ABSTRACT

Title of Document: REVERSE LOGISTICS NETWORK DESIGN WITH CENTRALIZED RETURN CENTER

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Natural resources and landfills have been overused and exhausted, resulting in the necessity of product recovery. Today, as a growing number of producers engage in product recovery, the need for efficient reverse logistics networks has become more significant than ever.

An optimization modeling approach is used to develop a generic integrated forward and reverse logistics network for a firm involved in product recovery. The proposed modeling framework demonstrates and compares the performance of centralized return centers (CRC) and conventional collection centers in the reverse

logistics network. Several case studies are used to analyze the sensitivity of the network structures and performances to various modeling parameters including product return ratio, product disposition ratios, and processing and handling costs at collection centers. Lastly, recommendations are made to remove model limitations and improve reverse logistics network models.

REVERSE LOGISTICS NETWORK DESIGN WITH CENTRALIZED RETURN CENTER.

By

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Dedication

I dedicate this thesis to my parents.

Acknowledgements

Words cannot express my gratitude towards my dear parents, Zhilla and Mohammad, and my beloved sister, Sepideh, for their unconditional love and support, helping me throughout the difficult times and sharing the joy during the cheerful moments.

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Chapter 1: Introduction

Research motivation and objectives

For decades, humans have focused on the advancement of living standards and the ways in which they make more economic profit. Often, they ignore the fact that our environment and natural resources have only so much to offer. Higher consumption rates and demands from the customers' side have pushed producers to increase their supplies and have amplified the competition between supply and demand. As a result, logistics activities have become a substantial portion of our economy. To no surprise, this phenomenon has led to an accumulation of large amounts of waste and the exhaustion of both our resources and landfills. Although enormous efforts have been made during more recent years to limit environmental damage, there are still opportunities to undo past damage.

Several governments have initiated environmental legislation and education in an effort to reduce the extent to which our environment is deteriorated. Moreover, many suppliers and producers have embraced the initiatives and are interested in or even engaging in more sustainable logistics and product recovery activities. In many countries today, producers are often held responsible for their product's life cycle and are required to conform to environmental legislations including landfill bans on certain products, recycling goals, and take-back obligations. Being a "green" producer and maintaining that image attracts environmentally concerned customers, may lower insurance rates and consumer disposal costs, and holds potential for future liabilities. Additionally, regaining value from discarded products could potentially reduce production costs.

The management of used or discarded products and materials by the producer as a way to maximize recovered economic and environmental value and minimize the disposed amount is called product recovery management (Thiery et al. 1995). For product recovery management to work, a logistics network is needed to provide the channel through which used products and materials are collected from end users and transported to producers for recovery purposes. This network works in the opposite direction from the original logistics network and is often referred to as the reverse logistics network.

Reverse logistics networks are more complicated than forward logistics networks because the quality of the returned products are often very inconsistent, and various processes and facilities are needed to handle them appropriately.

Several attempts have been made to reduce infrastructure and administrative costs so reverse networks can increase the profitability of product recovery. For instance, the integration of some forward network facilities with the reverse network facilities may result in better space and labor utilization. In recent years, the concept of centralizing return facilities has gained some attention for the cost saving potentials that it may bring over conventional decentralized return facilities.

The objective of this thesis is to develop a comprehensive logistics network for a company involved in product manufacturing and recovery. An optimization model is developed to configure the facility locations for both forward and reverse logistics channels such that the total profit is maximized. Two different approaches are taken to compare the performance of a model with a centralized return center (CRC) and the model with decentralized return centers (DRC). Several case studies are designed, and the applications of the two models, sensitivity of network performance and structure to different model parameters are demonstrated through these case studies.

Organization of the thesis

This thesis is organized in six chapters. Chapter 2 provides a review of the literature on reverse logistics network design. Several aspects and considerations of reverse logistics network design are discussed in this chapter and examples of the existing models in the literature are provided. In Chapter 3, the problem of interest is thoroughly defined and the structure of the proposed model is discussed. Chapter 4 provides the mathematical formulations for the proposed CRC and DRC models. The applications of the models are demonstrated on several case studies in Chapter 5, followed by more meaningful investigations of the model characteristics through sensitivity analysis on different parameters. Chapter 6 summarizes the findings and provides directions and ideas for further investigation and future research on reverse logistics network design.

Chapter 2: Literature Review and Background

What are reverse logistics?

The Council of Supply Chain Management Professionals (CSCMP) defines logistics management as "that part of supply chain management that plans, implements, and controls the efficient, effective forward and reverse flow of goods, services, and related information between the point of origin and the point of consumption, in order to meet customers' requirements" (CSCMP, 2013). In fact, reverse logistics is the process of moving products and materials in the opposite direction from the conventional forward supply chain to regain value from unwanted goods or to properly dispose the unwanted material (Rogers & Tibben-Lembke, 1998). According to the 24th Annual State of Logistics Report, during 2012, the cost of logistics activities accounted for approximately 8.5 percent of U.S. economy, which amounts to approximately $1.3 trillion. Figure 1 shows logistics cost as a percentage of the Gross Domestic Product (GDP) for the U.S. over a 10-year span, and Figure 2 shows the logistics cost as a percent of GDP among different countries in 2012 (Wilson, 2013).

It is difficult to determine the percentage of logistics cost devoted to reverse logistics. In 1998, Rogers and Tibben-Lembke interviewed and surveyed several reverse logistics managers across the U.S. and estimated the reverse logistics costs to account for approximately four percent of total logistics costs. Due to increasing attention to reverse logistics over the past decade, this portion is expected to be much larger today.

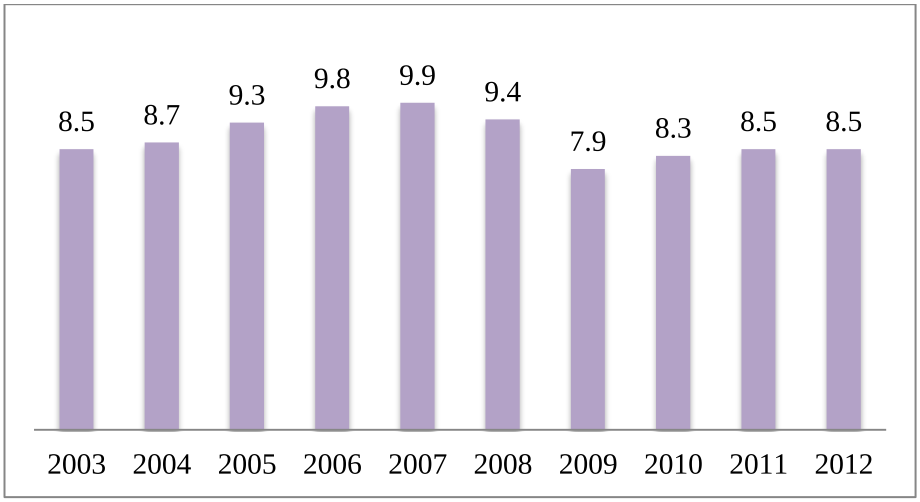


Figure 1. Logistics cost as a percent of GDP for US
Source: CSCMP's 24th Annual State of Logistics Report

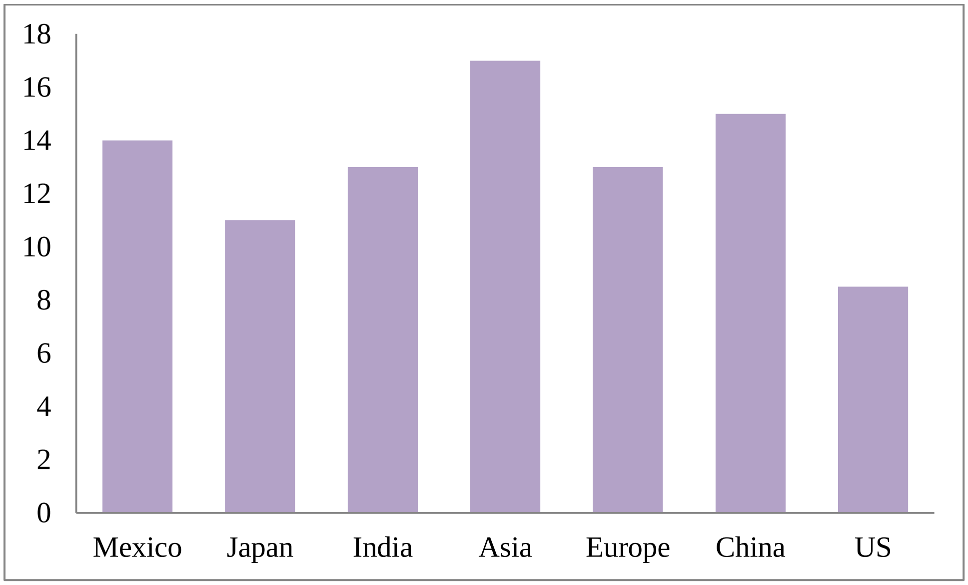


Figure 2. Logistics cost as a percent of GDP in 2012
Source: CSCMP's 24th Annual State of Logistics Report

Reasons and motivations for reverse logistics

The rise of environmental concerns in recent years has boosted the growth of reverse logistics. Today we experience increased disposal costs, restrictions on landfill capacities, landfill bans for certain products and materials and take back obligations (Fleischmann et al. 1997). Besides legislation, the pressure coming from environmentally conscious customers forces the producers to maintain a “green image” to be able to remain in the market. However, it is important to distinguish reverse logistics from “green” or “ecological” logistics. The former, as mentioned earlier, deals with the moving of products from the end user to the producer for recovery or disposal, whereas the later focuses on efforts to minimize the ecological and environmental impacts of logistics, such as reducing the use of energy and material resources (Rogers & Tibben-Lembke, 1998).

More recently, economic motivations have also added to the driving force for developing reverse logistics networks. Recovery processes do not always denote the disposal of end-of-life products. In fact, some recovery processes, such as refurbishing and remanufacturing, are used to capture the incorporated value in old and used products. Several products and packaging material could be reused or sold to secondary markets after minor cleaning and repair (Fleischmann et al. 1997). Moreover, due to an overwhelming growth of technology and high competency between producers, having a firm reverse logistics network to take out-of-date products off the shelves could result in overall profitability over the long run (Rogers & Tibben-Lembke, 1998). In some cases, such systems could help avoid lawsuits and loss of customers, possibly saving the future of a business. An interesting example is a case that happened to the McNeil Laboratories division of Johnson & Johnson in 1982, when several deaths were reported across Chicago due to Tylenol capsules being contaminated with potassium cyanide. In response, Johnson & Johnson used their reverse logistics system to quickly remove all Tylenol packages from the stores and offered to exchange all purchased capsules with solid tablets. The public and media took this act so positively that only three days later, McNeil Laboratories experienced an all-time sales record (Wikipedia, 2013).

Reverse logistics elements

It is important to determine the answer to three main questions, before designing any logistics network. They are:

(1) What logistics activities and recovery processes are involved?

(2) What parties are in charge of performing the logistics activities?

(3) What facilities are required to perform such activities?

In a reverse logistics network, returned products need to be collected, tested to determine whether recovery is feasible, and then be sorted based on the applicable recovery process. The products are then transported to the appropriate recovery facility for further processing.

Product recovery processes

After collection, returned products should be reprocessed and redistributed, or properly disposed if they have no value remaining in them. The “valuable” returns may be reused directly (possibly after minimal maintenance/cleaning) or used after some level of reprocessing. Several recovery options are available to recapture the value incorporated in the returned product based on the type of it. Thierry et al. (1995) introduced five major recovery processes based on the required level of disposition of the original product, which are: repairing, refurbishing, remanufacturing, cannibalization, and recycling.

Repairing involves making minor fixes and replacements with the least amount of disassembly required to restore the product back into "working order". Repair can be done either at customer location or at company's designated repair location.

Refurbishing involves the disassembling of a product to its module level and either fixing or replacing problematic modules to bring the product up to a certain quality level, usually less restrictive than that of new products. Refurbishing often extends a product's service life. However, the remaining service life is usually less than the expected service life of a new product.

Remanufacturing involves the highest level of disassembly, inspection, and replacement of modules and parts and is intended to bring the product to "as new" quality level. Both refurbishing and remanufacturing may be combined with technological upgrades, where out-dates parts are replaced by newer technology.

Cannibalization is different from repairing, refurbishing, and remanufacturing in that only a small portion of the used product is retrieved. The reusable parts are inspected and tested for certain quality levels required to be used in repairing, refurbishing and remanufacturing of other products.

Recycling involves reusing the material in used products without preserving the identity of the original product. The recycled material may re-enter the production cycle as raw material and be used for production of new parts and components.

Reverse logistics involves several activities that can be studied from different perspectives. Fleischman et al. (1997), classifies reverse logistics activities from a logistical point of view. The first step, distribution planning, involves reverse distribution and transportation of the products from the end user to the producer, and it is the main focus of this thesis. Other steps involve production planning and inventory management, which are topics out of the scope of this thesis.

In-house vs. third party logistics providers

Logistics activities in whole or in part may be performed by the manufacturer or by specialized parties, known as third party logistics (3PL) providers. Companies interested in engaging in reverse logistics but who are without enough resources or find it disadvantageous to their businesses may hire third parties to perform logistics activities on their behalf. Examples of successful 3PL's include FedEx, Genco and ASTAR (Krumwiede & Sheu, 2002).

