 constant**

Total costs from the stochastic solution are decreasing at a constant rate. EVPI decreases as the return rate increases. VSS shows significant savings for scenario 1, moderate savings for scenario 2 and no savings for scenario 3.

- **When the return rate of scenario 3 is increasing, maintaining scenario 1 and 2 constant**

Total costs from the stochastic solution is decreasing at a constant rate. EVPI remains almost constant through all the variations. VSS shows significant savings for scenarios 1 and 2, but scenario 3 does not show any savings.

The total costs from the stochastic solution shows an upward trend with the increase of number of scenarios and a downward trend when the return rates from the scenarios are high and also when the probability variation between the scenarios is high. Hence the current model (deterministic equivalent of a stochastic model) shows high cost savings when there are fewer scenarios with higher return rates and high probability variation between the scenarios. Value of Stochastic Solution (VSS) measures the importance of stochastic solution over deterministic solution. Stochastic solution shows best results when there are fewer numbers of scenarios and when there is good variation of the probability between the scenarios. When the return rates increase there are significant savings, but there is not much variation in the savings. Expected Value of Perfect Information (EVPI) remains almost constant through all the variations.

Chapter Five

Conclusion and Future Directions

This chapter provides concluding remarks about the reverse logistics network design and future directions for research in this area.

5.1 Concluding Remarks

Reverse logistics network design normally faces uncertainties in quality, quantity and the timing of the product returns. Hence a robust network design is necessary to build an efficient recovery network. For proper planning of location of plants, warehouses and disassembly centres and to reduce transportation costs between them, uncertain factors must be considered. Stochastic programming models provide good solution to handle such problems.

In this thesis a mathematical model is proposed for designing a closed-loop network model for product recovery. The model presented is a generic mixed integer linear program that can be applied to solving certain types of network designing problems in this area. Several example problems are solved to identify the parameters which significantly influence the reverse logistic network design. The variations of the total costs are tabulated. Two statistical tools for stochastic optimization problems: Expected Value of Perfect Information (EVPI) and Value of Stochastic Solution (VSS) are measured and the variations are depicted.

5.2 Contribution to the Research

This research extended the work of Fleischmann et al (2001) by incorporating additional features in the model. Most of the available generic product recovery network models are deterministic supporting a single product recovery and without considering capacity limits of facility centres.

The current thesis:

- Presents generic product recovery network model.
- Mainly concentrates on solving the problem with uncertainty in time and in quantity of product returns. Stochastic programming model is introduced to handle this problem.
- The generic recovery model is enhanced to include the feature for multiple product-type recovery.
- Capacity constraints are included for the plants, warehouses and the disassembly centres to make model more practical.
- The developed model is extensively tested by several hypothetical example problems with realistic features. Computational results show that stochastic programming is an effective approach in solving such and similar problems.

5.3 Future Directions for Research

In this research a closed-loop supply chain model is considered, which integrates the traditional forward flow and the recovery process as well. However, the scope of the thesis is confined to the network design process. It does not consider other aspects of the closed-loop supply chain process such as inventory control, remanufacturing and production planning. The model presented in the thesis includes basic features of a stochastic modeling.

The author would consider the following aspects for future research of this study:

- The computation time for running the stochastic model was about 4.5 hrs. The formulation can be strengthened by modifying some constraints, which can reduce the computation time.
- More robust stochastic models can be developed which are capable of handling more complex product recovery problems.
- More statistical analysis can be conducted with much more variations to identify the sensitive parameters of the network model.
- Meta-heuristics can be designed for providing "good" solutions to large size problems in reasonable amount of computation time.
- Other procedures can be developed to handle the uncertainty issue of the product returns
- Other issues of the closed-loop supply chain such as inventory control, production planning, remanufacturing can be integrated to construct a complete product recovery system.

References

1. Barros, A.I., Dekker, R., Scholten, V., 1998. A two-level network for recycling sand: A case study. European Journal of Operational Research, 110, 2, 199-214.
2. Birge, J.R. and Louveaux, F., 1997. Introduction to Stochastic Programming. Springer Series in Operations Research, ISBN 0-387-98217-5.
3. Bloemhof-Ruwaard, J.M., Salomon, M., Van Wassenhove, L.N., 1996. The capacitated distribution and waste disposal problem. European Journal of Operational Research, 88, 3, 490-503.
4. Caruso, C., Colorni, A., Paruccini, M., 1993. The regional urban solid waste management system: a modeling approach. European Journal of Operational Research, 70, 1, 16-30.
5. de Brito, M.P., 2003. Promising Areas for Future Research on Reverse Logistics: an exploratory study. ERIM Report Series Research in Management, ERS-2003-061-LIS, Erasmus University Rotterdam, The Netherlands.
6. de Brito, M.P., Dekker, R., Flapper, S.D.P., 2003. Reverse Logistics - a review of case studies. ERIM Report Series Research in Management, ERS-2003-012-LIS, Erasmus University Rotterdam, The Netherlands.
7. European Working Group on Reverse Logistics, RevLog. http://www.fbk.eur.nl/OZ/REVLOG/

8. Fleischmann, M., Bloemhof-Ruwaard, J.M., Dekker, R., van der Laan, E., van Nunen, J.A.E.E., Van Wassenhove, L.N., 1997. Quantitative models for reverse logistics: A review. European Journal of Operational Research, 103, 1, 1-17.

9. Fleischmann, M., Krikke, H.R., Dekker, R., Flapper, S.D.P., 2000. A characterization of logistics networks for product recovery. Omega, 28, 6, 653-666.

10. Fleischmann, M., 2001. Reverse Logistics Network Structures and Design. ERIM Report Series Research in Management, ERS-2001-52-LIS, Erasmus University Rotterdam, The Netherlands.

11. Fleischmann, M., Beullens, P., Bloemhof-Ruwaard, J.M., Van Wassenhove, L.N., 2001. The Impact of Product Recovery on Logistics Network Design. Production and Operations Management, 10, 2, 156-173.

12. Ginter, P.M. and Starling, J.M., 1978. Reverse Distribution Channels for Recycling. California Management Review, 20, 3, 72-82.

13. Guide, Jr., V.D.R., Jayaraman, V., Srivastava, R., Benton, W.C., 2000. Supply-Chain Management for Recoverable Manufacturing Systems. Interfaces, 30, 3, 125-142.

14. Hinojosa, Y., Puerto, J., Fernandez, F.R., 2000. A multiperiod two-echelon multicommodity capacitated plant location problem. European Journal of Operational Research, 123, 2, 271-291.

15. Jayaraman, V., Guide Jr, V.D.R., Srivastava, R., 1999. A closed-loop logistics model for remanufacturing. Journal of Operational Research Society, 50, 497-508.

16. Jayaraman, V., Patterson, R.A., Rolland, E., 2003. The design of reverse distribution networks: Models and solution procedures. European Journal of Operational Research, 150, 1, 128-149.

17. Krikke, H.R., Van Harten, A., Schuur, P.C., 1999. Business Case OCE: Reverse Logistic Network Re-Design for Copiers. OR Spektrum, 21, 3, 381-409.

18. Krikke, H., Bloemhof-Ruwaard, J.M., Van Wassenhove, L.N., 2001. Design of Closed-Loop Supply Chains: A Production and Return Network for Refrigerators. ERIM Report Series Research in Management, ERS-2001-45-LIS, Erasmus University Rotterdam, The Netherlands.

19. Kroon, L. and Vrijens, G., 1995. Returnable containers: an examples of reverse logistics. International Journal of Physical Distribution and Logistics Management, 25, 2, 56-68.

20. Listes, O., Dekker, R., 2003. A stochastic approach to a case study for product recovery network design. European Journal of Operational Research, 160, 1, 268-287.

21. Louwers, D., Kip, B.J., Peters, E., Souren, F., Flapper, S.D.P., 1999. A facility location allocation model for reusing carpet materials. Computers and Industrial Engineering, 36, 4, 855-869.

22. Marin, A. and Pelegrin, B., 1998. The return plant location problem: Modeling and resolution. European Journal of Operational Research, 104, 2, 375-392.

23. Mazzola, J.B. and Neebe, A.W., 1999. Lagrangian-relaxation-based solution procedures for a multiproduct capacitated facility location problem with choice of facility type. European Journal of Operational Research, 115, 2, 285-299.

24. Ottoman, J., 1998. Waste not: Green strategies key to efficient products. Marketing News, 32, 12-21.

25. Realff, M.J., Ammons, J.C., Newton, D., 2000. Strategic design of reverse production systems. Computers and Chemical Engineering, 24, 2-7, 991-996.

26. Retzlaff-Roberts, D. and Frolick, M.N., 1997. Reducing cycle time in reverse logistics. University of Memphis, Cycle Time Research, 3, 1.

27. Shih, Li-Hsing, 2001. Reverse logistics system planning for recycling electrical appliances and computers in Taiwan. Resources, Conservation and Recycling, 32, 1, 55-72.

28. Spengler, T., Puchert, H., Penkuhn, T., Rentz, O., 1997. Environmental integrated production and recycling management. European Journal of Operational Research, 97, 2, 308-326.

29. Sridharan, R., 1995. The capacitated plant location problem. European Journal of Operational Research, 87, 2, 203-213.

30. Thierry, M., Salomon, M., Van Nunen, J., Van Wassenhove, L., 1995. Strategic Issues in Product Recovery Management. California Management Review, 37, 2, 114-135.

31. Tragantalerngsak, S., Holt, J., Ronnqvist, M., 1997. Lagrangian heuristics for the two-echelon, single-source, capacitated facility location problem. European Journal of Operational Research, 102, 3, 611-625.

32. Wang, Chin-Huang, Even, Jr., J.C., Adams, S.K., 1995. A mixed-integer linear model for optimal processing and transport of secondary materials. Resources, Conservation and Recycling, 15, 1, 65-78.

Appendix 1

Tables utilized in solving the model

Table A1: Fixed costs of facility centres

Fixed Costs		
Plant	Warehouse	Disassembly centre
1400000	900000	750000
1350000	750000	850000
1500000	800000	780000
	850000	800000
	900000	730000
	950000	750000
	820000	
	850000	
	880000	

Table A2: Setup costs

		MACHINERY			
		PLANT	DISASSEMBLY		
Plant 1	Product 1	3000	1500	Product 1	Disassembly 1
	Product 2	2500	4000	Product 2	
	Product 3	3100	3500	Product 3	
Plant 2	Product 1	2400	2000	Product 1	Disassembly 2
	Product 2	3000	3050	Product 2	
	Product 3	3300	2500	Product 3	
Plant 3	Product 1	3000	2300	Product 1	Disassembly 3
	Product 2	3200	3400	Product 2	
	Product 3	3500	3000	Product 3	
			3000	Product 1	Disassembly 4
			2800	Product 2	
			2850	Product 3	
			2900	Product 1	Disassembly 5
			2500	Product 2	
			2600	Product 3	
			2680	Product 1	Disassembly 6
			2000	Product 2	
			3200	Product 3	

Table A3: Capacity limitations of facility centres

Capacity Limitations		
Plant	Warehouse	Disassembly centre
650000	89000	95000
550000	100000	100000
600000	97000	98000
	90000	90000
	87000	85000
	90000	88000
	95000	
	98000	
	90000	

Table A4: Other parameters

Minimum Disposal α_1	Maximum Selling α_2	β_p	γ_p	τ_p
0.09	0.3	8	3	2
		7	2	3
		6	2	3

Table A5: Demand and penalty costs

Demand	Unsatisfied penalty	Uncollected penalty
2000	234.2	85.1
3000	170.1	88.9
3000	181.3	40.0
3000	200.4	122.5
2600	215.2	74.1
1000	199.7	68.3
1000	207.4	124.7
1000	203.9	116.2
1700	176.6	40.0
2000	190.9	124.2
1750	231.3	60.1
1250	194.2	71.3
1500	168.6	90.4
2200	203.4	105.2
1300	172.7	89.7
2200	218.7	97.4
2000	216.1	93.9
1400	161.0	90.2
1670	217.5	56.9

1800	175.8	126.4
1400	247.4	41.4
1350	150.8	136.9
1600	241.0	133.1
1500	246.2	55.1
1540	163.9	124.5
1560	205.3	40.0
1700	245.9	76.4
1800	204.9	40.0
1300	185.7	119.4
1570	150.0	67.3
1650	167.8	107.1
2000	160.6	111.4
2300	155.1	105.2
3000	150.0	52.7
1400	220.6	40.0
1500	226.5	65.1

Table A6: Manufacturing, Transportation and Handling costs for forward flow

143.0	200.0	176.0	183.0	180.0	125.8	197.6	160.8
178.0	199.0	169.0	268.0	160.0	131.3	200.8	156.5
174.0	179.0	155.0	103.0	115.0	202.0	204.5	215.1
143.0	169.0	265.0	177.0	103.0	154.8	143.3	158.6
174.0	168.0	285.0	145.0	104.0	214.4	184.5	167.9
209.0	122.0	257.0	168.0	99.0	142.2	120.0	161.7
195.0	150.0	309.0	215.0	140.0	172.5	205.2	141.1
176.0	200.0	230.0	188.0	162.0	160.3	174.9	215.3
209.0	190.0	280.0	192.0	161.0	175.1	141.0	138.6
167.0	210.0	203.0	206.0	182.0	120.0	136.7	142.4
194.0	260.0	220.0	195.0	195.0	214.4	134.7	219.5
143.0	185.0	257.0	160.0	155.0	133.8	149.8	219.5
178.0	165.0	274.0	188.0	120.0	164.3	193.0	120.0
189.0	168.0	288.0	218.0	140.0	129.9	213.3	204.3
216.0	168.0	125.0	195.0	168.0	195.3	126.8	215.1
220.0	205.0	168.0	206.0	172.0	150.1	184.5	203.7
195.0	203.0	170.0	205.0	173.0	206.9	206.5	143.0
168.0	147.0	180.0	265.0	177.0	162.9	120.0	150.5
178.0	178.0	160.0	220.0	205.0	212.5	151.4	127.7
177.0	216.0	150.0	194.0	162.0	126.0	158.0	201.4
141.0	210.0	177.0	120.0	144.0	163.4	141.6	194.7
120.0	166.0	209.0	140.0	149.0	201.7	146.5	123.0
119.0	150.0	212.0	130.0	148.0	121.3	161.6	127.9
107.0	196.0	214.0	144.0	140.0	198.6	204.9	204.6
175.0	206.0	195.0	136.0	177.0	191.7	212.4	121.4
165.0	216.0	193.0	192.0	185.0	132.2	139.8	190.1
167.0	120.0	220.0	134.0	184.0	139.1	209.6	135.6
176.0	103.0	160.0	130.0	120.0	161.4	175.0	140.8

147.0	96.0	260.0	135.0	160.0	128.0	191.0	211.8
179.0	111.0	293.0	138.0	170.0	165.5	124.4	185.6
216.0	112.0	280.0	100.0	177.0	202.4	163.6	152.6
230.0	119.0	265.0	103.0	179.0	214.4	121.6	162.2
190.0	170.0	110.0	114.0	155.0	215.5	211.8	156.9
120.0	162.0	104.0	145.0	157.0	131.0	164.0	132.1
120.0	203.0	195.0	195.0	158.0	173.1	172.7	131.7
192.0	195.0	100.0	182.0	140.0	132.4	191.1	198.9
182.0	206.0	265.0	152.0	192.0	122.0	209.5	205.1
154.0	216.0	110.0	165.0	125.0	173.1	132.4	166.5
177.0	195.0	295.0	144.0	157.0	131.6	135.3	217.2
124.0	155.0	224.0	120.0	178.0	194.4	154.0	122.5
126.0	140.0	251.0	124.0	122.0	218.6	218.6	168.5
128.0	177.0	260.0	126.0	216.1	190.2	166.1	151.2
114.0	123.0	270.0	129.0	149.1	132.4	149.0	215.9
102.0	129.0	109.0	144.0	207.6	147.5	205.3	162.5
93.0	130.0	165.0	147.0	132.9	214.4	192.6	205.5
149.0	177.0	140.0	154.0	120.0	176.0	209.6	120.0
163.0	188.0	106.0	178.0	155.9	181.3	180.9	213.1
195.0	173.0	110.0	195.0	120.0	123.4	137.5	142.7
176.0	168.0	92.0	182.0	139.6	159.5	151.2	143.8
174.0	218.0	119.0	178.4	168.6	166.5	124.4	178.1
188.0	177.0	295.0	217.8	136.0	132.7	127.1	212.7
180.0	188.0	288.0	185.7	120.0	198.2	132.7	174.7
160.0	157.0	314.0	129.3	120.0	135.9	161.3	121.7
135.0	230.0	177.0	186.4	124.8	176.0	210.2	205.4
162.8	265.0	200.7	152.4	212.7	163.9	191.4	202.4
166.7	106.0	140.1	203.6	217.9	138.5	206.5	131.4
203.0	114.0	211.6	189.6	156.0	212.2	156.6	134.1
175.0	199.7	211.1	160.4	189.2	160.5	122.0	196.3
195.4	120.0	177.2	139.0	144.5	169.5	205.2	130.5
150.0	151.3	137.3	208.4	201.3	216.4	194.0	214.4
151.4	203.6	137.7	133.6	164.2	120.1	143.0	142.2
166.2	154.9	167.4	139.3	138.6	190.2	178.0	172.5
132.1	148.8	120.0	167.0	173.4	195.5	189.0	160.3
188.1	121.7	123.7	211.7	142.7	216.7	216.0	175.1
131.5	214.7	120.0	167.2	188.7	189.1	220.0	120.0
219.7	147.9	146.5	170.6	186.1	140.8	195.0	214.4
133.4	180.4	204.5	125.3	131.0	130.1	168.0	133.8
199.6	176.2	120.0	195.3	187.5	174.7	178.0	164.3
179.1	152.6	156.4	121.0	145.8	126.0	177.0	129.9
152.3	136.5	120.0	199.4	217.4	196.8	141.0	195.3
159.8	201.2	174.4	147.3	120.8	170.4	120.0	150.1
162.2	121.6	180.9	187.1	211.0	144.6	119.0	206.9
142.9	164.5	195.0	191.4	216.2	145.6	107.0	162.9
145.2	134.7	210.3	185.2	133.9	192.3	175.0	212.5
142.0	189.6	120.0	132.7	175.3	168.0	165.0	126.0
171.7	137.3	203.5	120.0	215.9	164.9	167.0	178.6
178.6	186.5	120.0	145.1	174.9	145.6	176.0	135.6
135.6	185.8	149.1	168.9	155.7	182.7	309.0	140.6
140.6	192.8	120.0	120.0	191.8	129.1	230.0	188.8
188.8	120.0	189.7	202.5	211.3	131.7	280.0	172.8
172.8	141.1	120.9	154.1	167.6	120.0	203.0	199.4