In fact, there is no concrete form of third party logistics. In some instances, it may only involve outsourcing transportation and/or warehousing activities, whereas in other instances it may refer to outsourcing the entire logistics process (Marasco, 2008). The extent to which logistics activities could be outsourced also depends on the type of product and industry. Certain activities, such as remanufacturing, require more specialized levels of knowledge and technology and are often carried out in-house, whereas less specialized activities, such as recycling, may be outsourced to third parties (Fleischmann et al. 1997).

The challenge for 3PL providers is designing a logistics network that adapts to all requirements and demands of their several clients. However, an efficient network will enable 3PLs to consolidate volumes and shipments and benefit from economies of scale and scope (Fong, 2005).

Integrated vs. separate facilities

It is possible to combine some of the reverse logistics facilities with other forward or reverse logistics facilities. For instance, it is possible to combine manufacturing and re-manufacturing plants into integrated (i.e. hybrid) plants. Similarly, hybrid centers may be used to carry out both forward distribution and the collection of returned products. Hybrid centers may benefit from savings in transportation, administrative costs and improved space utilization. However, it is important to note that combining forward and reverse logistics facilities, especially at the distribution and collection level, often result in reverse flows being undermined or ignored, as forward flows are often prioritized over what is considered to be "junk" (Rogers & Tibben-Lembke, 1998).

Centralized vs. decentralized facilities

Centralized return centers (CRC) are exclusively devoted to efficient handling of returns. Over the past few years, they have gained more popularity among firms greatly engaged in reverse logistics. When incorporating CRCs, it is ideal to locate initial collection points close to customer locations and then carefully establish the centralized return center, such that small shipments from collection points can be consolidated and sent to their recovery destination in larger batches, potentially saving in processing and transportation costs (Diabat et al. 2013).

All returned items are transported to one or more CRCs based on the size of the company. For instance, Kmart Corporation and Sears, Roebuck and Company have four and three CRCs in their systems, respectively. At CRCs, the manufacturer's guidelines are used to determine what recovery processes are needed and where the returned products should be shipped next. Rogers & Tibben-Lembke (1998) suggest several advantages for CRCs that are listed below.

- Processing and handling of the returned items becomes more consistent and less erroneous as a result of using standard processing guidelines. CRC staff are often more experienced in the efficient handling of returns than employees at retail centers.
- Better space utilization is achieved via CRCs as holding non-selling items at the stores is not favored by the retailers, who prefer to use the majority of their shelf space for new products.

- Savings in freight costs may be achieved as a result of consolidating boxes into pallets. Some argue however, that transportation costs may increase as all products are shipped to the CRC, regardless of whether there is any value incorporated in them. But, the savings in disposition time and consolidation revenues usually outweigh the additional transportation costs.
- Customer service may improve as using CRC speeds the return process and helps the provider recognize trends in the returns. It also shows the commitment of the company to handling the returns appropriately.
- Disposition cycle times reduce as a result of incorporating CRCs into the logistics network. Unlike conventional return facilities and retail centers, CRCs treat product returns as a priority.

Reverse logistics network design aspects

Integration of forward and reverse networks

When a reverse logistics network is to be designed, one must determine what the relationship and level of interaction between the reverse and forward logistics networks is; additionally, it must be determined whether the structure of one affects the other. In other words, is an integrated logistics network superior to separately designed networks?

Fleischmann et al (2001) discussed the general framework for designing reverse logistics networks in various contexts and studied the impacts of product recovery on the structure of logistics networks. More specifically, they determined whether product recovery implies major changes to the overall network structure or if it can be integrated with existing conventional networks. Their generic recovery network model consists of three levels of facilities and two types of disposition processes for the returned products. The facilities include factories for new production and/or reprocessing, distribution warehouses, and disassembly centers. The processes include recovery and disposal. It is important to note that in this generic model, the disassembly center does not necessarily reflect the mechanical disassembly of the products; rather it refers to any facility at which the feasibility of recovery and the level of quality of the returned products are determined. Figure 3 shows the suggested framework for the recovery network.

To determine the effect of product recovery on the logistics network, the researchers compared two different examples inspired by real-life scenarios in the industry: copier remanufacturing and paper recycling. In both examples, they compared the sequential and integrated network designs in terms of costs and structure, and they studied the changes imposed by the integration of the recovery network into the conventional forward logistics network.

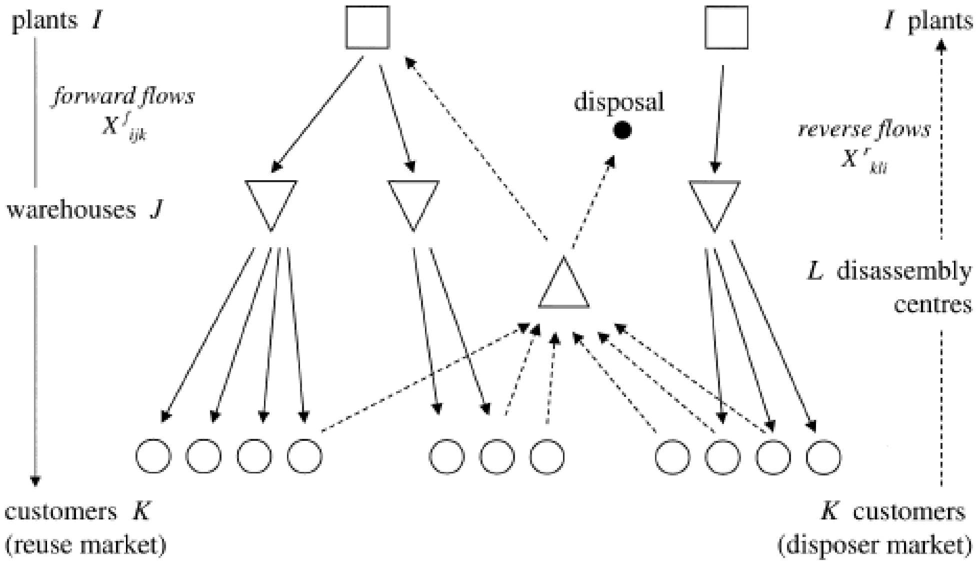


Figure 3. Recovery network structure by Fleischman et al. (2001)

For the sequential design, a conventional approach with no product recovery is first taken and the locations of production plants and facilities are determined. Then, product recovery is introduced to the network as a new activity and the locations of recovery facilities are determined, assuming fixed locations for the forward network. In the integrated design, both networks are designed together; therefore the locations of both forward and reverse logistics facilities are determined simultaneously.

The researchers applied this methodology to the copier remanufacturing example in a European context, where environmental regulations dictate that all returned products be collected. Figure 4 shows the results from both design approaches.

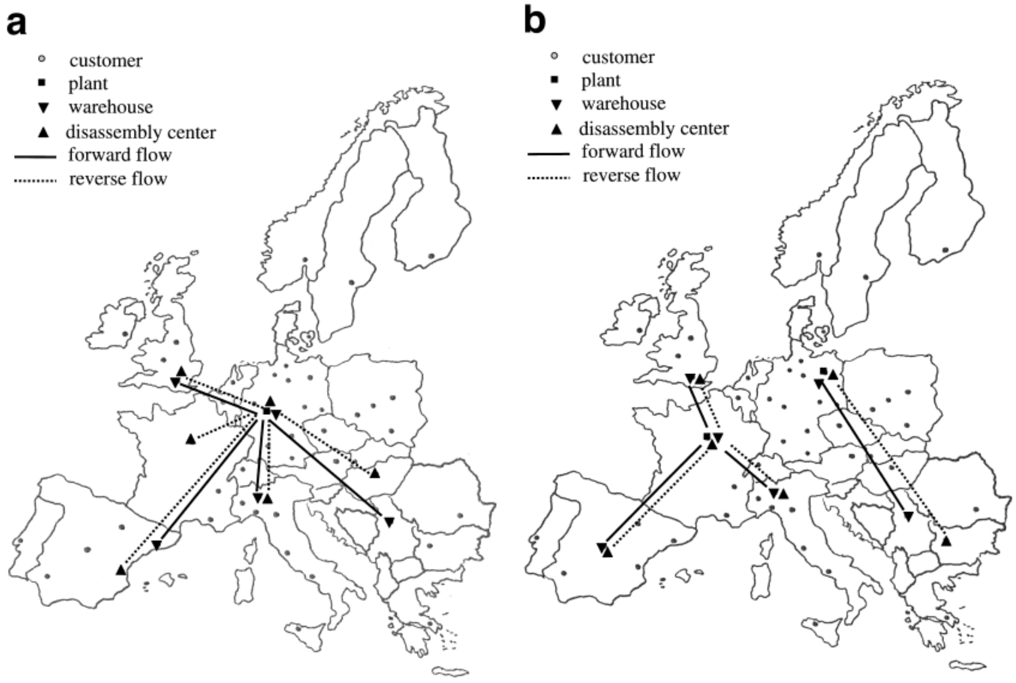


Figure 4. Copier remanufacturing (a) optimal sequential network, (b) optimal integrated network

The structures of the two networks are clearly different, suggesting a significant impact imposed on the forward network when integrated with the recovery network. However, researchers found that integration of the two networks yields a total cost saving of less than 1 percent. This means that although the sequential and integrated designs lead to different solutions, the fixation of the facilities of the forward network does not impose cost inefficiency on the recovery network. The results suggest that industries seeking to engage in product recovery activities may be able to do so without having to redesign their existing logistics network.

However, when applying the same methodology on the paper recycling industry in the same context, the researchers came across very different findings. Here, the costumer and potential facility locations are the same as the copier remanufacturing example. However, the pulpwood needed for paper production is only supplied from forests in Scandinavia, which adds an additional cost element to the problem. Assuming no obligations for collecting used paper, the collection follows a pull approach. Figure 5 shows the results from both approaches.

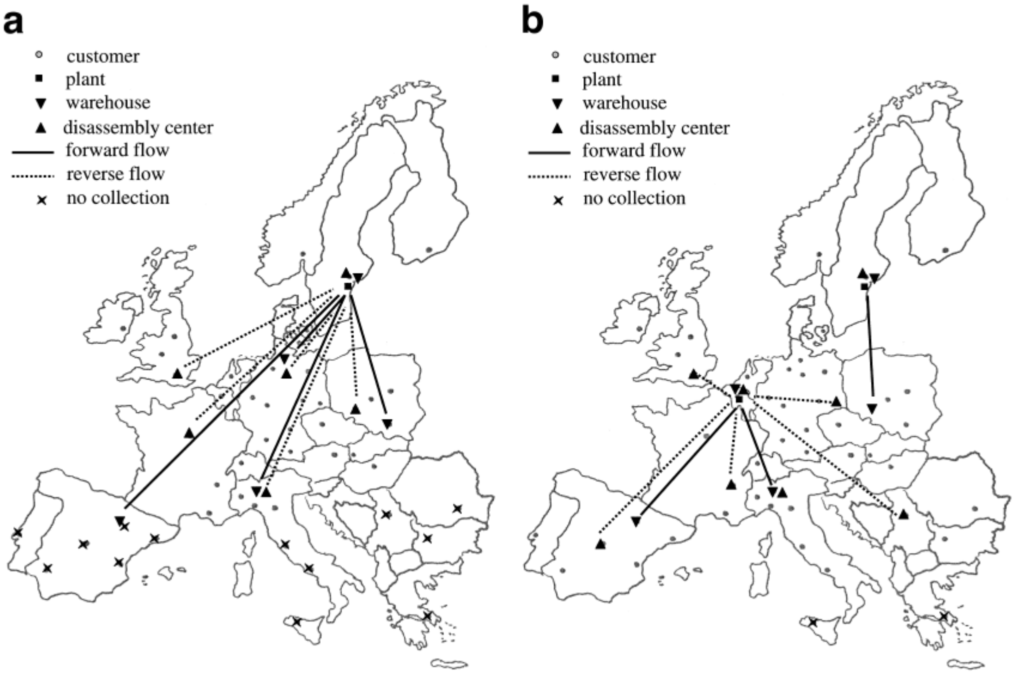


Figure 5. Paper recycling (a) optimal sequential network, (b) optimal integrated network

Again, the networks appear significantly different in terms of structure. In the sequential design, since the forward network is designed first, the high cost of transporting supply material from Scandinavia does not justify plant locations very far from the supply location. However, in the integrated design, the collection of used paper becomes attractive at more locations, and the benefits justify an additional production plant in Brussels. Besides the change in the network structure, the integrated design also yields a 20 percent reduction in the cost.

This is a very important finding because it suggests differences in geographical distribution and cost elements for supply and demand determine the impact of recovery activities on the overall logistics network. Fleischman et al. argue that similar results may be obtained in case of differences in labor intensity between production and recovery processes, or in case of large distances between disposer and reuse market. They also argue that economic incentive plays an influential role on the extent to which the return flows impact the network. Lower penalty costs for uncollected returns, for instance, reduces the impact of returns on the network as “mismatching” returns might go uncollected at low cost to the producer.