199.4	177.7	201.3	148.3	179.7	123.9	220.0	167.8
167.8	146.8	186.3	204.7	150.9	177.7	257.0	173.2
173.2	122.6	120.0	196.2	120.0	128.3	274.0	210.5
210.5	163.2	163.8	120.0	120.0	155.6	288.0	216.8
216.8	157.2	120.0	204.2	120.0	183.2	125.0	132.4
132.4	132.3	207.2	140.1	205.6	137.2	168.0	191.1
191.1	131.9	184.4	151.3	214.1	147.9	170.0	193.7
193.7	184.0	190.7	170.4	174.3	159.1	180.0	178.7
178.7	120.0	195.2	185.2	206.3	192.9	160.0	193.2
193.2	143.0	146.9	169.7	180.2	202.2	150.0	166.7
141.4	172.1	199.9	177.4	120.0	207.9	177.0	166.3
141.8	127.9	141.0	173.9	120.5	213.0	209.0	120.0
163.3	170.0	159.9	170.2	157.4	193.1	212.0	168.9
180.5	161.6	120.0	136.9	202.3	179.1	214.0	139.0
120.0	182.2	215.2	206.4	148.3	170.1	195.0	132.9
195.8	179.1	120.5	121.4	171.3	173.3	193.0	203.5
166.7	123.1	154.2	216.9	200.2	131.9	220.0	162.0
166.3	208.1	120.0	213.1	140.6	219.0	160.0	203.0
193.5	127.6	146.9	135.1	155.8	194.6	260.0	195.0
154.3	146.1	167.7	210.5	161.5	143.2	293.0	206.0
130.2	168.8	190.8	171.9	120.0	120.0	280.0	216.0
121.6	152.2	149.6	139.6	151.5	141.6	265.0	195.0
179.7	165.4	154.2	163.6	216.6	189.5	110.0	155.0
204.7	153.2	124.2	151.8	176.6	148.2	120.0	140.0
212.0	195.6	195.7	183.2	206.7	190.2	155.9	177.0
149.4	194.9	173.3	188.2	128.2	120.8	120.0	123.0
160.8	159.0	162.4	169.1	190.7	175.2	139.6	129.0
215.7	193.2	121.2	179.3	123.7	203.3	168.6	130.0
158.1	184.4	209.4	188.9	173.7	143.0	136.0	177.0
120.0	151.1	206.9	165.3	126.9	174.0	120.0	188.0
128.4	120.0	175.1	120.0	193.7	209.0	120.0	173.0
177.4	138.1	157.9	145.5	173.8	195.0	125.8	169.0
198.9	136.3	132.6	122.2	127.2	176.0	131.3	155.0
182.0	154.1	139.7	146.6	174.7	209.0	202.0	265.0
204.8	120.0	167.7	160.9	135.2	167.0	154.8	285.0
257.0	230.0	203.0	120.0	107.0	165.0	176.0	179.0
309.0	280.0	220.0	119.0	175.0	167.0	147.0	216.0
230.0	182.0	128.0	163.0	180.0	169.0	149.0	
190.0	154.0	114.0	195.0	160.0	168.0	188.0	
120.0	177.0	102.0	176.0	200.0	192.0	179.0	
120.0	124.0	93.0	174.0	199.0	126.0		

Table A7: Remanufacturing, Transportation and Handling costs for return flow

-53.2	-55.0	-55.7	-64.6	-59.8	-62.2	-57.2	-64.5
-56.0	-64.0	-57.7	-55.0	-60.0	-63.6	-57.6	-63.4
-54.2	-57.7	-55.0	-53.3	-61.0	-62.5	-59.2	-57.3
-58.3	-60.2	-53.3	-52.6	-59.0	-59.0	-63.5	-58.0
-55.6	-53.4	-58.1	-54.1	-58.0	-61.8	-64.2	-55.8
-55.0	-57.2	-55.0	-54.2	-60.7	-64.8	-57.0	-63.1
-55.0	-61.4	-57.0	-54.9	-63.9	-62.5	-64.0	-62.5

-55.0	-63.5	-55.0	-60.0	-64.2	-63.6	-60.5	-55.3
-64.4	-54.1	-63.6	-59.2	-64.4	-63.5	-62.1	-55.8
-61.9	-55.0	-55.0	-63.3	-62.5	-66.5	-55.4	-63.5
-63.8	-58.0	-55.4	-62.5	-62.3	-62.0	-59.4	-55.1
-57.0	-54.0	-55.0	-63.6	-62.0	-62.4	-55.2	-62.0
-55.0	-59.0	-53.6	-64.6	-59.0	-55.0	-64.2	-56.6
-55.1	-54.3	-63.5	-62.5	-66.0	-57.0	-59.4	-57.1
-59.5	-63.9	-53.9	-58.5	-69.3	-56.0	-60.3	-64.2
-55.0	-64.5	-55.9	-57.0	-68.0	-57.4	-62.1	-61.6
-56.2	-64.9	-57.9	-60.7	-66.5	-56.6	-63.9	-58.3
-53.8	-55.0	-62.4	-55.3	-54.0	-62.2	-56.2	-59.2
-64.2	-62.2	-60.2	-55.9	-53.4	-56.4	-56.5	-58.7
-64.7	-55.0	-57.8	-56.0	-62.5	-56.0	-58.4	-56.2
-63.5	-55.0	-55.0	-60.7	-53.0	-56.5	-64.9	-56.2
-55.0	-53.2	-61.7	-61.8	-66.5	-56.8	-59.6	-62.9
-53.5	-55.0	-61.2	-60.3	-54.0	-53.0	-57.9	-63.5
-62.3	-61.8	-55.0	-59.8	-69.5	-53.3	-63.5	-59.7
-55.0	-56.3	-55.9	-64.8	-62.4	-54.4	-62.3	-64.7
-63.0	-54.1	-62.3	-60.7	-65.1	-57.5	-64.0	-55.3
-57.6	-55.0	-61.6	-61.8	-66.0	-62.5	-61.1	-59.8
-55.5	-56.8	-55.0	-58.7	-67.0	-61.2	-56.8	-58.1
-59.9	-55.0	-52.0	-63.0	-53.9	-58.2	-58.1	-64.6
-55.9	-62.1	-57.1	-66.5	-59.5	-59.5	-55.4	-59.2
-64.3	-55.0	-50.8	-53.6	-57.0	-57.4	-55.7	-63.6
-55.3	-56.0	-59.4	-54.4	-53.6	-55.0	-56.3	-55.0
-55.2	-60.4	-54.6	-60.6	-54.0	-55.4	-59.1	-64.3
-59.3	-64.5	-55.0	-59.9	-52.2	-55.6	-59.1	-57.3
-59.3	-59.6	-55.0	-58.5	-54.9	-55.9	-58.6	-57.4
-60.1	-58.7	-53.8	-66.5	-69.5	-57.4	-64.5	-60.8
-55.5	-59.8	-62.4	-68.5	-68.8	-57.7	-58.9	-64.3
-58.7	-55.0	-55.0	-65.7	-71.4	-58.4	-59.8	-60.5
-54.7	-57.6	-56.9	-70.9	-60.7	-60.8	-59.2	-55.2
-63.7	-55.0	-58.1	-63.0	-61.3	-62.5	-57.1	-56.5
-58.6	-58.5	-55.0	-68.0	-66.8	-61.2	-64.5	-59.3
-55.0	-57.3	-61.4	-63.3	-53.3	-61.0		
-62.5	-60.3	-63.4	-62.0	-60.7	-59.0		
-63.1	-63.0	-55.0	-65.7	-57.5	-54.5		
-55.0	-55.0	-56.2	-67.4	-59.8	-53.3		
-63.6	-55.0	-57.0	-68.8	-64.5	-58.1		
-64.8	-56.6	-64.3	-55.5	-61.8	-58.8		
-61.6	-64.3	-55.5	-59.5	-59.1	-55.0		
-55.9	-64.8	-62.3	-63.6	-60.4	-55.0		
-61.6	-58.6	-55.0	-61.1	-64.8	-62.5		
-58.2	-60.6	-62.5	-55.0	-55.0	-63.6		
-63.4	-59.4	-55.1	-60.1	-57.1	-59.4		
-62.0	-56.8	-55.0	-64.9	-64.1	-64.7		
-55.0	-63.3	-59.8	-60.9	-63.5	-56.1		
-59.5	-62.0	-59.8	-58.2	-58.1	-65.0		
-64.1	-55.0	-63.5	-59.0	-63.4	-56.3		
-55.0	-54.9	-63.3	-59.2	-58.5	-63.0		
-59.0	-53.7	-57.7	-57.3	-57.9	-55.8		
-55.0	-60.5	-60.8	-57.5	-55.2	-60.7		
-56.0	-59.5	-64.6	-57.2	-64.5	-62.9		