Integration of forward and reverse facilities

It is important to note that hybrid facilities belonging to both forward and reverse networks also impose some level of integration between the two networks, which may affect the structure and cost of the network. Sahyouni et al. (2007) argue that few firms optimize their forward and reverse networks independently; thus, it is important to find out if an integrated design would be more efficient. In the researchers’ opinion, although forward logistics activities dominate some industries and reverse logistics activities dominate the others, many industries transition from one to another throughout their products’ life cycle. More specifically, when the product is first introduced to the market (i.e. introductory stage), forward flows dominate the network because there is high demand for new product and few returns in the market. However, closer to the end of product's life cycle, product recovery dominates the logistics activities. Due to the decrease in demand for new products at this stage, it is called the decline stage. When both forward and recovery flows are in balance, (i.e. the maturity stage), the researchers suggest a "colocation" model, where intermediate logistics facilities allow for bidirectional flows, without favoring one over the other.

The researchers then compared the cost and structure of the logistics networks under sequential and integrated design for all three types of networks. The results show that sequential and integrated designs lead to significantly different network structures for forward-dominant and the colocation models, but very similar networks for the reverse-dominant model. Also, the integration of the two networks can decrease the cost up to 30 percent for the forward-dominant model, moderately for the colocation model and minimally for the reverse dominant model.

Besides these two studies that discuss the integration of the two networks, several other studies have briefly discussed and suggested that the integration of the two networks removes the potential for sub-optimality and therefore is recommended if the circumstances allow (Easwaran and Ǜster 2009, Ramezani et al. 2012, Khajavi et al. 2011, Pishvaee et al. 2010, etc.).

Other modeling aspects

Reverse logistics network modeling approaches in the literature can be categorized based on the following aspects:

- Scope: generic vs. problem specific
- Period: single vs. multi period
- Product: single vs. multi product
- Variables: facility locations vs. distribution vs. both/ vehicle routing
- Capacity limitations: un-capacitated vs. capacitated facilities
- Facility co-location: hybrid vs. separate manufacturing/ remanufacturing plants, hybrid vs. separate distribution/ collection centers
- Parameters: deterministic vs. stochastic
- Logistics provider: In-house logistics vs. third party logistics providers

Several researchers addressed the waste management and product recovery problems in specific contexts and proposed problem-tailored models and heuristics to solve the reverse logistics problem for certain industries. The majority of these models attempt to minimize the total logistics costs within the capacity and operational limits.

A fair amount of research has been done on waste management for the electric and electronic products (EEPs) (Dat et al. 2012, Grunow et al. 2009, Janga & Kim 2010, Franke et al. 2006, etc.). Dat et al. (2012) proposed a mathematical model for multi-products reverse logistics networks. Their proposed model determines the optimal facility locations and flows in the reverse logistics network through minimizing the total cost of reverse logistics. Their work extends the existing models to address a more complete and realistic recycling system with several stages of recovery of EEPs, including collection, disassembly, recycling, and repair, as well as taking into consideration several final destinations, including disposal sites, primary and secondary markets.

Schultman et al. (2006) discuss the problem of end-of-life vehicle (ELV) treatment in a closed-loop supply chain system. They propose a vehicle routing model for the ELV network in Germany. Activities such as draining, disassembly and packing take place at dismantling centers, while recovery processes such as shredding, cleaning, extraction and compounding are done at the reprocessing facilities. The proposed model minimizes the total distance travelled between the dismantlers and reprocessing sites during several collection periods.

Spengler et al. (1997) addressed the problem of byproduct management in the iron and steel industry in Germany. They proposed a mixed integer linear model to determine the location of recycling facilities and the flow of different byproduct materials between these facilities. The researchers also studied the changes in the recycling ratio, under various disposal fee rates and concluded that increasing disposal fees result in higher recycling rates.

Barros et al. (1998) addressed the problem of recycling sieved sand, a sub-product of construction wastes, in The Netherlands, by developing a mixed integer program for the capacitated two-level location problem. In their model, construction waste is first shipped to a sorting and crushing facility to separate reusable sand from non-reusable sand. The sieved sand is then classified based on pollution level as clean, half clean, and polluted, which is transformed into clean sand at additional treatment facilities. The recovered sand is then used in new construction projects.

Problem-specific models are very specialized and are best at addressing every detailed procedure and facility involved in the recovery process. However, in a broader view, they lack applicability. In recent years, due to the growing interest in product recovery and reverse logistics, most studies in this field have shifted towards more generic models and solution methods that are applicable to various contexts with minor modifications.

Some newer studies propose multi-objective models that extend the objective of the network models, not only minimizing total network monetary costs, but also improving the quality of responsiveness and customer care. Ku and Evans (2008) developed a deterministic bi-objective optimization model for outsourced return services that minimizes total cost and total cycle time. The study of the relationship between the two objectives showed that focusing on cost minimization leads to a more centralized network, whereas focusing on delay minimization leads to a more decentralized network design.

Pishvaee and Torabi (2010) proposed a bi-objective model that minimizes the cost and the expected tardiness of the delivery time using a stochastic approach for an integrated logistics network with hybrid facilities.

Khajavi et al. (2011) proposed a bi-objective model for an integrated logistics network with capacitated facilities. They defined network responsiveness as the sum of ratios of delivered products/ collected returns based on product/ return demands, weighted by the level of importance of the forward and reverse flows. Their optimization model minimizes total cost while maximizing network responsiveness. Sensitivity analysis of the model shows that forward responsiveness of the network significantly affects total network costs, while an increased reverse responsiveness may only affect return costs.

Ramezani et al. (2012) may have proposed the most complex model; they take a stochastic approach to a multi-objective model for an integrated network with multiple products and study the trade-offs between all objectives. Besides total cost and network responsiveness, their model also minimizes the total number of defects in raw materials obtained from various suppliers in order to maximize the quality of the manufactured products.

Chapter 3: Problem Statement and Modeling Framework

An integrated logistics network consists of forward and reverse logistics networks. The forward network includes the facilities required to manufacture the product in demand, store the products at warehouses and distribute them among several customer locations at times they are needed. The reverse network includes the facilities required to collect the returned products form the costumers, sort the returns based on the recovery process they qualify for, and ship them to the according recovery locations.

The two networks interact with each other in several ways. Part of this interaction comes from shared facilities between the two networks. For instance, if the company is involved in remanufacturing and refurbishing activities, the same locations used for new product manufacturing might be used for remanufacturing activities in the reverse network. Also, a company involved in recycling activities might use some of the recycled material in the production of new goods. Beyond sharing facilities and materials, the two networks usually work together toward meeting the objective of the manufacturer that maximizes the monetary profit or combines monetary and non-monetary objectives.

The problem of interest in this thesis is to design a generic integrated logistics network for an arbitrary company involved in product recovery activities. The forward logistics network consists of manufacturing locations, warehousing and distribution locations, and retailer centers (i.e. primary customer locations). The reverse logistics network consists of collection and sorting centers, repairing facilities, recycling facilities, remanufacturing facilities, disposal locations, and secondary customer locations.

Based on the primary market demand, products are produced at manufacturing locations and then shipped to and stored at distribution centers. The products are then shipped to retail centers where they are sold to costumers. Some products are returned due to meeting the end of their life cycle or not meeting customers' expectations, etc. Therefore, they need to be collected, inspected and sorted out based on the level of damage and wear. This activity is carried out at collection and sorting centers. After determining the appropriate recovery process for each returned product, they are shipped to appropriate recovery facilities.

The disposition (i.e. recovery) processes involved in this thesis include direct reuse, repair, remanufacture, recycle, and disposal. It was attempted to generate a generic model that captures most general recovery processes. However, minor modifications may be needed if the proposed model is being used for different or more industry-specific recovery processes. Multiple products and time periods are considered to expand the applicability of the model.

Among the returned products, those in very good shape or those that have never been used could be sold again, usually with a decent price in a secondary market. Moreover, some returned products might also be resold after minor fixes and repair. Products that could be remanufactured or used in manufacturing new products may be shipped back to the manufacturing locations. Products that contain a fair amount of recoverable materials could be shipped to recycling centers. Those products that contain no value should be disposed properly at designated disposal locations (i.e. landfills).

Figure 6 shows a schematic of the proposed network structure. The facilities within the dashed line are the ones that the company has control over; thus their locations are to be determined by the model. The arrows depict the flows of products between network facilities.

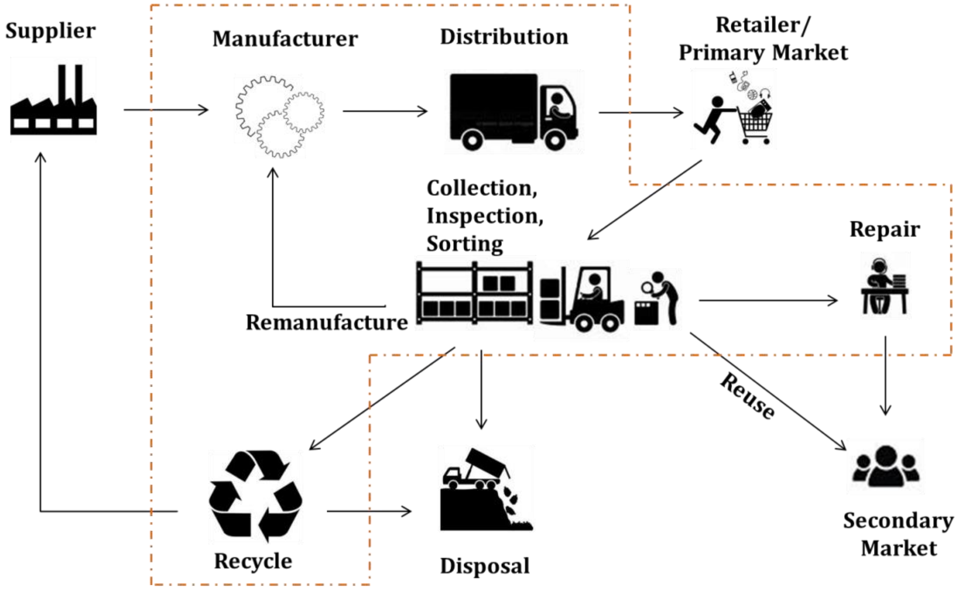


Figure 6. The proposed network structure

Obviously, the company is interested in reducing total network costs as much as possible. However, it might be the case that performing certain recovery processes results in an increase in the total cost. For instance, there is no profit in collecting, transporting, and disposing products that have no value incorporated in them. Even for recovery processes such as remanufacturing and recycling, the cost associated with collecting and recovering the material may outweigh the revenue that is made through reusing the recovered material. However, companies are sometimes forced to meet sustainability constraints that are enforced by legislations and/or customer expectations.

The problem involves several immediate questions that need to be answered. These questions are listed as follows:

i) Based on demands and rate of return for different products, where should the company build its manufacturing, distribution, collection, repair, and recycling facilities? It is important to note that the locations of the primary and secondary markets as well as the disposal fields are not determined by the company.

ii) What number of units of each product type should be manufactured at each manufacturing location during each period?

iii) What number of units of each product type should be transported between different facilities during each period?

Beyond the above questions, this thesis attempts to determine if centralization of the return facilities improves network performance. The literature suggests that incorporating CRCs leads to lower logistics costs compared to decentralized collection centers. However, there is not much research to reinforce this hypothesis. The goal of this thesis is to investigate the impact of CRC on profitability and structure of the logistics network.

Chapter 4: Mathematical Formulation and Modeling

Two mathematical models are presented in this chapter. The first model is developed based on the idea of collecting all returned products at a CRC, where the products are scanned and sorted based on the type of recovery process they qualify for. This model is referred to as the CRC model because it uses a centralized return center. In the second model, all products returned to retail centers are sorted and categorized at the retail centers. Therefore, there is no need for shipping the products to recovery facilities through a return center. This model is referred to as the DRC model because it uses decentralized return centers. The following sections provide modeling assumptions and details of the formulation for both models.

CRC model

Assumptions

Logistics networks that perform several recovery activities are challenging to model. When a general model is to be developed, several assumptions need to be made due to the absence of knowledge about the specific network being modeled. This section provides all the assumptions that were made for the proposed CRC model.

Facilities

i. The locations for the retailers (i.e. primary customer locations), secondary customer locations, and disposal locations (i.e. landfills) are assumed to be known, as they are usually out of the control of the producers.

ii. It is assumed that manufacturing and remanufacturing activities are performed at the same location, hence the hybrid manufacturing plants.

iii. New facilities may be established any time during the study period as needed. However, once a facility is opened, it cannot be closed.

iv. Facilities at which production and/or recovery processes take place are assumed to have limited capacity for different product types. These processes include manufacturing, remanufacturing, repairing, and recycling. Besides, warehouses are assumed to have limited storage capacity.

v. CRC is assumed to have unlimited capacity. This assumption was made because a CRC is supposed to have enough capacity to handle all the product returns that the company would potentially deal with.

Costs

i. A one-time cost is incurred when a new facility is established. After a facility is established, a recurring maintenance cost is incurred every year.

ii. Per unit costs of transportation between locations are assumed to be proportional to distance between the location as well as the weight of the products being transported.

iii. Costs and prices are time dependent, adding flexibility to the model to adapt changes in the market prices.

Demands and returns

i. Demands and returns are assumed to be deterministic for the whole study period.
ii. Demands for different products in both primary and secondary markets follow uniform distributions and vary over time.
iii. The amounts of returns for all products during each period are assumed to be a fixed portion of total products that are sold during that same period.
iv. Percentages of returned items that qualify for each recovery process are pre-determined. The CRC center keeps a separate inventory for each category.
v. A penalty cost is incurred for the proportion of the primary and secondary demand that is not met during each period. Per unit penalty rate is proportional to the original price that the product could have been sold for and is slightly higher to account for losing customer liability and possibly future sales.
vi. It is assumed that all returns are collected due to social and legal obligations.
vii. No back-ordering is considered, meaning that once a customer's demand is not met, it is considered a lost order and cannot be met during the next periods.