-63.9	-59.7	-64.0	-60.2	-57.8	-61.2
-56.9	-60.6	-59.6	-60.9	-61.0	-64.9
-62.1	-57.7	-58.0	-56.6	-60.6	-64.9
-63.1	-60.9	-62.6	-57.1	-58.3	-55.0
-61.0	-64.6	-63.6	-61.9	-56.6	-63.4
-58.3	-63.0	-64.2	-60.3	-63.1	-53.5
-58.9	-62.0	-64.0	-62.9	-55.2	-63.8
-59.0	-55.0	-62.1	-59.8	-59.4	-65.0
-60.6	-55.0	-63.7	-60.3	-56.5	-58.0
-57.5	-62.2	-58.7	-64.0	-62.0	-59.6
-59.7	-61.2	-63.5	-64.7	-56.7	-55.0
-59.6	-58.4	-63.2	-56.2	-61.6	-63.1
-55.0	-60.7	-56.1	-62.1	-61.6	-57.0
-59.9	-55.4	-56.4	-62.4	-62.3	-64.2
-56.9	-55.6	-57.3	-60.9	-55.0	-60.8
-56.3	-55.8	-60.5	-62.3	-57.1	-56.1
-63.3	-54.4	-62.5	-57.1	-60.8	-59.8
-59.2	-53.2	-63.0	-57.2	-57.7	-60.1
-63.3	-52.3	-55.0	-59.3	-55.3	-64.2
-62.5	-57.9	-64.1	-61.0	-59.3	-55.0
-63.6	-59.3	-60.7	-55.0	-58.7	-55.4
-64.6	-62.5	-59.0	-62.6	-56.2	-59.5
-62.5	-60.6	-56.9	-59.7	-56.2	-56.9
-58.5	-60.4	-61.9	-59.6	-61.4	-57.2
-57.0	-61.8	-57.4	-62.3	-55.0	-59.7
-60.7	-61.0	-59.0	-58.4	-57.3	-63.3
-55.3	-59.0	-60.0	-56.0	-60.2	
-55.9	-63.0	-55.2	-55.2	-55.8	
-56.0	-62.9	-63.5	-61.0	-62.9	
-60.7	-60.9	-62.6	-63.5	-65.7	
-61.8	-59.9	-56.0	-64.2	-70.9	
-60.3	-59.8	-58.0	-57.9	-63.0	
-59.9	-55.2	-58.1	-59.1	-68.0	
-58.5	-58.0	-59.6	-64.6	-64.0	
-66.5	-63.0	-56.2	-58.8	-66.0	
-68.5	-62.0	-61.8	-55.0	-61.5	

Table A8: Disposal costs

65.5	82.5	103.3	40.0	90.2
42.2	79.5	80.6	94.4	56.9
66.6	131.2	43.3	100.9	126.4
80.9	120.6	43.5	115.0	41.4
121.3	49.7	104.0	130.3	136.9
84.2	133.2	124.1	40.0	133.1
58.6	40.0	40.0	123.5	55.1
93.4	137.2	51.6	40.0	98.0
62.7	40.0	110.7	69.1	94.0
108.7	104.1	61.1	40.0	63.0
106.1	61.4	139.1	109.7	94.0
51.0	40.0	40.0	40.9	129.0
107.5	91.7	50.1	121.3	115.0

65.8	64.1	112.0	106.3	96.0
137.4	46.2	83.1	40.0	129.0
40.8	114.4	134.0	83.8	140.0
131.0	85.9	52.9	40.0	115.0
136.2	132.0	123.5	127.2	88.0
53.9	40.0	66.4	104.4	98.0
95.3	58.5	114.9	110.7	97.0
135.9	45.1	40.0	177.0	122.4
94.9	84.8	40.0	194.0	51.4
75.7	43.0	41.0	208.0	65.5
111.8	51.2	40.0	45.0	42.2
131.3	44.2	88.9	88.0	66.6
87.6	131.0	59.0	90.0	80.9
69.2	71.7	52.9	100.0	121.3
71.1	40.0	123.5	80.0	84.2
106.7	76.4	66.4	70.0	
40.0	86.1	114.9	97.0	
47.9	40.0	40.0	129.0	
68.2	110.3	57.8	132.0	
68.9	119.8	50.6	134.0	
83.6	100.3	45.1	115.0	
44.9	137.1	40.0	113.0	
70.9	78.2	110.6	140.0	
53.7	123.0	116.5	80.0	
108.1	85.7	84.3	180.0	
70.6	58.8	57.7	213.0	
86.8	139.0	87.4	200.0	
40.0	133.8	40.0	185.0	
123.9	63.6	43.7	30.0	
82.0	117.1	40.0	90.4	
121.8	132.9	66.5	105.2	
123.2	118.6	124.5	89.7	
61.8	100.5	40.0	97.4	
55.6	118.9	76.4	93.9	

Table A9: Revenue from material buyers minus Transportation and Handling costs

23.0	31.0	42.0	10.0	35.0
11.0	30.0	30.0	37.0	18.0
23.0	56.0	12.0	40.0	53.0
30.0	50.0	12.0	47.0	11.0
51.0	15.0	42.0	55.0	58.0
32.0	57.0	52.0	10.0	57.0
19.0	10.0	10.0	52.0	18.0
37.0	59.0	16.0	10.0	39.0
21.0	10.0	45.0	25.0	37.0
44.0	42.0	21.0	10.0	22.0
43.0	21.0	60.0	45.0	37.0
15.0	10.0	10.0	10.0	55.0
44.0	36.0	15.0	51.0	48.0
23.0	22.0	46.0	43.0	38.0

59.0	13.0	32.0	10.0	55.0
10.0	47.0	57.0	32.0	60.0
56.0	33.0	16.0	10.0	48.0
58.0	56.0	52.0	54.0	34.0
17.0	10.0	23.0	42.0	39.0
38.0	19.0	47.0	45.0	39.0
58.0	13.0	10.0	79.0	51.0
37.0	32.0	10.0	87.0	16.0
28.0	11.0	10.0	94.0	23.0
46.0	16.0	10.0	13.0	11.0
56.0	12.0	34.0	34.0	23.0
34.0	56.0	20.0	35.0	30.0
25.0	26.0	16.0	40.0	51.0
26.0	10.0	52.0	30.0	32.0
43.0	28.0	23.0	25.0	
10.0	33.0	47.0	39.0	
14.0	10.0	10.0	55.0	
24.0	45.0	19.0	56.0	
24.0	50.0	15.0	57.0	
32.0	40.0	13.0	48.0	
12.0	59.0	10.0	47.0	
25.0	29.0	45.0	60.0	
17.0	52.0	48.0	30.0	
44.0	33.0	32.0	80.0	
25.0	19.0	19.0	97.0	
33.0	59.0	34.0	90.0	
10.0	57.0	10.0	83.0	
52.0	22.0	12.0	5.0	
31.0	49.0	10.0	35.0	
51.0	56.0	23.0	43.0	
52.0	49.0	52.0	35.0	
21.0	40.0	10.0	39.0	
18.0	49.0	28.0	37.0	

Appendix 2

Tables utilized in presenting the discussion

Results of EVPI vs Return rate

Table A10: Stochastic and individual scenario costs for return rate variations of all scenarios simultaneously

Return Rate	Total Cost from Stochastic Soln	Best Objective of Scenario 1 alone	Best Objective of Scenario 2 alone	Best Objective of Scenario 3 alone
0.1, 0.1, 0.1	12685990	12058930	12414970	12387920
0.2, 0.2, 0.2	12386950	11773510	12114910	12075930
0.3, 0.3, 0.3	12122960	11485750	11834170	11822370
0.4, 0.4, 0.4	11934180	11192920	11600750	11629210
0.5, 0.5, 0.5	11724940	10900090	11332610	11347140
0.6, 0.6, 0.6	11709280	10772920	11285020	11380210
0.7, 0.7, 0.7	11977530	11008660	11513110	11681450
0.8, 0.8, 0.8	11797600	11119610	11584080	11647560
0.9, 0.9, 0.9	11467990	11069610	11316430	11309650

Table A11: EVPI for return rate variations of all scenarios simultaneously

Expected Value	EVPI	% Difference
12363136	322854.00	2.54
12057382	329568.00	2.66
11792248	330712.00	2.73
11577043	357137.00	2.99
11298076	426864.00	3.64
11290924	418356.00	3.57
11563669	413861.00	3.46
11575721	221879.00	1.88
11287680	180310.00	1.57

Table A12: Stochastic and individual scenario costs for return rate variation of scenario 1

Return Rate	Total Cost from Stochastic Soln	Best Objective of Scenario 1 alone	Best Objective of Scenario 2 alone	Best Objective of Scenario 3 alone
0.1, 0.6, 0.9	12005180.00	12058930.00	11285020.00	11309650.00
0.2, 0.6, 0.9	11974030.00	11773510.00	11285020.00	11309650.00
0.3, 0.6, 0.9	11942880.00	11485750.00	11285020.00	11309650.00
0.4, 0.6, 0.9	11911740.00	11192920.00	11285020.00	11309650.00
0.5, 0.6, 0.9	11880590.00	10900090.00	11285020.00	11309650.00
0.6, 0.6, 0.9	11849440.00	10772920.00	11285020.00	11309650.00
0.7, 0.6, 0.9	11818290.00	11008660.00	11285020.00	11309650.00
0.8, 0.6, 0.9	11787170.00	11119610.00	11285020.00	11309650.00
0.9, 0.6, 0.9	11756150.00	11069610.00	11285020.00	11309650.00

Table A13: EVPI for return rate variations of scenario 1

Expected Value	EVPI	% Difference
11377189.00	627991.00	5.23
11348647.00	625383.00	5.22
11319871.00	623009.00	5.22
11290588.00	621152.00	5.21
11261305.00	619285.00	5.21
11248588.00	600852.00	5.07
11272162.00	546128.00	4.62
11283257.00	503913.00	4.28
11278257.00	477893.00	4.07

Table A14: Stochastic and individual scenario costs for return rate variation of scenario 2

Return Rate	Total Cost from Stochastic Soln	Best Objective of Scenario 1 alone	Best Objective of Scenario 2 alone	Best Objective of Scenario 3 alone
0.3, 0.1, 0.9	12424770.00	11485750.00	12414970.00	11309650.00
0.3, 0.2, 0.9	12328390.00	11485750.00	12114910.00	11309650.00
0.3, 0.3, 0.9	12232020.00	11485750.00	11834170.00	11309650.00
0.3, 0.4, 0.9	12135640.00	11485750.00	11600750.00	11309650.00
0.3, 0.5, 0.9	12039260.00	11485750.00	11332610.00	11309650.00
0.3, 0.6, 0.9	11942880.00	11485750.00	11285020.00	11309650.00
0.3, 0.7, 0.9	11846710.00	11485750.00	11513110.00	11309650.00
0.3, 0.8, 0.9	11750580.00	11485750.00	11584080.00	11309650.00
0.3, 0.9, 0.9	11654720.00	11485750.00	11316430.00	11309650.00

Table A15: EVPI for return rate variations of scenario 2

Expected Value	EVPI	% Difference
11658856.00	765914.00	6.16
11568838.00	759552.00	6.16
11484616.00	747404.00	6.11
11414590.00	721050.00	5.94
11334148.00	705112.00	5.86
11319871.00	623009.00	5.22
11388298.00	458412.00	3.87
11409589.00	340991.00	2.90
11329294.00	325426.00	2.79

Table A16: Stochastic and individual scenario costs for return rate variation of scenario 3

Return Rate	Total Cost from Stochastic Soln	Best Objective of Scenario 1 alone	Best Objective of Scenario 2 alone	Best Objective of Scenario 3 alone
0.3, 0.6, 0.1	12385490.00	11485750.00	11285020.00	12387920.00
0.3, 0.6, 0.2	12197370.00	11485750.00	11285020.00	12075930.00
0.3, 0.6, 0.3	12041940.00	11485750.00	11285020.00	11822370.00
0.3, 0.6, 0.4	11932280.00	11485750.00	11285020.00	11629210.00
0.3, 0.6, 0.5	11763040.00	11485750.00	11285020.00	11347140.00
0.3, 0.6, 0.6	11782880.00	11485750.00	11285020.00	11380210.00
0.3, 0.6, 0.7	11955050.00	11485750.00	11285020.00	11681450.00
0.3, 0.6, 0.8	12145630.00	11485750.00	11285020.00	11647560.00
0.3, 0.6, 0.9	11942880.00	11485750.00	11285020.00	11309650.00

Table A17: EVPI for return rate variations of scenario 3

Expected Value	EVPI	% Difference
11966833.00	418657.00	3.38
11779639.00	417731.00	3.42
11627503.00	414437.00	3.44
11511607.00	420673.00	3.53
11342365.00	420675.00	3.58
11362207.00	420673.00	3.57
11542951.00	412099.00	3.45
11522617.00	623013.00	5.13
11319871.00	623009.00	5.22

Results of VSS vs Return rate

Table A18: VSS, return rate variation of all scenarios simultaneously, fixing scenario1 location variables

Return Rate	Total Cost Stochastic Soln	Scenario 1	Scenario 2	Scenario3	Expected Costs	VSS
0.1, 0.1, 0.1	12685990.00	12058930.00	13186990.00	13818470.00	13453072	767082
0.2, 0.2, 0.2	12386950.00	11773510.00	12907200.00	13523480.00	13163599	776649
0.3, 0.3, 0.3	12122960.00	11485750.00	12659220.00	13242700.00	12891961	769001
0.4, 0.4, 0.4	11934180.00	11192920.00	12383410.00	12945820.00	12601807	667627
0.5, 0.5, 0.5	11724940.00	10900090.00	12107600.00	12685700.00	12333709	608769
0.6, 0.6, 0.6	11709280.00	10772920.00	12030730.00	12605280.00	12249679	540399
0.7, 0.7, 0.7	11977530.00	11008660.00	12287880.00	12875290.00	12512404	534874
0.8, 0.8, 0.8	11797600.00	11119610.00	12340820.00	12948950.00	12583577	785977
0.9, 0.9, 0.9	11467990.00	11069610.00	11402870.00	12264990.00	11886816	418826

Table A19: VSS, return rate variation of all scenarios simultaneously, fixing scenario2 location variables

Return Rate	Total Cost Stochastic Soln	Scenario 1	Scenario 2	Scenario3	Expected Costs	VSS
0.1, 0.1, 0.1	12685990.00	12664740.00	12414970.00	13002400.00	12792405	106415
0.2, 0.2, 0.2	12386950.00	12375150.00	12114910.00	12709880.00	12497916	110966
0.3, 0.3, 0.3	12122960.00	12076950.00	11834170.00	12440540.00	12222270	99310
0.4, 0.4, 0.4	11934180.00	12386750.00	11600750.00	12872270.00	12442262	508082
0.5, 0.5, 0.5	11724940.00	12145880.00	11332610.00	12581700.00	12163391	438451
0.6, 0.6, 0.6	11709280.00	12023290.00	11285020.00	12625000.00	12162835	453555
0.7, 0.7, 0.7	11977530.00	12195410.00	11513110.00	12863240.00	12391418	413888
0.8, 0.8, 0.8	11797600.00	12271730.00	11584080.00	12935360.00	12463613	666013
0.9, 0.9, 0.9	11467990.00	11439360.00	11316430.00	11726740.00	11574909	106919

Table A20: VSS, return rate variation of all scenarios simultaneously, fixing scenario3 location variables

Return Rate	Total Cost Stochastic Soln	Scenario 1	Scenario 2	Scenario3	Expected Costs	VSS
0.1, 0.1, 0.1	12685990.00	13276590.00	13085250.00	12387920.00	12685986	-4
0.2, 0.2, 0.2	12386950.00	13001180.00	12804230.00	12075930.00	12386945	-5
0.3, 0.3, 0.3	12122960.00	12725770.00	12523220.00	11822370.00	12122965	5
0.4, 0.4, 0.4	11934180.00	12338360.00	12661660.00	11629210.00	12009860	75680
0.5, 0.5, 0.5	11724940.00	12049580.00	12376830.00	11347140.00	11726291	1351
0.6, 0.6, 0.6	11709280.00	11891140.00	12306800.00	11380210.00	11709280	0
0.7, 0.7, 0.7	11977530.00	12138810.00	12544740.00	11681450.00	11986173	8643
0.8, 0.8, 0.8	11797600.00	12022410.00	12022750.00	11647560.00	11797602	2
0.9, 0.9, 0.9	11467990.00	11712240.00	11703230.00	11309650.00	11467983	-7

Table A21: VSS, return rate variation of scenario1 only, fixing scenario1 location variables

Return Rate	Total Cost Stochastic Soln	Scenario 1	Scenario 2	Scenario3	Expected Costs	VSS
0.1, 0.6, 0.9	12005180.00	12058930.00	12383770.00	14150490.00	13411318	1406138
0.2, 0.6, 0.9	11974030.00	11773510.00	12383770.00	14150490.00	13382776	1408746
0.3, 0.6, 0.9	11942880.00	11485750.00	12302160.00	14014070.00	13247665	1304785
0.4, 0.6, 0.9	11911740.00	11192920.00	12302160.00	14014070.00	13218382	1306642
0.5, 0.6, 0.9	11880590.00	10900090.00	12302160.00	14014070.00	13189099	1308509
0.6, 0.6, 0.9	11849440.00	10772920.00	12030730.00	13578140.00	12833395	983955
0.7, 0.6, 0.9	11818290.00	11008660.00	12030730.00	13578140.00	12856969	1038679
0.8, 0.6, 0.9	11787170.00	11119610.00	12488810.00	13040480.00	12682892	895722
0.9, 0.6, 0.9	11756150.00	11069610.00	12374760.00	12264990.00	12178383	422233