Mathematical formulation

Notations

$P = \{1,2,\dots,p\} = Set\ of\ product\ types$

$T = \{1,2,\ldots,t\} = Set\ of\ time\ periods$

$B = \{1,2,\ldots,b\} = Set\ of\ primary\ customer\ locations$

$G = \{1,2,\ldots,g\} = Set\ of\ secondary\ costumer\ locations$

$W = \{1,2,\ldots,w\} = Set\ of\ disposal\ locations$

$MC = \{1,2,\ldots,mc\} = Set\ of\ candidate\ manufacturing\ locations$

$RC = \{1,2,\ldots,rc\} = Set\ of\ candidate\ recycling\ locations$

$DC = \{1,2,\ldots,dc\} = Set\ of\ candidate\ distribution\ center\ locations$

$CC = \{1,2,\ldots,cc\} = Set\ of\ candidate\ return\ center\ locations$

$FC = \{1,2,\ldots,fc\} = Set\ of\ candidate\ repair\ center\ locations$

Model parameters

$C^{p}_{mc,dc,t} = \ Cost\ of\ shipping\ one\ unit\ of\ product\ p\ from$

$manufacturere\ mc\ to\ distribution\ center\ dc\ during\ period\ t$

$C^{p}_{dc,b,t} = \ Cost\ of\ shipping\ one\ unit\ of\ product\ p\ from$

$distribution\ center\ dc\ to\ primary\ customer\ b\ during\ period\ t$

$C^{p}_{b,cc,t} = \ Cost\ of\ shipping\ one\ unit\ of\ product\ p\ from$

$primary\ costumer\ b\ to\ return\ center\ cc\ during\ period\ t$

$C^{p}_{cc,mc,t} = \ Cost\ of\ shipping\ one\ unit\ of\ product\ p\ from$

$return\ center\ cc\ to\ manufacturer\ mc\ during\ period\ t\ (remanufacture)$

$C^{p}_{cc,fc,t} = \ Cost\ of\ shipping\ one\ unit\ of\ product\ p\ from\ return\ center\ cc$

$to\ repair\ location\ fc\ during\ period\ t\ (repair)$

$C^{p}_{cc,g,t} = \ Cost\ of\ shipping\ one\ unit\ of\ product\ p\ from\ return\ center\ cc$

to secondary costomer g during period t (reuse)

$C^{p}_{cc,w,t} =$ Cost of shipping one unit of product p from return center cc to disposal location w during period t (disposal)

$C^{p}_{cc,rc,t} =$ Cost of shipping one unit of product p from return center cc to recycling location rc during period t (recycle)

$C^{p}_{fc,g,t} =$ Cost of shipping one unit of product p from retpair location fc to secondary costumer g during period t

$C^{p}_{t} =$ Cost of manufacturing one unit of product p during period t

$CW^{p}_{t} =$ Cost of disposing one unit of product p during period t

$F_{mc,t} =$ Fixed cost of opening a manufacturer at location mc during period t

$F_{dc,t} =$ Fixed cost of opening a distribution center at location dc during period t

$F_{cc,t} =$ Fixed cost of opening a return center at location cc during period t

$F_{fc,t} =$ Fixed cost of opening a repair center at location fc during period t

$F_{rc,t} =$ Fixed cost of opening a recycling center at location rc during period t

$V_{dc,t} =$ Maintenance and operating cost for distribution center at location dc during period t

$V_{cc,t} =$ Maintenance and operating cost for return center at location cc during period t

$V_{mc,t}$ = Maintenance and operating cost for manufacturer

at location mc during period t

$V_{fc,t}$ = Maintenance and operating cost for repair center

at location fc during period t

$V_{rc,t}$ = Maintenance and operating cost for recycling center

at location rc during period t

PP_t^p = Price of product p in primary market during period t

SP_t^p = Price of product p in secondary market during period t

L_{mc}^p = Maximum unit production capacity for product p

at manufacturer mc

L_{rmc}^p = Maximum unit remanufacturing capacity for product p

at manufacturer mc

L_{dc}^p = Maximum unit storage capacity for product p

at distribution center dc

L_{fc}^p = Maximum unit repairing capacity for product p

at repair center fc

L_{rc}^p = Maximum unit recycling capacity for product p

at recycle center rc

$S_{cc,mc,t}^p$ = Saving from remanufacturing one unit of product p

during period t

$S_{cc,rc,t}^p$ = Saving from recycling one unit of product p

$during\ period\ t$

$S_t^p = \ Per\ unit\ storage\ cost\ for\ product\ p\ during\ period\ t$

$D_{b,t}^p = Demand\ of\ primary\ costumer\ b\ for\ product\ p\ during\ period\ t$

$D_{g,t}^p = Demand\ of\ secondary\ costumer\ g\ for\ product\ p\ during\ period\ t$

$\varepsilon_t^p = Rate\ of\ return\ of\ product\ p\ during\ period\ t$

$k_t^p = \ Rate\ of\ disposal\ of\ product\ p\ during\ period\ t$

$r_t^p = \ Rate\ of\ recycling\ of\ product\ p\ during\ period\ t$

$f_t^p = \ Rate\ of\ repairing\ of\ product\ p\ during\ period\ t$

$u_t^p = \ Rate\ of\ reuse\ of\ product\ p\ during\ period\ t$

$m_t^p = \ Rate\ of\ remanufacturing\ of\ product\ p\ during\ period\ t$

$J_{b,t}^p = \ Per\ unit\ penalty\ for\ not\ meeting\ the\ demand\ of$

$primary\ customer\ b\ for\ product\ p\ during\ period\ t$

$J_{g,t}^p = \ Per\ unit\ penalty\ for\ not\ meeting\ the\ demand\ of$

$secondary\ customer\ g\ for\ product\ p\ during\ period\ t$

$M = Very\ big\ positive\ number$

Decision variables

$$Y_{mc,t} = \begin{cases} 1, manufacturer\ is\ opened\ at\ location\ mc\ during\ period\ t \\ 0, otherwise \end{cases}$$

$$Y_{dc,t} = \begin{cases} 1, distribution\ center\ is\ opened\ at\ location\ dc\ during\ period\ t \\ 0, otherwise \end{cases}$$

$$Y_{cc,t} = \begin{cases} 1, collection\ center\ is\ opened\ at\ location\ cc\ during\ period\ t \\ 0, otherwise \end{cases}$$

$Y_{fc,t} = \begin{cases} 1, repair\ center\ is\ opened\ at\ location\ fc\ during\ period\ t \\ 0, otherwise \end{cases}$

$Y_{rc,t} = \begin{cases} 1, recycle\ center\ is\ opened\ at\ location\ rc\ during\ period\ t \\ 0, otherwise \end{cases}$

$Z_{mc,t}^{p} = Number\ of\ units\ of\ product\ p\ manufactured\ at$

$manufacturer\ mc\ during\ period\ t$

$I_{dc,t}^{p} = Inventory\ level\ for\ product\ p\ at\ distribution\ center\ dc$

$during\ period\ t$

$X_{mc,dc,t}^{p} = \ Number\ of\ units\ of\ product\ p\ shipped\ from$

$manufacturere\ mc\ to\ distribution\ center\ dc\ during\ period\ t$

$X_{dc,b,t}^{p} = \ Number\ of\ units\ of\ product\ p\ shipped\ from$

$distribution\ center\ dc\ to\ primary\ customer\ b\ during\ period\ t$

$X_{b,cc,t}^{p} = \ Number\ of\ units\ of\ product\ p\ shipped\ from$

$primary\ costumer\ b\ to\ return\ center\ cc\ during\ period\ t$

$X_{cc,mc,t}^{p} = \ Number\ of\ units\ of\ product\ p\ shipped\ from\ return\ center\ cc$

$to\ manufacturere\ mc\ during\ period\ t\ (remanufacture)$

$X_{cc,fc,t}^{p} = \ Number\ of\ units\ of\ product\ p\ shipped\ from\ return\ center\ cc$

$to\ repair\ location\ fc\ during\ period\ t\ (repair)$

$X_{cc,g,t}^{p} = \ Number\ of\ units\ of\ product\ p\ shipped\ from\ return\ center\ cc$

$to\ secondary\ costomer\ g\ during\ period\ t\ (reuse)$

$X_{cc,w,t}^{p} = \ Number\ of\ units\ of\ product\ p\ shipped\ from\ return\ center\ cc$

$to\ disposal\ location\ w\ during\ period\ t\ (disposal)$

$X^{p}_{cc,rc,t} =$ Number of units of product p shipped from return center cc to recycling location rc during period t (recycle)

$X^{p}_{fc,g,t} =$ Number of units of product p shipped from repair location fc to secondary costumer g during period t

$RI^{p}_{cc,t} =$ Total number of product p shipped to return center cc during period t

$RI(u)^{p}_{cc,t} =$ Inventory level for reusable product p at return center cc during period t

$RI(f)^{p}_{cc,t} =$ Inventory level for repairable product p at return center cc during period t

$RI(r)^{p}_{cc,t} =$ Inventory level for recyclable product p at return center cc during period t

$RI(m)^{p}_{cc,t} =$ Inventory level for remanufacturable product p at return center cc during period t

$Shortage^{p}_{b,t} =$ Proportion of unsatisfied demand for product p at primary customer location b during period t

$Shortage^{p}_{g,t} =$ Proportion of unsatisfied demand for product p at secondary customer location b during period t

The model

All costs and revenues for the model and how each is calculated are explained in the following section. The objective of the model is also discussed.

i. Total production cost

This is the sum of all products manufactured during each period multiplied by per unit cost of production during that period.

$$C1 = \sum_{t} \sum_{p} \sum_{mc} Z^{p}_{mc,t} \,.\, C^{p}_{t}$$

ii. Total facility opening cost

This is the sum of opening costs of all facilities that are established during the study period.

$$C2 = \sum_{t} \left[\sum_{mc} Y_{mc,t} \,.\, F_{mc,t} + \sum_{dc} Y_{dc,t} \,.\, F_{dc,t} + \sum_{cc} Y_{cc,t} \,.\, F_{cc,t} + \sum_{fc} Y_{fc,t} \,.\, F_{fc,t} + \sum_{rc} Y_{rc,t} \,.\, F_{rc,t} \right]$$

iii. Total transportation cost

This is the sum of per unit transportation cost between every two facilities multiplied by the number of products being transported.

$$C3 = \sum_{t}\sum_{p}\left[\sum_{mc}\sum_{dc} X^{p}_{mc,dc,t} \cdot C^{p}_{mc,dc,t} + \sum_{dc}\sum_{b} X^{p}_{dc,b,t} \cdot C^{p}_{dcbc,t} + \sum_{b}\sum_{cc} X^{p}_{b,cc,t} \cdot C^{p}_{b,cc,t} + \sum_{cc}\sum_{mc} X^{p}_{cc,mc,t} \cdot C^{p}_{cc,mc,t} + \sum_{cc}\sum_{fc} X^{p}_{cc,fc,t} \cdot C^{p}_{cc,fc,t} + \sum_{cc}\sum_{g} X^{p}_{cc,g,t} \cdot C^{p}_{cc,g,t} + \sum_{cc}\sum_{rc} X^{p}_{cc,rc,t} \cdot C^{p}_{cc,rc,t} + \sum_{cc}\sum_{w} X^{p}_{cc,w,t} \cdot C^{p}_{cc,w,t} + \sum_{fc}\sum_{g} X^{p}_{fc,g,t} \cdot C^{p}_{fc,g,t}\right]$$

iv. Total facility operating and maintenance cost

This is the sum of the operational and maintenance costs for all facilities for every year the facilities are operating.

$$C4 = \sum_{t' \in T}\left[\sum_{mc} V_{mc,t'} \cdot \sum_{t}^{t'} Y_{mc,t} + \sum_{dc} V_{dc,t'} \cdot \sum_{t}^{t'} V_{cc,t} + \sum_{cc} V_{cc,t'} \cdot \sum_{t}^{t'} Y_{cc,t} + \sum_{fc} V_{fc,t'} \cdot \sum_{t}^{t'} Y_{fc,t} + \sum_{rc} V_{rc,t'} \cdot \sum_{t}^{t'} Y_{rc,t}\right]$$

v. Total shortage cost

This is the sum of the per unit penalty for not meeting the demand multiplied by the amount of shortage for each product, both for primary and secondary customers during all periods.

$$C5 = \sum_{t}\sum_{p}\left[\sum_{b} J_{b,t}^{p} \,.\, Shortage_{b,t}^{p} + \sum_{g} J_{g,t}^{p} \,.\, Shortage_{g,t}^{p}\right]$$

vi. Total storage cost

This is the sum of product storage costs at warehouses and collection centers during all periods.

$$C6 = S_{t}^{p}.\left(\sum_{t}\sum_{p}\sum_{dc} I_{dc,t}^{p} + \sum_{t}\sum_{p}\sum_{cc}\left(RI(u)_{cc,t}^{p} + RI(f)_{cc,t}^{p} + RI(m)_{cc,t}^{p} + RI(r)_{cc,t}^{p} + RI(w)_{cc,t}^{p}\right)\right)$$

vii. Total disposal cost

This is the total cost of disposing the waste shipped to the collection center during all periods.

$$C7 = \sum_{t}\sum_{p}\sum_{cc}\sum_{w} X_{cc,w,t}^{p} \,.\, CW_{t}^{p}$$

viii. Total benefit from sales

This is the sum of the revenues made through selling products in primary and secondary markets during all periods.

$$B1 = \sum_{t}\sum_{p}\left[\sum_{dc}\sum_{b} X_{dc,b,t}^{p} \, . \, PP_{t}^{p} + \sum_{g}\sum_{cc} X_{cc,g,t}^{p} \, . \, SP_{t}^{p} + \sum_{fc}\sum_{g} X_{fc,g,t}^{p} \, . \, SP_{t}^{p}\right]$$

ix. Total saving from recycling and remanufacturing

This is the sum of the number of remanufactured and recycled products multiplied by per unit saving made through remanufacturing and recycling.

$$B2 = \sum_{t}\sum_{p}\left[\sum_{mc}\sum_{cc} X_{cc,mc,t}^{p} \, . \, S_{cc,mc,t}^{p} + \sum_{rc}\sum_{cc} X_{cc,rc,t}^{p} \, . \, S_{cc,rc,t}^{p}\right]$$

x. Objective function

The objective function maximizes the sum of all revenues minus the sum all costs.

Maximize OBJ = B1 + B2 – (C1 + C2 + C3 + C4 + C5 + C6 + C7)

<u>*Constraints*</u>

$$(1)\ Z_{mc,t}^{p} \geq \sum_{dc} X_{mc,dc,t}^{p} \qquad \forall\, mc \in MC;\ \in P;\ t \in T$$

$$(2) \sum_{dc} X_{dc,b,t}^{p} + Shortage_{b,t}^{p} \geq D_{b,t}^{p} \qquad \forall\, b \in B;\ p \in P;\ t \in T$$

$$(3) \sum_{dc} X_{dc,b,t}^{p} \leq D_{b,t}^{p} \qquad \forall\, b \in B;\ \forall\, p \in P;\ \forall\, t \in T$$

$$(4)\ I_{dc,t}^{p} = I_{dc,t-1}^{p} + \sum_{mc} X_{mc,dc,t}^{p} - \sum_{b} X_{dc,b,t}^{p} \qquad \forall\, dc \in DC;\ p \in P;\ t \in T$$

$$(5) \sum_{b} X_{b,cc,t}^{p} = RI_{cc,t}^{p} \qquad \forall\, cc \in CC;\ p \in P;\ t \in T$$

$$(6)\ \varepsilon_t^p . D_{b,t}^p = \sum_{cc} X_{b,cc,t}^p \qquad \forall\, b \in B;\ p \in P;\ t \in T$$

$$(7)\ IR(u)_{cc,t}^p = IR(u)_{cc,t-1}^p + u_t^p . RI_{cc,t}^p - \sum_{g} X_{cc,g,t}^p \qquad \forall\, cc \in CC;\ p \in P;\ t \in T$$

$$(8)\ IR(f)_{cc,t}^p = IR(f)_{cc,t-1}^p + f_t^p . RI_{cc,t}^p - \sum_{fc} X_{cc,fc,t}^p \qquad \forall\, cc \in CC;\ p \in P;\ t \in T$$

$$(9)\ IR(m)_{cc,t}^p = IR(m)_{cc,t-1}^p + m_t^p . RI_{cc,t}^p - \sum_{mc} X_{mc,g,t}^p \qquad \forall\, cc \in CC;\ p \in P;\ t \in T$$

$$(10)\ IR(r)_{cc,t}^p = IR(r)_{cc,t-1}^p + r_t^p . RI_{cc,t}^p - \sum_{rc} X_{cc,rc,t}^p \qquad \forall\, cc \in CC;\ p \in P;\ t \in T$$

$$(11)\ k_t^p . RI_{cc,t}^p = \sum_{w} X_{cc,w,t}^p \qquad \forall\, cc \in CC;\ p \in P;\ t \in T$$

$$(12) \sum_{cc} X_{cc,g,t}^p + \sum_{fc} X_{fc,g,t}^p + Shortage_{g,t}^p \geq D_{g,t}^p \qquad \forall g \in G;\ p \in P;\ t \in T$$

$$(13) \sum_{cc} X_{cc,g,t}^p + \sum_{fc} X_{fc,g,t}^p \leq D_{g,t}^p \qquad \forall\, g \in G;\ p \in P;\ t \in T$$

$$(14) \sum_{t} Y_{mc,t} \leq 1 \qquad \forall\, mc \in MC$$

$$(15) \sum_{t} Y_{dc,t} \leq 1 \qquad \forall\, dc \in DC$$

$$(16) \sum_{t} Y_{cc,t} \leq 1 \qquad \forall cc \in CC$$

$$(17) \sum_{t} Y_{fc,t} \leq 1 \qquad \forall\, fc \in FC$$

$$(18) \sum_{t} Y_{rc,t} \leq 1 \qquad \forall\, rc \in RC$$

$$(19)\ Z^{p}_{mc,t'} \leq \sum_{t}^{t'} Y_{mc,t}\ .\ L^{p}_{mc} \qquad \forall\, mc\ \in MC;\ p\ \in P;\ t' \in T$$

$$(20) \sum_{cc} X^{p}_{cc,mc,t'} \leq \sum_{t}^{t'} Y_{mc,t}\,.\ L^{p}_{rmc} \qquad \forall\, mc\ \in MC;\ p\ \in P;\ t' \in T$$

$$(21)\ I^{p}_{dc,t'} \leq \sum_{t}^{t'} Y_{dc,t}\ .\ L^{p}_{dc} \qquad \forall\, dc\ \in DC;\ p\ \in P;\ t' \in T$$

$$(22) \sum_{b} X^{p}_{b,cc,t'} \leq \sum_{t}^{t'} Y_{cc,t}\,.\,M \qquad \forall\, cc\ \in CC;\ \forall\ \in P;\ t'\ \in T$$

$$(23) \sum_{cc} X^{p}_{cc,rc,t'} \leq \sum_{t}^{t'} Y_{rc,t}\ .\ L^{p}_{rc,t} \qquad \forall\, rc\ \in RC;\ p\ \in P;\ t'\ \in T$$

$$(24) \sum_{cc} X^{p}_{cc,fc,t} \leq \sum_{t}^{t'} Y_{fc,t}\,.\,L^{p}_{fc,t} \qquad \forall\, fc\ \in FC;\ p\ \in P;\ t'\ \in T$$

$$(25) \sum_{t} \sum_{cc} Y_{cc,t} = 1$$

$$(26)\ X^{p}_{mc,dc,t}, X^{p}_{dc,b,t}, X^{p}_{b,cc,t}, X^{p}_{cc,mc,t}, X^{p}_{cc,fc,t}, X^{p}_{cc,rc,t}, X^{p}_{cc,g,t}, X^{p}_{cc,w,t}, X^{p}_{fc,g,t}$$

$$Z^{p}_{mc,t}, I^{p}_{dc,t}, RI^{p}_{cc,t} \in \quad Z^{+}$$

$$\forall\, mc \in MC, dc \in DC, cc \in CC, fc \in FC, rc \in RC, b \in B, g \in G, p \in P, t \in T$$

$$(27)\ Y_{mc,t}, Y_{dc,t,} Y_{cc,t}, Y_{fc,t,}\ Y_{rc,t}\ \in \{0,1\}$$

$$\forall\, mc \in MC, dc \in DC, cc \in CC, fc \in FC, rc \in RC, t \in T$$

Constraints (1) ensure that the total amount of each product shipped out of a manufacturing location does not exceed the production at that location. Constraints (2) calculate the shortage in satisfying the primary customers' demand, while constraints (3) ensure that total products sold to primary customers do not exceed their demand. Constraints (4) define both the product inventory at warehouses at the end of each time period and its relationship with product inventory at the end of the previous period. Constraints (5) calculate the total amount of returned products shipped to collection center(s) during each time period. Constraints (6) calculate the total amount of returns from retailers during each period. Constraint (7), (8), (9), and (10) calculate inventory levels for each category of recoverable products at collection center(s) at the end of each period. Constraints (11) ensure that all disposable products are directly shipped to landfills and are not stored at collection center(s). Similar to constraints (2) and (3), constraints (12) and (13) calculate the shortage in satisfying secondary customers' demand and ensure that total products sold to secondary customers do not exceed their demand. Constraints (14), (15), (16), (17), and (18) ensure that each facility is established at most one time during the study period. Constraints (19) ensure that production only occurs at established manufacturing locations and does not exceed production capacity. Constraints (20) ensure that for the purpose of remanufacturing, products only get shipped to a previously established manufacturing location and the amount of shipment does not exceed the remanufacturing capacity. Constraint (21) ensures that total product inventory at a previously established warehouse does not exceed the storage limit. Constraints (22) ensure that returned products only get shipped to a previously established collection center. Similarly, constraints (23) and (24) ensure that repairable and recyclable products only get shipped to previously established facilities and the amounts of shipments do not exceed repairing and recycling capacity at those locations. Constraint (25) ensures that during all time periods, only one collection center is opened. This location is the so-called central return center (CRC). Note that for large networks that need more than one CRC, this number could be changed accordingly. Constraints (26) and (27) ensure the integrality of decision variables.

DRC model

DRC is a model very similar to the CRC model. However, there are minor assumptions and model characteristics that differ between the two models. Here, only assumptions and characteristics that are changed or totally new are listed to avoid redundancy.

Assumptions

Facilities

i. It is assumed that all returned products are collected at primary customer locations (i.e. retail centers), and the personnel at these locations are in charge of sorting returns based on different recovery processes for which they qualify.

ii. It is assumed that returns can be stored at the retail centers without limit. However, the company pays for the storage costs, if the returns are not shipped to recovery facilities.

<u>Costs</u>

i. Per unit processing cost is incurred at the retail location for returned items. This is to account for the additional processing costs due to lack of experience and a standardized processing system, as suggested by the literature.
ii. Since there is no collection center to establish, there will be no cost to establish and maintain return centers. All other facilities have similar fixed and recurring costs.

<u>Demands and returns</u>

i. Percentages of returned items that qualify for each recovery process are pre-determined. The retail center keeps a separate inventory for each category.

Mathematical formulation

<u>Notations</u>

Notations for the DRC model are the same as notions for the CRC model, except that the set representing candidate CRC locations (i.e. CC) is removed from the notation.

<u>Model parameters</u>

Many model parameters for the DRC model are the same as the parameters for the CRC model. Only parameters that have been added or have changed indices are included in this section to avoid redundancy.

$C_{b,fc,t}^{p} = \ Cost\ of\ shipping\ one\ unit\ of\ product\ p\ from$

retailer b to repair center fc during period t (repair)

$C_{b,mc,t}^{p} =$ Cost of shipping one unit of product p from

retailer b to manufacturer mc during period t (remanufacture)

$C_{b,\mathrm{rc},t}^{p} =$ Cost of shipping one unit of product p from retailer b

to recycling location rc during period t (recycle)

$C_{b,g,t}^{p} =$ Cost of shipping one unit of product p from retailer b

to secondary costomer g during period t (reuse)

$C_{b,w,t}^{p} =$ Cost of shipping one unit of product p from retailer b

to disposal location w during period t (disposal)

$PC_{t}^{p} =$ Cost of processing one unit of returned product p

at a retail center during period t

Decision variables

Many decision variables for the DRC model are the same as the variables for the CRC model. Only variables that have been added or have changed indices are included in this section to avoid redundancy.