Table A22: VSS, return rate variation of scenario1 only, fixing scenario2 location variables

Return Rate	Total Cost Stochastic Soln	Scenario 1	Scenario 2	Scenario3	Expected Costs	VSS
0.1, 0.6, 0.9	12005180.00	13206200.00	11285020.00	13567050.00	12846356	841176
0.2, 0.6, 0.9	11974030.00	12969620.00	11285020.00	13567050.00	12822698	848668
0.3, 0.6, 0.9	11942880.00	12733030.00	11285020.00	1356750.00	12799039	856159
0.4, 0.6, 0.9	11911740.00	12496450.00	11285020.00	13567050.00	12775381	863641
0.5, 0.6, 0.9	11880590.00	12259870.00	11285020.00	13567050.00	12751723	871133
0.6, 0.6, 0.9	11849440.00	12023290.00	11285020.00	13567050.00	12728065	878625
0.7, 0.6, 0.9	11818290.00	12195410.00	11285020.00	13567050.00	12745277	926987
0.8, 0.6, 0.9	11787170.00	12470490.00	11285020.00	13567050.00	12772785	985615
0.9, 0.6, 0.9	11756150.00	12800660.00	11285020.00	13567050.00	12805802	1049652

Table A23: VSS, return rate variation of scenario1 only, fixing scenario3 location variables

Return Rate	Total Cost Stochastic Soln	Scenario 1	Scenario 2	Scenario3	Expected Costs	VSS
0.1, 0.6, 0.9	12005180.00	14201720.00	12663780.00	11309650.00	12005096	-84
0.2, 0.6, 0.9	11974030.00	13891060.00	12663780.00	11309650.00	11974030	0
0.3, 0.6, 0.9	11942880.00	13579580.00	12663780.00	11309650.00	11942882	2
0.4, 0.6, 0.9	11911740.00	13268090.00	12663780.00	11309650.00	11911733	-7
0.5, 0.6, 0.9	11880590.00	12956610.00	12663780.00	11309650.00	11880585	-5
0.6, 0.6, 0.9	11849440.00	12645130.00	12663780.00	11309650.00	11849437	-3
0.7, 0.6, 0.9	11818290.00	12333650.00	12663780.00	11309650.00	11818289	-1
0.8, 0.6, 0.9	11787170.00	12022410.00	12663780.00	11309650.00	11787165	-5
0.9, 0.6, 0.9	11756150.00	11712240.00	12663780.00	11309650.00	11756148	-2

Table A24: VSS, return rate variation of scenario2 only, fixing scenario1 location variables

Return Rate	Total Cost Stochastic Soln	Scenario 1	Scenario 2	Scenario3	Expected Costs	VSS
0.3, 0.1, 0.9	12424770.00	11485750.00	13210850.00	14014070.00	13520272	1095502
0.3, 0.2, 0.9	12328390.00	11485750.00	12935030.00	14014070.00	13437526	1109136
0.3, 0.3, 0.9	12232020.00	11485750.00	12659220.00	14014070.00	13354783	1122763
0.3, 0.4, 0.9	12135640.00	11485750.00	12383410.00	14014070.00	13272040	1136400
0.3, 0.5, 0.9	12039260.00	11485750.00	12107600.00	14014070.00	13189297	1150037
0.3, 0.6, 0.9	11942880.00	11485750.00	12302160.00	14014070.00	13247665	1304785
0.3, 0.7, 0.9	11846710.00	11485750.00	12594540.00	14014070.00	13335379	1488669
0.3, 0.8, 0.9	11750580.00	11485750.00	12942670.00	14014070.00	13439818	1689238
0.3, 0.9, 0.9	11654720.00	11485750.00	13326920.00	14014070.00	13555093	1900373

Table A25: VSS, return rate variation of scenario2 only, fixing scenario2 location variables

Return Rate	Total Cost Stochastic Soln	Scenario 1	Scenario 2	Scenario3	Expected Costs	VSS
0.3, 0.1, 0.9	12424770.00	12086140.00	12414970.00	13638950.00	13116475	691705
0.3, 0.2, 0.9	12328390.00	12086140.00	12114910.00	13638950.00	13026457	698067
0.3, 0.3, 0.9	12232020.00	12076950.00	11834170.00	13551350.00	12888756	656736
0.3, 0.4, 0.9	12135640.00	12620870.00	11600750.00	14118200.00	13213232	1077592
0.3, 0.5, 0.9	12039260.00	12625220.00	11332610.00	13669800.00	12864185	824925
0.3, 0.6, 0.9	11942880.00	12733030.00	11285020.00	13567050.00	12799039	856159
0.3, 0.7, 0.9	11846710.00	12733030.00	11513110.00	13567050.00	12867466	1020756
0.3, 0.8, 0.9	11750580.00	13339910.00	11584080.00	13036200.00	12630935	880355
0.3, 0.9, 0.9	11654720.00	13383680.00	11316430.00	11726740.00	11769341	114621

Table A26: VSS, return rate variation of scenario2 only, fixing scenario3 location variables

Return Rate	Total Cost Stochastic Soln	Scenario 1	Scenario 2	Scenario3	Expected Costs	VSS
0.3, 0.1, 0.9	12424770.00	13579580.00	14267430.00	11309650.00	12423977	-793
0.3, 0.2, 0.9	12328390.00	13579580.00	13947270.00	11309650.00	12327929	-461
0.3, 0.3, 0.9	12232020.00	13579580.00	13626550.00	11309650.00	12231713	-307
0.3, 0.4, 0.9	12135640.00	13579580.00	13305830.00	11309650.00	12135497	-143
0.3, 0.5, 0.9	12039260.00	13579580.00	12985040.00	11309650.00	12039260	0
0.3, 0.6, 0.9	11942880.00	13579580.00	12663780.00	11309650.00	11942882	2
0.3, 0.7, 0.9	11846710.00	13579580.00	12343210.00	11309650.00	11846711	1
0.3, 0.8, 0.9	11750580.00	13579580.00	12022750.00	11309650.00	11750573	-7
0.3, 0.9, 0.9	11654720.00	13579580.00	11703230.00	11309650.00	11654717	-3

Table A27: VSS, return rate variation of scenario3 only, fixing scenario1 location variables

Return Rate	Total Cost Stochastic Soln	Scenario 1	Scenario 2	Scenario3	Expected Costs	VSS
0.3, 0.6, 0.1	12385490.00	11485750.00	12302160.00	13836460.00	13141099	755609
0.3, 0.6, 0.2	12197370.00	11485750.00	12302160.00	13539580.00	12962971	765601
0.3, 0.6, 0.3	12041940.00	11485750.00	12302160.00	13242700.00	12784843	742903
0.3, 0.6, 0.4	11932280.00	11485750.00	12302160.00	12945820.00	12606715	674435
0.3, 0.6, 0.5	11763040.00	11485750.00	12302160.00	12685700.00	12450643	687603
0.3, 0.6, 0.6	11782880.00	11485750.00	12302160.00	12898960.00	12578599	795719
0.3, 0.6, 0.7	11955050.00	11485750.00	12302160.00	13222600.00	12772783	817733
0.3, 0.6, 0.8	12145630.00	11485750.00	12302160.00	13592670.00	12994825	849195
0.3, 0.6, 0.9	11942880.00	11485750.00	12302160.00	14014070.00	13247665	1304785

Table A28: VSS, return rate variation of scenario3 only, fixing scenario2 location variables

Return Rate	Total Cost Stochastic Soln	Scenario 1	Scenario 2	Scenario3	Expected Costs	VSS
0.3, 0.6, 0.1	12385490.00	12733030.00	11285020.00	13835150.00	12959899	574409
0.3, 0.6, 0.2	12197370.00	12733030.00	11285020.00	13551430.00	12789667	592297
0.3, 0.6, 0.3	12041940.00	12733030.00	11285020.00	13267720.00	12619441	577501
0.3, 0.6, 0.4	11932280.00	12733030.00	11285020.00	12984000.00	12449209	516929
0.3, 0.6, 0.5	11763040.00	12733030.00	11285020.00	12700280.00	12278977	515937
0.3, 0.6, 0.6	11782880.00	12733030.00	11285020.00	12625000.00	12233809	450929
0.3, 0.6, 0.7	11955050.00	12733030.00	11285020.00	12863240.00	12376753	421703
0.3, 0.6, 0.8	12145630.00	12733030.00	11285020.00	13194770.00	12575671	430041
0.3, 0.6, 0.9	11942880.00	12733030.00	11285020.00	13567050.00	12799039	856159

Table A29: VSS, return rate variation of scenario3 only, fixing scenario3 location variables

Return Rate	Total Cost Stochastic Soln	Scenario 1	Scenario 2	Scenario3	Expected Costs	VSS
0.3, 0.6, 0.1	12385490.00	12725770.00	12453810.00	12387920.00	12441472	55982
0.3, 0.6, 0.2	12197370.00	12725770.00	12453810.00	12075930.00	12254278	56908
0.3, 0.6, 0.3	12041940.00	12725770.00	12453810.00	11822370.00	12102142	60202
0.3, 0.6, 0.4	11932280.00	12627150.00	12306800.00	11629210.00	11932281	1
0.3, 0.6, 0.5	11763040.00	12627150.00	12306800.00	11347140.00	11763039	-1
0.3, 0.6, 0.6	11782880.00	12627150.00	12306800.00	11380210.00	11782881	1
0.3, 0.6, 0.7	11955050.00	12627150.00	12306800.00	11681450.00	11963625	8575
0.3, 0.6, 0.8	12145630.00	13579580.00	12663780.00	11647560.00	12145628	-2
0.3, 0.6, 0.9	11942880.00	13579580.00	12663780.00	11309650.00	11942882	2