$X_{b,mc,t}^{p} =$ Number of units of product p shipped from retailer b

to manufacturere mc during period t (remanufacture)

$X_{b,fc,t}^{p} =$ Number of units of product p shipped from retailer b

to repair location fc during period t (repair)

$X_{b,g,t}^{p} =$ Number of units of product p shipped from retailer b

$to\ secondary\ costomer\ g\ during\ period\ t\ (reuse)$

$X^{p}_{b,rc,t} =\ Number\ of\ units\ of\ product\ p\ shipped\ from\ retailer\ b$

$to\ recycling\ location\ rc\ during\ period\ t\ (recycle)$

$X^{p}_{b,w,t} =\ Number\ of\ units\ of\ product\ p\ shipped\ from\ retailer\ b$

$to\ disposal\ location\ w\ during\ period\ t\ (disposal)$

$RI^{p}_{b,t} = Total\ number\ of\ product\ p$ returned $at\ retailer\ b$

$during\ period\ t$

$RI(u)^{p}_{b,t} = Returned\ inventory\ level\ for\ reusable\ product\ p$

$at\ retailer\ b\ \ during\ period\ t$

$RI(f)^{p}_{b,t} = Returned\ inventory\ level\ for\ repairable\ product\ p$

$at\ retailer\ b\ \ during\ period\ t$

$RI(r)^{p}_{b,t} = Returned\ inventory\ level\ for\ recyclable\ product\ p$

$at\ retailer\ b\ \ during\ period\ t$

$RI(m)^{p}_{b,t} = Returned\ inventory\ level\ for\ remanufacturable\ product\ p$

$at\ retailer\ b\ \ during\ period\ t$

The model

In the DRC model, half of the variables and parameters from the CRC model are changed and the other half are left unchanged; thus, all costs and revenues for the model are listed below to avoid confusion.

i. Total production cost

This is the sum of all products manufactured during each period multiplied by per unit cost of production during that period.

$$C1 = \sum_{t} \sum_{p} \sum_{mc} Z_{mc,t}^{p} \,.\, C_{t}^{p}$$

ii. Total facility opening cost

This is the sum of opening costs of all facilities that are established during the study period.

$$C2 = \sum_{t} \left[\sum_{mc} Y_{mc,t} \,.\, F_{mc,t} + \sum_{dc} Y_{dc,t} \,.\, F_{dc,t} + \sum_{fc} Y_{fc,t} \,.\, F_{fc,t} + \sum_{rc} Y_{rc,t} \,.\, F_{rc,t} \right]$$

iii. Total transportation cost

This is the sum of per unit transportation cost between every two facilities multiplied by the number of products being transported.

$$\begin{aligned} C3 = \sum_{t} \sum_{p} \Bigg[& \sum_{mc} \sum_{dc} X_{mc,dc,t}^{p} \,.\, C_{mc,dc,t}^{p} + \sum_{dc} \sum_{b} X_{dc,b,t}^{p} \,.\, C_{dcbc,t}^{p} \\ & + \sum_{b} \sum_{fc} X_{b,fc,t}^{p} \,.\, C_{b,fc,t}^{p} + \sum_{b} \sum_{mc} X_{b,mc,t}^{p} \,.\, C_{b,mc,t}^{p} \\ & + \sum_{b} \sum_{rc} X_{b,\mathrm{rc},t}^{p} \,.\, C_{b,\mathrm{rc},t}^{p} + \sum_{b} \sum_{g} X_{b,g,t}^{p} \,.\, C_{b,g,t}^{p} + \sum_{fc} \sum_{g} X_{fc,g,t}^{p} \,.\, C_{fc,g,t}^{p} \\ & + \sum_{b} \sum_{w} X_{b,w,t}^{p} \,.\, C_{b,w,t}^{p} \Bigg] \end{aligned}$$

iv. Total facility operating and maintenance cost

This is the sum of the operational and maintenance costs for all facilities for every year the facility is under operation.

$$C4 = \sum_{t' \in T} \left[\sum_{mc} V_{mc,t'} \cdot \sum_{t}^{t'} Y_{mc,t} + \sum_{dc} V_{dc,t'} \cdot \sum_{t}^{t'} V_{cc,t} + \sum_{fc} V_{fc,t'} \cdot \sum_{t}^{t'} Y_{fc,t} + \sum_{rc} V_{rc,t'} \cdot \sum_{t}^{t'} Y_{rc,t} \right]$$

v. Total shortage cost

This is the sum of the per unit penalty for not meeting the demand multiplied by the amount of shortage for each product, both for primary and secondary customers.

$$C5 = \sum_{t} \sum_{p} \left[\sum_{b} J_{b,t}^{p} \ . \ Shortage_{b,t}^{p} + \sum_{g} J_{g,t}^{p} \ . \ Shortage_{g,t}^{p} \right]$$

vi. Total storage cost

This is the sum of product storage costs at warehouses and the collection centers (i.e. retail centers).

$$C6 = S_{t}^{p} . \left(\sum_{t} \sum_{p} \sum_{dc} I_{dc,t}^{p} + \sum_{t} \sum_{p} \sum_{b} \left(RI(u)_{b,t}^{p} + RI(f)_{b,t}^{p} + RI(m)_{b,t}^{p} + RI(r)_{b,t}^{p} \right) \right)$$

vii. Total disposal cost

This is the total cost of disposing the waste that are shipped to the collection center during all periods.

$$C7 = \sum_{t}\sum_{p}\sum_{cc}\sum_{w} X_{cc,w,t}^{p} \,.\, CW_{t}^{p}$$

viii. Total processing cost

This is the total cost of sorting and processing the returned products at all retail locations.

$$C8 = \sum_{t}\sum_{p}\sum_{b} RI_{b,t}^{p} \,.\, PC_{t}^{p}$$

ix. Total benefit from sales

This is the sum of the revenues made through selling products in primary and secondary markets during all periods.

$$B1 = \sum_{t}\sum_{p}\left[\sum_{dc}\sum_{b} X_{dc,b,t}^{p} \,.\, PP_{t}^{p} + \sum_{g}\sum_{b} X_{b,g,t}^{p} \,.\, SP_{t}^{p} + \sum_{fc}\sum_{g} X_{fc,g,t}^{p} \,.\, SP_{t}^{p}\right]$$

x. Total saving from recycling and remanufacturing

This is the sum of the number of remanufactured and recycled products multiplied by per unit saving made through remanufacturing and recycling.

$$B2 = \sum_{t}\sum_{p}\left[\sum_{mc}\sum_{b} X^{p}_{b,mc,t} \cdot\ S^{p}_{b,mc,t} + \sum_{rc}\sum_{b} X^{p}_{b,rc,t} \cdot S^{p}_{b,rc,t}\right]$$

xi. Objective function

The objective function maximizes the sum of all revenues minus the sum all costs (i.e. maximizes the total profit).

Maximize OBJ = B1 + B2 – (C1 + C2 + C3 + C4 + C5 + C6 + C7+C8)

Constraints

In the DRC model, half of the variables and parameters from the CRC model are changed and the other half are left unchanged; thus, all constraints for the model are listed below to avoid confusion.

$$(1)\ Z^{p}_{mc,t} \geq \sum_{dc} X^{p}_{mc,dc,t} \qquad \forall\, mc\ \in MC;\ \in P;\ t\ \in T$$

$$(2) \sum_{dc} X^{p}_{dc,b,t} + Shortage^{p}_{b,t}\ \geq\ D^{p}_{b,t} \qquad \forall\, b\ \in B;\ p\ \in P;\ t\ \in T$$

$$(3) \sum_{dc} X^{p}_{dc,b,t} \leq\ D^{p}_{b,t} \qquad \forall\, b\ \in B;\ \forall\, p\ \in P;\ \forall\, t\ \in T$$

$$(4)\ I^{p}_{dc,t} =\ I^{p}_{dc,t-1} + \sum_{mc} X^{p}_{mc,dc,t} - \sum_{b} X^{p}_{dc,b,t} \qquad \forall\, dc\ \in DC;\ p\ \in P;\ t\ \in T$$

$$(5)\ \varepsilon^{p}_{t} . \sum_{dc} X^{p}_{dc,\mathrm{b},t} =\ RI^{p}_{b,t} \qquad \forall\, b\ \in B;\ p \in P;\ t \in T$$

$$(6)\ IR(u)^{p}_{b,t} =\ IR(u)^{p}_{b,t-1} +\ u^{p}_{t} . RI^{p}_{b,t} - \sum_{g} X^{p}_{b,g,t} \qquad \forall\, b \in B; p\ \in P; t \in T$$

$$(7)\ IR(f)_{b,t}^{p} = IR(f)_{b,t-1}^{p} + f_t^p . RI_{b,t}^{p} - \sum_{fc} X_{b,fc,t}^{p} \qquad \forall\, b \in B; p \in P; t \in T$$

$$(8)\ IR(m)_{b,t}^{p} = IR(m)_{b,t-1}^{p} + m_t^p . RI_{b,t}^{p} - \sum_{mc} X_{b,mc,t}^{p} \qquad \forall\, b \in B; p \in P; t \in T$$

$$(9)\ IR(r)_{b,t}^{p} = IR(r)_{b,t-1}^{p} + r_t^p . RI_{b,t}^{p} - \sum_{rc} X_{b,rc,t}^{p} \qquad \forall\, b \in B; p \in P; t \in T$$

$$(10)\ k_t^p . RI_{b,t}^{p} = \sum_{w} X_{b,w,t}^{p} \qquad \forall\, b \in B; p \in P; t \in T$$

$$(11)\ \sum_{b} X_{b,g,t}^{p} + \sum_{fc} X_{fc,g,t}^{p} + Shortage_{g,t}^{p} \geq D_{g,t}^{p} \qquad \forall g \in G;\ p \in P;\ t \in T$$

$$(12)\ \sum_{b} X_{b,g,t}^{p} + \sum_{fc} X_{fc,g,t}^{p} \leq D_{g,t}^{p} \qquad \forall\, g \in G;\ p \in P;\ t \in T$$

$$(13)\ \sum_{t} Y_{mc,t} \leq 1 \qquad \forall\, mc \in MC$$

$$(14)\ \sum_{t} Y_{dc,t} \leq 1 \qquad \forall\, dc \in DC$$

$$(15)\ \sum_{t} Y_{fc,t} \leq 1 \qquad \forall\, fc \in FC$$

$$(16)\ \sum_{t} Y_{rc,t} \leq 1 \qquad \forall\, rc \in RC$$

$$(17)\ Z_{mc,t'}^{p} \leq \sum_{t}^{t'} Y_{mc,t} \ .\ L_{mc}^{p} \qquad \forall\, mc \in MC;\ p \in P;\ t' \in T$$

$$(18)\ \sum_{b} X_{rc,mc,t'}^{p} \leq \sum_{t}^{t'} Y_{mc,t} .\ L_{rmc}^{p} \qquad \forall\, mc \in MC;\ p \in P;\ t' \in T$$

$$(19)\ I_{dc,t'}^{p} \leq \sum_{t}^{t'} Y_{dc,t} \ .\ L_{dc}^{p} \qquad \forall\, dc \in DC;\ p \in P;\ t' \in T$$

$$(20) \sum_{b} X^{p}_{b,rc,t\prime} \leq \sum_{t}^{t\prime} Y_{rc,t} \ . \ L^{p}_{rc,t} \qquad \forall\, rc \in RC;\ p \in P;\ t' \in T$$

$$(21) \sum_{b} X^{p}_{b,fc,t} \leq \sum_{t}^{t'} Y_{fc,t} \,.\, L^{p}_{fc,t} \qquad \forall\, fc \in FC;\ p \in P;\ t' \in T$$

$$(22)\ X^{p}_{mc,dc,t}, X^{p}_{dc,b,t}, X^{p}_{b,fc,t}, X^{p}_{b,mc,t}, X^{p}_{b,rc,t}, X^{p}_{b,g,t}, X^{p}_{b,w,t}, X^{p}_{fc,g,t}$$

$$Z^{p}_{mc,t}, I^{p}_{dc,t}, RI^{p}_{b,t}, RI^{p}_{b,t}, RI(u)^{p}_{b,t}, RI(m)^{p}_{b,t}, RI(f)^{p}_{b,t}, RI(r)^{p}_{b,t} \in \quad Z^{+}$$

$$\forall\, mc \in MC, dc \in DC, fc \in FC, rc \in RC, b \in B, g \in G, p \in P, t \in T$$

$$(23)\ Y_{mc,t}, Y_{dc,t,}\, Y_{fc,t,}\ Y_{rc,t} \ \in \{0,1\}$$

$$\forall\, mc \in MC, dc \in DC, fc \in FC, rc \in RC, t \in T$$

The functions the constraints serve are very similar to those in the CRC model. However, a major difference is that the return center index (i.e. cc) has changed to the retail center index (i.e. b) and all constraints have changed accordingly. Also, the constraint that limits the number of CRC locations to one is removed, as there is no CRC in this model.

Chapter 5: Application and Results

The CRC and the DRC models were coded in Xpress Mosel version 3.2.0. Xpress Optimizer version 21.01.00 was used to solve the two networks. Xpress optimizer uses the branch and bound method to solve the integer programing problems.

The CRC model was applied to three different case studies with networks of various sizes. A reasonable size network with a reasonable solution time was then selected from the three problems to compare the performance of the CRC and DRC networks.

It is important to note that the data used in all case studies are synthesized and are not from real world case studies. This makes the result of these applications highly dependent on the assumptions made in the construction of the data. Therefore, sensitivity analysis should be performed on parameters that are believed to create major impacts on the output.

The following sections provide details of the application of the models to different case studies along with the sensitivity analysis for several model parameters. In all cases, an arbitrary company involved in production and some or all of the recovery processes including reuse, repair, remanufacture, and recycle is used as the basis to construct the data.

CRC model application

It is assumed that the company intends to build all of its logistics facilities within an area of 150 miles by 150 miles, where all customers are located. Table 1 shows the number of locations considered in each scenario along with the resulting number of variables and constraints. Also shown in the table is the time it takes for the solver to solve the problem. As shown, slightly increasing the size of the problem significantly increases the number of variables and constraints, and also significantly increases solution time.

Table 1. The relationship between problem sizes
and solution times in the CRC model

#	mc	dc	cc	fc	cc	b	g	w	np	nt	Var.	Const.	Time (sec)	Gap (%)
A	5	5	5	5	5	10	3	1	1	5	1,540	2,037	25.7	0
B	5	5	5	5	5	10	3	1	3	10	8,590	10,726	317.7	0.005
C	10	15	10	10	10	25	10	2	3	10	42,640	47,237	10516.8	0.009

** mc = number of candidate manufacturing locations, dc = number of candidate warehouse locations, cc = number of candidate CRC locations, fc = number of candidate repairing locations, rc = number of candidate recycling locations, b = number of primary customer locations, g = number of secondary customer locations, w = number of disposal locations, np = number of product types, nt = number of time periods.*

As an example, case study "B" is explained in more detail to demonstrate the performance of the CRC model. This case study is later also used to compare the performance of the CRC and the DRC models and to perform sensitivity analysis.