Appendix 3

LINGO program of the Generic Stochastic Product Recovery Model

```
MODEL:
SETS:

!INITIALIZING MAIN VARIABLES;
PLANT/P1..P3/:SELECTP,COSTP,CAPACITYP;
WAREHOUSE/W1..W9/:SELECTW,COSTW,CAPACITYW;
DISASSEMBLY/L1..L6/:SELECTL,COSTL,CAPACITYL;
RAWMATL/R1/:;
CUSTOMER/K1..K12/:;
PRODUCT/F1..F3/:BF,GF,TF;
SCENARIO/S1..S3/:PROB,FACTOR;
DISPOSAL/D/:;
ALPHA/VALUE/:A1,A2;

!INITIALIZING FORWARD,REVERSE AND DISPOSAL COSTS AND VARIABLES;
FORWARD(SCENARIO,PLANT,WAREHOUSE,CUSTOMER,PRODUCT):C_SIJKF,X_SIJKF;
REVERSE(SCENARIO,PRODUCT,CUSTOMER,DISASSEMBLY,PLANT):C_SFKLI,X_SFKLI;
DISPOSE(SCENARIO,PRODUCT,CUSTOMER,DISASSEMBLY,DISPOSAL):C_SFKLO,X_SFKLO;
RAWSUPPL(SCENARIO,PRODUCT,CUSTOMER,DISASSEMBLY,RAWMATL):P_SFKLR,X_SFKL
R;

!INITIALIZING DEMAND, RETURN RATES AND FIXED COSTS;
UNSATISFIED(SCENARIO,CUSTOMER,PRODUCT):D_SFK,U_SFK,P_SFK;
UNCOLLECTED(SCENARIO,CUSTOMER,PRODUCT):R_SFK,W_SFK,Q_SFK;
PEQUIPPEDF(PLANT,PRODUCT):Y_IF,G_IF;
LEQUIPPEDF(DISASSEMBLY,PRODUCT):Z_LF,H_LF;

!INITIALIZING TEMP VARIABLES FOR OBJECTIVE FUNCTION;
TEMPFORWARD(PLANT,WAREHOUSE,CUSTOMER,PRODUCT):;
TEMPREVERSE(PRODUCT,CUSTOMER,DISASSEMBLY,PLANT):;
TEMPDISPOSE(PRODUCT,CUSTOMER,DISASSEMBLY,DISPOSAL):;
TEMPRAW(PRODUCT,CUSTOMER,DISASSEMBLY,RAWMATL):;
TEMPUNSATISFIED(CUSTOMER,PRODUCT):;
TEMPUNCOLLECTED(CUSTOMER,PRODUCT):;

!INITIALIZING TEMP VARIABLES FOR CONSTRAINT (1) & (2);
TEMP1(PLANT,WAREHOUSE):;
TEMP2(DISASSEMBLY,PLANT):;

!TEMP3(DISASSEMBLY,DISPOSAL):;
TEMP4(PLANT,PRODUCT):;
TEMP5(CUSTOMER,DISASSEMBLY):;
TEMP6(WAREHOUSE,CUSTOMER):;
TEMP16(DISASSEMBLY,CUSTOMER,DISPOSAL):;
TEMP17(DISASSEMBLY,DISPOSAL):;
TEMP19(DISASSEMBLY,RAWMATL):;
TEMP20(DISASSEMBLY,CUSTOMER,RAWMATL):;

!INITIALIZING TEMP VARIABLE FOR MINIMUM DISPOSAL FRACTION;
TEMP7(DISASSEMBLY,CUSTOMER,PRODUCT):;
```

```
!INITIALIZING TEMP VARIABLES FOR CAPACITY CONSTRAINTS AND FACILITY OPENING
CONDITIONS;
TEMP8(WAREHOUSE,CUSTOMER,PRODUCT):;
TEMP9(PRODUCT,CUSTOMER,DISASSEMBLY):;
TEMP10(PLANT,CUSTOMER,PRODUCT):;
TEMP11(PRODUCT,CUSTOMER,PLANT):;
TEMP12(PRODUCT,CUSTOMER,DISPOSAL):;
TEMP13(DISASSEMBLY,CUSTOMER,PRODUCT):;
TEMP21(PRODUCT,CUSTOMER,RAWMATL):;

!INITIALIZING TEMP VARIABLES FOR INSTALLING MACHINERY AT PLANT AND
DISASSEMBLY CENTRE;
TEMP14(PLANT,PRODUCT,CUSTOMER):;
TEMP15(DISASSEMBLY,PRODUCT,CUSTOMER):;


!INITIALIZING TEMP VARIABLE FOR ASSIGNING RETURN RATE AS A PROPORTION OF
DEMAND;
TEMP18(CUSTOMER,PRODUCT):;

ENDSETS

!-------------------------OBJECTIVE FUNCTION----------------------------------------------------------------------;
MIN =
        !EXPECTED VALUE OF THE SECOND STAGE ALONG WITH SCENARIO
PROBABILITIES;
        @SUM(SCENARIO(S): PROB(S)*
        ( @SUM(TEMPFORWARD(I1,J1,K1,F1): C_SIJKF(S,I1,J1,K1,F1) * X_SIJKF(S,I1,J1,K1,F1) *
D_SFK(S,K1,F1)) +
         @SUM(TEMPREVERSE(F2,K2,L2,I2): C_SFKLI(S,F2,K2,L2,I2) * X_SFKLI(S,F2,K2,L2,I2)
* R_SFK(S,K2,F2)) +
         @SUM(TEMPUNSATISFIED(K5,F5): P_SFK(S,K5,F5) * D_SFK(S,K5,F5) *
U_SFK(S,K5,F5)) +
         @SUM(TEMPUNCOLLECTED(K6,F6): Q_SFK(S,K6,F6) * R_SFK(S,K6,F6) *
W_SFK(S,K6,F6)) +
         @SUM(TEMPDISPOSE(F10,K10,L10,O10): C_SFKLO(S,F10,K10,L10,O10) *
X_SFKLO(S,F10,K10,L10,O10) * R_SFK(S,K10,F10))-
         @SUM(TEMPRAW(F11,K11,L11,R11): P_SFKLR(S,F11,K11,L11,R11) *
X_SFKLR(S,F11,K11,L11,R11) * R_SFK(S,K11,F11))
        ))+

        !FIXED COSTS OF PLANT, WAREHOUSE AND DISASSEMBLY CENTRES;
        @SUM(PLANT(I7): SELECTP(I7) * COSTP(I7)) +
        @SUM(WAREHOUSE(J8): SELECTW(J8) * COSTW(J8)) +
        @SUM(DISASSEMBLY(L9): SELECTL(L9) * COSTL(L9)) +

        !FIXED COSTS OF MACHINERY INSTALLED IN PLANT AND DISASSEMBLY CENTRE;
        @SUM(PEQUIPPEDF(I3,F3): G_IF(I3,F3) * Y_IF(I3,F3)) +
        @SUM(LEQUIPPEDF(L4,F4): H_LF(L4,F4) * Z_LF(L4,F4));


!----------------------------CONSTRAINTS-------------------------------------------------------------------------------
!1) LOGICAL CONSTRAINTS FOR CUSTOMER DEMAND AND RETURNS FOR EVERY
PRODUCT;
```

```
@FOR(SCENARIO(S): @FOR(TEMPUNSATISFIED(K,F): @SUM(TEMP1(I,J): X_SIJKF(S,I,J,K,F)) +
U_SFK(S,K,F) = 1));

@FOR(SCENARIO(S): @FOR(TEMPUNCOLLECTED(K,F): @SUM(TEMP2(L,I):
X_SFKLI(S,F,K,L,I)) + @SUM(TEMP17(L,O): X_SFKLO(S,F,K,L,O)) + @SUM(TEMP19(L,R):
X_SFKLR(S,F,K,L,R)) + W_SFK(S,K,F) = 1));

!-------------------------------------------------------------------------------------------------------------------;

!2) OUTGOING FLOW TO BE ATLEAST AS BIG AS INCOMING FLOW;

@FOR(SCENARIO(S): @FOR(TEMP4(I,F):  @SUM(TEMP5(K,L): R_SFK(S,K,F) *
X_SFKLI(S,F,K,L,I)) <= @SUM(TEMP6(J,K): X_SIJKF(S,I,J,K,F) * D_SFK(S,K,F))));


@FOR(SCENARIO(S): @FOR(TEMPUNSATISFIED(K,F):  (@SUM(TEMP2(L,I): R_SFK(S,K,F) *
X_SFKLI(S,F,K,L,I)) + @SUM(TEMP19(L,R): R_SFK(S,K,F) * X_SFKLR(S,F,K,L,R)) +
@SUM(TEMP17(L,O): R_SFK(S,K,F) * X_SFKLO(S,F,K,L,O))) <= @SUM(TEMP1(I,J):
X_SIJKF(S,I,J,K,F) * D_SFK(S,K,F))));

!-------------------------------------------------------------------------------------------------------------------;

!3) MINIMUM DISPOSAL FRACTION FOR EACH RETURN  OF A PARTICULAR PRODUCT;

@FOR(SCENARIO(S): @FOR(TEMP7(L,K,F): @SUM(ALPHA: A1) * (@SUM(PLANT(I):
X_SFKLI(S,F,K,L,I)) + @SUM(DISPOSAL(O): X_SFKLO(S,F,K,L,O)) + @SUM(RAWMATL(R):
X_SFKLR(S,F,K,L,R))) <= @SUM(DISPOSAL(O): X_SFKLO(S,F,K,L,O))));

@FOR(SCENARIO(S): @FOR(TEMP7(L,K,F): @SUM(ALPHA: A2) * (@SUM(PLANT(I):
X_SFKLI(S,F,K,L,I)) + @SUM(DISPOSAL(O): X_SFKLO(S,F,K,L,O)) + @SUM(RAWMATL(R):
X_SFKLR(S,F,K,L,R)) ) >= @SUM(RAWMATL(R): X_SFKLR(S,F,K,L,R))));

!-------------------------------------------------------------------------------------------------------------------;

!4) CAPACITY CONSTRAINTS;

!A) FOR EVERY PLANT;
@FOR(SCENARIO(S): @FOR(PLANT(I): @SUM(TEMP8(J,K,F): X_SIJKF(S,I,J,K,F) * D_SFK(S,K,F)
* BF(F)) + @SUM(TEMP9(F,K,L): BF(F) * R_SFK(S,K,F) * X_SFKLI(S,F,K,L,I)) <= (CAPACITYP(I)
* SELECTP(I))));

!B) FOR EVERY WAREHOUSE;
@FOR(SCENARIO(S): @FOR(WAREHOUSE(J): @SUM(TEMP10(I,K,F): X_SIJKF(S,I,J,K,F) *
D_SFK(S,K,F) * GF(F)) <= (CAPACITYW(J) * SELECTW(J))));

!C) FOR EVERY DISASSEMBLY CENTRE;
@FOR(SCENARIO(S): @FOR(DISASSEMBLY(L): (@SUM(TEMP11(F,K,I): TF(F) * R_SFK(S,K,F) *
X_SFKLI(S,F,K,L,I)) + @SUM(TEMP12(F,K,O): TF(F) * R_SFK(S,K,F) * X_SFKLO(S,F,K,L,O)) +
@SUM(TEMP21(F,K,R): TF(F) * R_SFK(S,K,F) * X_SFKLR(S,F,K,L,R))) <= (CAPACITYL(L) *
SELECTL(L))));

!-------------------------------------------------------------------------------------------------------------------;

!6) INSTALLING MACHINERY AT PLANT;
@FOR(SCENARIO(S): @FOR(TEMP14(I,F,K): @SUM(WAREHOUSE(J): X_SIJKF(S,I,J,K,F)) <=
Y_IF(I,F)));
```

```
!-----------------------------------------------------------------------------------------------------------;

!7) INSTALLING MACHINERY AT DISASSEMBLY CENTRE;
@FOR(SCENARIO(S): @FOR(TEMP15(L,F,K): @SUM(PLANT(I): X_SFKLI(S,F,K,L,I)) <=
Z_LF(L,F)));

!-----------------------------------------------------------------------------------------------------------;

!DEFINING BINARY VARIABLES:

@FOR(PLANT: @BIN(SELECTP));
@FOR(WAREHOUSE: @BIN(SELECTW));
@FOR(DISASSEMBLY: @BIN(SELECTL));
@FOR(PEQUIPPEDF(I,F): @BIN(Y_IF(I,F)));
@FOR(LEQUIPPEDF(L,F): @BIN(Z_LF(L,F)));

!-----------------------------------------------------------------------------------------------------------;

!DEFINING CONTINUOUS VARIABLES;

@FOR(FORWARD(S,I,J,K,F): X_SIJKF(S,I,J,K,F) <= 1);
@FOR(FORWARD(S,I,J,K,F): X_SIJKF(S,I,J,K,F) >= 0);
@FOR(REVERSE(S,F,K,L,I): X_SFKLI(S,F,K,L,I) <= 1);
@FOR(REVERSE(S,F,K,L,I): X_SFKLI(S,F,K,L,I) >= 0);
@FOR(DISPOSE(S,F,K,L,O): X_SFKLO(S,F,K,L,O) <= 1);
@FOR(DISPOSE(S,F,K,L,O): X_SFKLO(S,F,K,L,O) >= 0);
@FOR(RAWSUPPL(S,F,K,L,R): X_SFKLR(S,F,K,L,R) <= 1);
@FOR(RAWSUPPL(S,F,K,L,R): X_SFKLR(S,F,K,L,R) >= 0);


@FOR(UNSATISFIED(S,K,F): U_SFK(S,K,F) <= 1);
@FOR(UNSATISFIED(S,K,F): U_SFK(S,K,F) >= 0);
@FOR(UNSATISFIED(S,K,F): W_SFK(S,K,F) <= 1);
@FOR(UNSATISFIED(S,K,F): W_SFK(S,K,F) >= 0);

!-----------------------------------------------------------------------------------------------------------;


!ASSIGNING RETURNS AS A PROPORTION OF DEMAND;

@FOR(SCENARIO(S): @FOR(TEMP18(K,F): R_SFK(S,K,F) = (D_SFK(S,K,F) * FACTOR(S))));

!-----------------------------------------------------------------------------------------------------------;

DATA:

C_SIJKF = @OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\STOCHASTIC_TEST.XLS', 'FORWARD');

C_SFKLI = @OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\STOCHASTIC_TEST.XLS', 'REVERSE');

C_SFKLO = @OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\STOCHASTIC_TEST.XLS', 'DISPOSAL');
```

```
P_SFKLR = @OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\STOCHASTIC_TEST.XLS', 'RAWMATL');

D_SFK = @OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\STOCHASTIC_TEST.XLS', 'DEMAND');

COSTP = @OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\STOCHASTIC_TEST.XLS', 'PLANT_COST');

COSTW = @OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\STOCHASTIC_TEST.XLS', 'WAREHOUSE_COST');

COSTL = @OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\STOCHASTIC_TEST.XLS',
'DISASSEMBLY_COST');

P_SFK = @OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\STOCHASTIC_TEST.XLS', 'UNSATISFIED');

Q_SFK = @OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\STOCHASTIC_TEST.XLS', 'UNCOLLECTED');

G_IF = @OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\STOCHASTIC_TEST.XLS', 'MACHINE_PLANT');

H_LF = @OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\STOCHASTIC_TEST.XLS',
'MACHINE_DISASSEMBLY');

A1 = @OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\STOCHASTIC_TEST.XLS', 'ALPHA1');

A2 = @OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\STOCHASTIC_TEST.XLS', 'ALPHA2');

BF = @OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\STOCHASTIC_TEST.XLS', 'BETA');

GF = @OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\STOCHASTIC_TEST.XLS', 'GAMMA');

TF = @OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\STOCHASTIC_TEST.XLS', 'TETA');

PROB = @OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\STOCHASTIC_TEST.XLS', 'PROB');

FACTOR = @OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\STOCHASTIC_TEST.XLS', 'FACTOR');

CAPACITYP = @OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\STOCHASTIC_TEST.XLS', 'CAPACITY_PLANT');

CAPACITYW = @OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\STOCHASTIC_TEST.XLS',
'CAPACITY_WAREHOUSE');
```

```
CAPACITYL = @OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\STOCHASTIC_TEST.XLS',
'CAPACITY_DISASSEMBLY');


!EXPORTING DATA TO SOLUTION.XLS FILE;
@OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\SOLUTION.XLS', 'FORWARD') = X_SIJKF;

@OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\SOLUTION.XLS', 'REVERSE') = X_SFKLI;

@OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\SOLUTION.XLS', 'DISPOSAL') = X_SFKLO;

@OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\SOLUTION.XLS', 'RAWMATL') = X_SFKLR;

@OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\SOLUTION.XLS', 'DEMAND') = D_SFK;

@OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\SOLUTION.XLS', 'RETURN') = R_SFK;

@OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\SOLUTION.XLS', 'SELECTP') = SELECTP;

@OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\SOLUTION.XLS', 'SELECTW') = SELECTW;

@OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE\SOLUTION.XLS', 'SELECTL') = SELECTL;

@OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\SOLUTION.XLS', 'MACHINE_DISASSEMBLY') =
Z_LF;

@OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\SOLUTION.XLS', 'MACHINE_PLANT') = Y_IF;

@OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\SOLUTION.XLS', 'UNSATISFIED') = U_SFK;

@OLE( 'C:\Documents and Settings\vdevu\Desktop\Thesis\test
programms\STOCHASTIC\TESTING\CHANGE1\SOLUTION.XLS', 'UNCOLLECTED') = W_SFK;

ENDDATA

END
```