Figure 7 shows where the primary and secondary customers and landfills are located for the addressed case study. Also, the candidate facility locations are shown on the diagram. Table 2 shows some of the costs and prices used in the input data. Table 3 provides additional assumption made about products and product demands, as well as the product handling capacities at different facilities. Table 4 provides the fractions of products that we assume will be returned, as well as the portions of the returned products that go through different recovery processes (i.e. the recovery ratios).

Table 2.Input model parameters

Fixed Facility Cost	
Manufacturing Center	$2,000,000
Warehouse	$200,000
CRC	$500,000
Repair Center	$200,000
Recycling Center	$400,000
Recurrent Facility Maintenance Cost	
Manufacturing Center	$60,000
Warehouse	$6,000
CRC	$15,000
Repair Center	$6,000
Recycling Center	$12,000
Transportation Cost	¢0.3/mile/lb
Storage Cost	$1/lb
Disposal Cost	10% of Unit Production Cost
Processing Cost (DRC Model)	40% of Unit Production Cost
Saving From Recycling	30% of Unit Production Cost
Saving From Remanufacturing	70% of Unit Production Cost
New Product Price	400% of Unit Production Cost
Used Product Price	200% of Unit Production Cost
Repair Cost	40% of Used Product Price
Penalty for Unsatisfied Primary Demand	110% of New Product Price
Penalty for Unsatisfied Secondary Demand	105% of Used Product Price

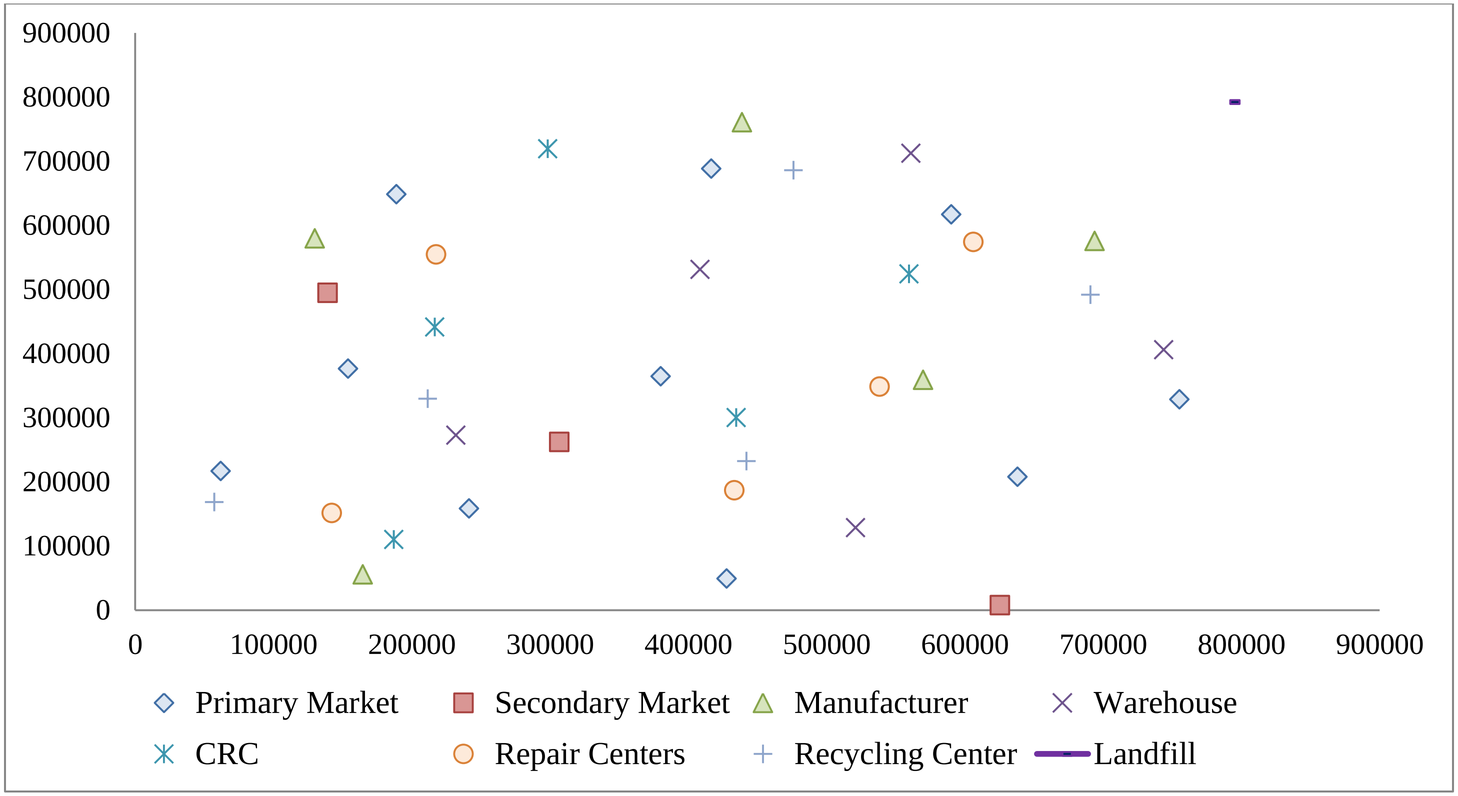


Figure 7. Customers and candidate facility locations for case study “B”

Note: Distances are in ft. (150 miles = 792,000 ft.)

Table 3. Product characteristics, demands and processing capacities

New Product Demand	u (3000,5000)
Used Product Demand	u (750,1000)
Product Weight	
Product 1	2 lb.
Product 2	4 lb.
Product 3	8 lb.
Capacity	
Production	25,000 units/facility
Remanufacturing	2,500 units/facility
Warehousing	25,000 units/facility
Repairing	2,500 units/facility
Recycling	2,500 units/facility

Table 4. Recovery ratios for case study "B"

Return Rate	10%
Direct Reuse	10%
repair	20%
Remanufacture	20%
Recycle	30%
Disposal	20%

Figure 8 shows the optimal numbers and locations for forward and reverse logistics facilities. As it can be seen, two manufacturing and two warehouse locations are selected for handling the forward flows. In the reverse network, there is one CRC location required by the model and one of each repairing and recycling facilities. Note that the return rate is only 10 percent, and no more facilities are needed to handle the returns.

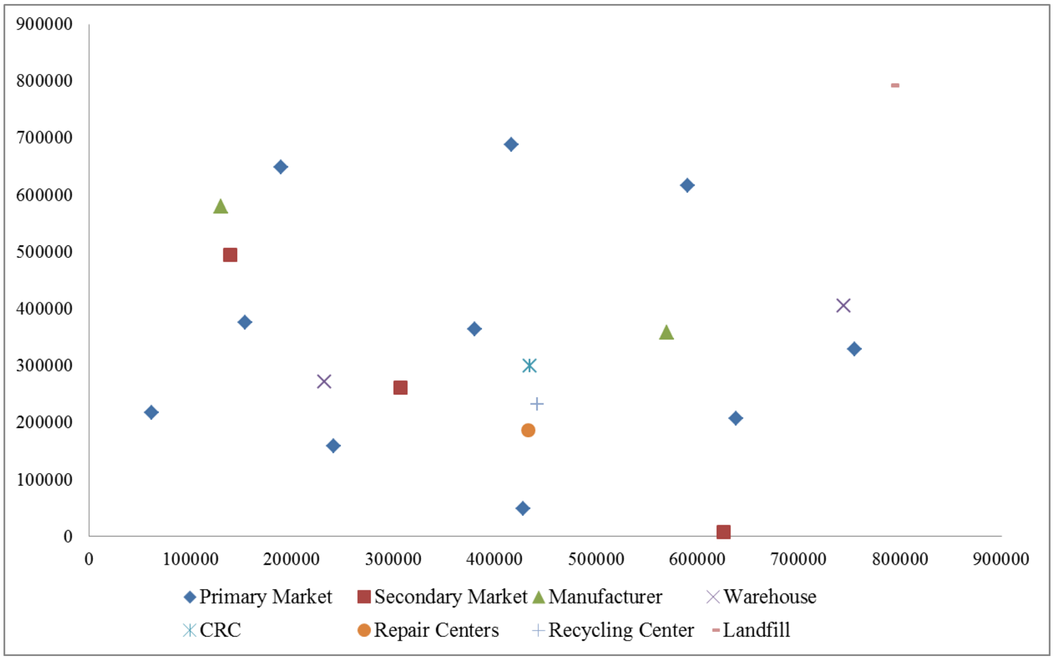


Figure 8. Solution for case study "B" under 10% return rate

Table 5 provides the total profit as well as all costs and revenues involved. All values represent the amounts for the whole study period of 10 years.

Table 5. Costs and revenues for case study "B"

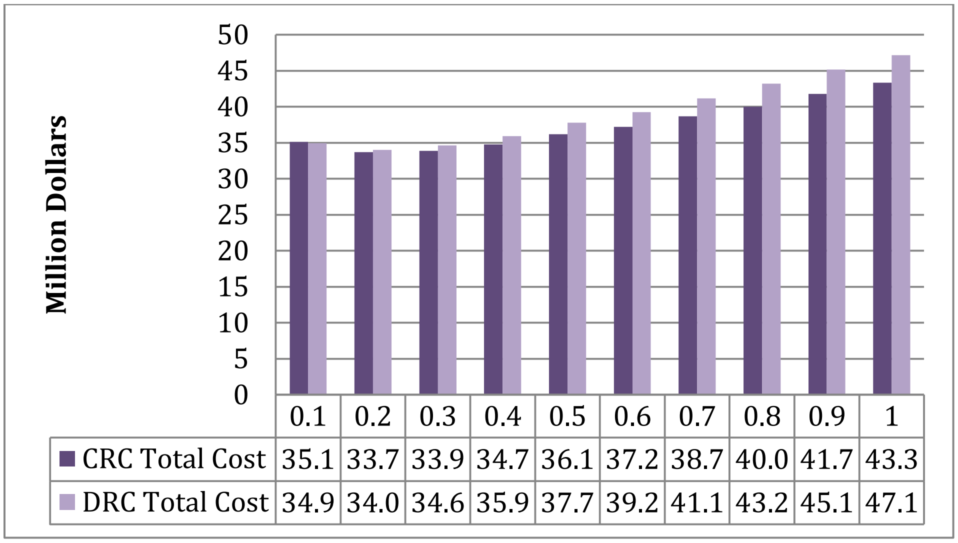
Total Profit	$65,410,490
Production Cost	$24,715,800
Transportation Cost	$782,620
Fixed Facility Cost	$5,500,000
Recurrent Maintenance Cost	$1,650,000
Storage Cost	$16,510
Shortage Cost	$2,396,920
Disposal Cost	$49,430
Primary Sales Revenue	$98,863,000
Secondary Sales revenue	$1,090,310
Saving from Remanufacturing	$346,020
Saving from Recycling	$222,440

Sensitivity of network performance to return ratio

The performances of the two models are compared in terms of total profit. The same demands for primary and secondary customers are used in the comparison and the penalties for not meeting the demands are set relatively high so that no primary customer demand is remained unsatisfied. This is done to ensure that the same number of units of product are produced and sold to the customers through the forward channel, in order for the comparison to be limited to the performance of the reverse channels only. In other words, the two networks are forced to yield equal revenues and production costs so that the costs that are relevant to the network structure can be compared for the same levels of production and product recovery.

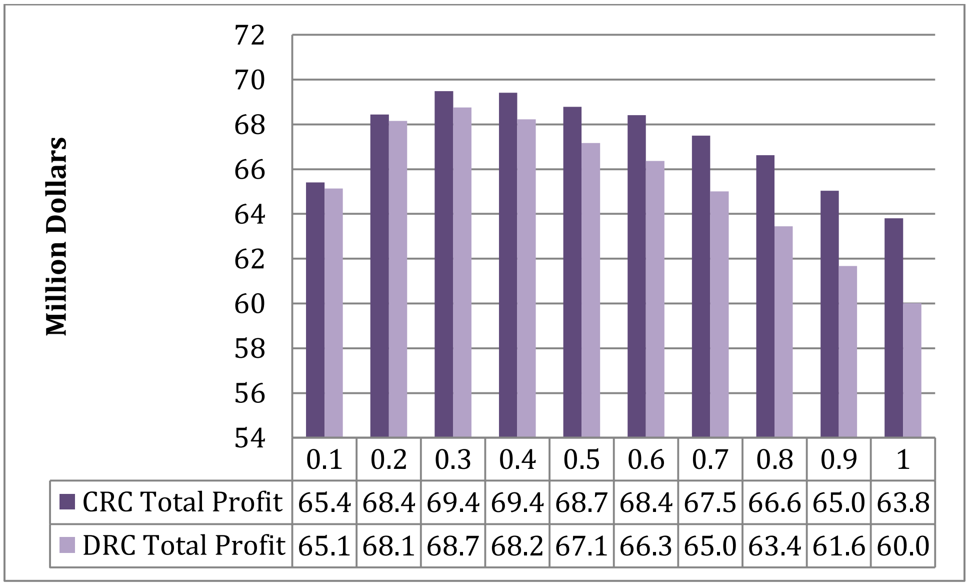
The two models are then tested for various rates of returns to analyze the sensitivity of profit to return rates and to compare the performance of the models under different levels of product return. The rates considered in this analysis start at 10 percent and increase by 10 percent increments up to 100 percent, which is the extreme and highly improbable case in which there are as many items returned as sold. Note that the highest return rate in the literature was a 70 percent return rate for the paper recycling industry in Europe, used by Fleischman et al. (2001).

Figures 9 and 10 show the total costs and profits for both CRC and DRC networks, respectively. The x-axis shows the return rate and the y-axis shows the according monetary values in million dollars for the whole study period (i.e. 10 years). As can be seen in Figure 9, total network costs follow the same trend in both networks and mostly increase as the return rate increases. What is more interesting is that the cost for the DRC network is higher than for the CRC network at all rates, except at the 10 percent rate where the two networks have almost equal costs. The difference in the costs becomes more significant as more products are returned.



	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
■ CRC Total Cost	35.1	33.7	33.9	34.7	36.1	37.2	38.7	40.0	41.7	43.3
■ DRC Total Cost	34.9	34.0	34.6	35.9	37.7	39.2	41.1	43.2	45.1	47.1

Figure 9. Total cost for CRC and DRC networks under various return rates



	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
■ CRC Total Profit	65.4	68.4	69.4	69.4	68.7	68.4	67.5	66.6	65.0	63.8
■ DRC Total Profit	65.1	68.1	68.7	68.2	67.1	66.3	65.0	63.4	61.6	60.0

Figure 10. Total profit for CRC and DRC networks under various return rates

Likewise, as can be seen in Figure 10, the profits for both networks follow a similar trend and hit their maximum profit at approximately 30 percent return rate.

Note that the CRC network produces higher profit amounts in all cases and the difference in profit becomes more significant as return rate increases. On average, the CRC network increases profit by approximately 3 percent.

A closer investigation of the results reveals an interesting point about the trend in the output. Figure 11 and 12 show the breakdown of costs and revenues for the CRC model. The x-axis shows the return rates and the y-axis shows the according values in dollars.

At the return rate of 40 percent, the shortage cost suddenly drops down to zero because there are more returned items that could be sold in the secondary market than the actual demand for them. This results in a big fraction of the returned products to be stacked at the return center (in the CRC model) or at the retailers (in the DRC model), for which storage costs should be paid. In the case of the DRC model, an additional cost is incurred to process and sort the returned items for which no revenue is gained. This suggests that the maximum profit does not necessarily occur at the 30 percent return rate and in fact may depend on the demand for used items.

It is important to keep in mind that a significant fraction of the revenue is made through selling new products in the primary market and used products in the secondary market. Due to the assumptions that a) new products are sold at a much higher price than used products, and b) demand for new products is greater than the demand for used products, the sales of new products account for a considerable portion of total revenue, suggesting that product recovery may not be profitable by itself, unless the savings and revenues gained through product recovery are great enough to make up for the cost of establishing and maintaining the reverse channel facilities.

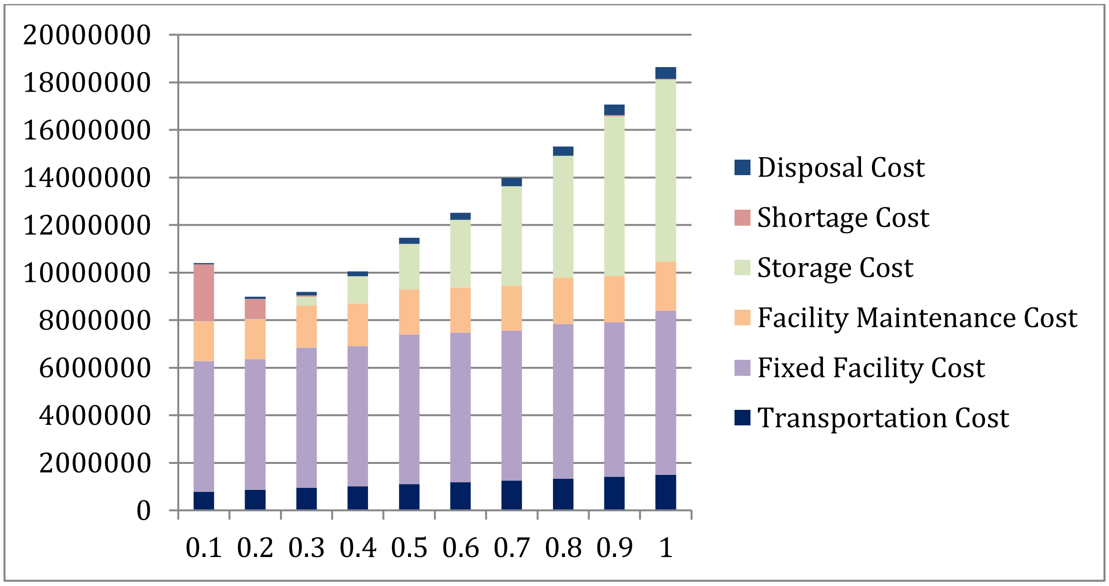


Figure 11. Breakdown of costs for CRC model in case study “B”

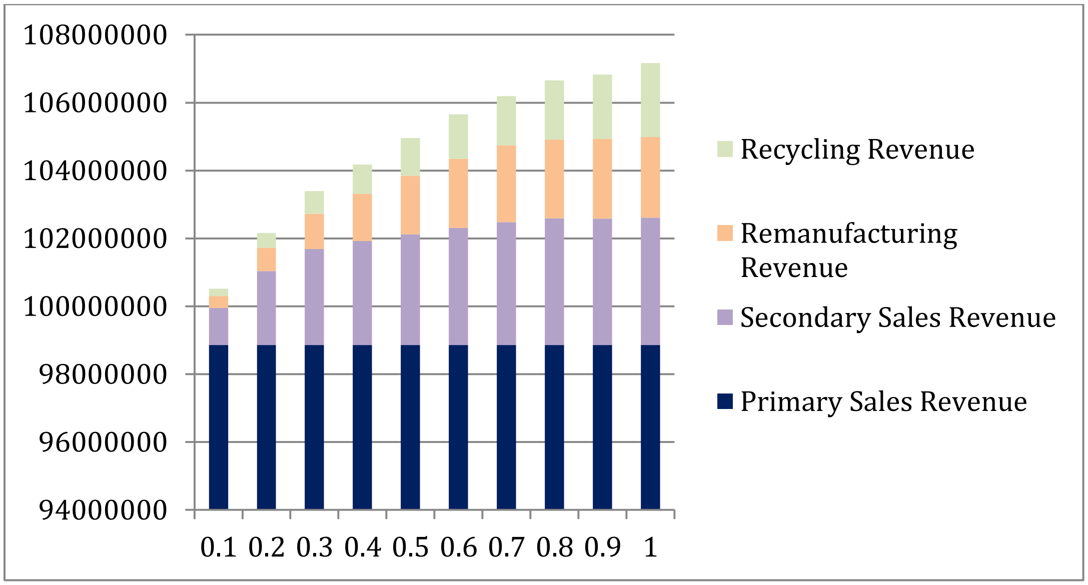


Figure 12. Breakdown of revenues for CRC model in case study “B”

Sensitivity of network performance to recovery ratios

It is hypothesized that the amount of revenue earned through product recovery is affected by how much profit is actually gained through each type of recovery process. In other words, the amount of revenue depends on how much product goes through each recovery process. For instance, in constructing the data for the discussed case studies, as shown in Table 2, it is assumed that among direct reusing, repairing, remanufacturing and recycling, direct reusing yields the most profit and recycling yields the least. Also, the fractions of returned products that go through different recovery processes may vary from one industry to another. In order to study the effects of these ratios on overall profitability of the two networks, sensitivity analysis should be performed on different combinations of these ratios.

In addition to the base case discussed in the previous section, three additional case studies are examined to compare the performance of the CRC and DRC networks. Since the recovery ratios are inter related and must sum to 100 percent, it is not possible to perform sensitivity analysis on each ratio independently. Moreover, not every ratio represents a real world scenario. In the construction of these case studies, it is attempted to represent different situations that might happen in reality. For instance, alternative “B” (i.e. the base case study) may represent items that do not use highly advanced technology and last long and are thus likely to be reused directly or after repair at an average level of probability. Alternative “D” represents items only reusable after repair (though at a low level of probability) and qualify mainly for remanufacturing or recycling. Alternative “E” represents items for which there is no demand in the secondary market and cannot be reused directly or after repairing. However, returned items may qualify for remanufacturing or recycling. Alternative “F” represents highly reusable items, either directly or after fixing and repairing, or recycling, but no remanufacturing may be done on them. Packaging materials are good example of such items. Of course in all cases, a considerable fraction of the returned items may have to be disposed directly. Table 6 presents the different recovery ratios used in these case studies. All other parameters are the same across the case studies to limit the comparison to the impacts that these ratios may have on the outcome.

Table 6. Ratios of different recovery processes for case studies

Case Study	Reuse	Repair	Remanufacture	Recycle	Dispose
B	10%	20%	20%	30%	20%
D	0	10%	20%	40%	30%
E	0	0%	30%	40%	30%
F	30%	30%	0	30%	10%

The performance of CRC and DRC models for case study “B” have already been discussed in the previous section. Figures 13, 14, and 15 show total profits made by the two networks in case studies “D”, “E”, and “F,” respectively. The x-axis represents the return rate and the y-axis represents total profit in million dollars for the whole study period.

It can be seen in Figure 13 that for case study “D”, the profit increases for both networks as return rate increases. Except for the 10 percent return rate, the CRC model results in more profit at all return rates. In fact, the CRC model results in approximately 2 percent increase in profit on average. Similar to case study “B”, the difference in total profits becomes more significant at higher return ratios. However, unlike case “B”, the profits keep increasing as return rates increase. This is due to removing direct reuse and lowering the repairing ratios, which results in a shortfall in meeting the demand for used products in the secondary market. Therefore, the more that is returned, the more profit is gained through sales of products in the secondary market.

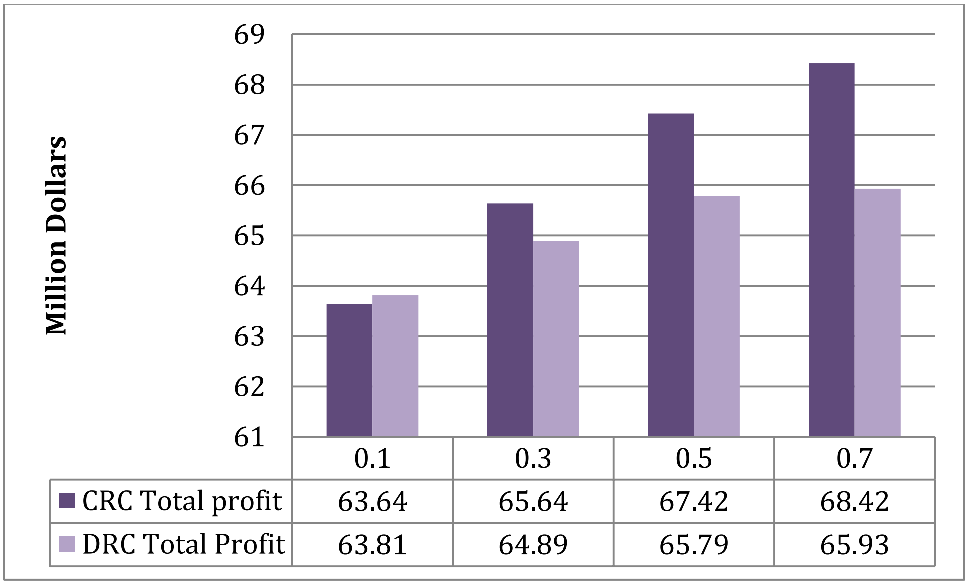
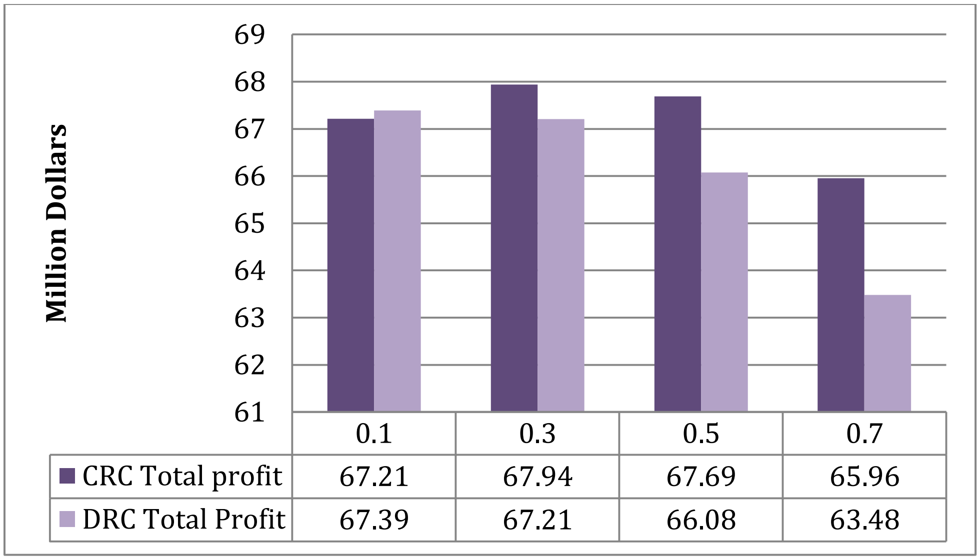


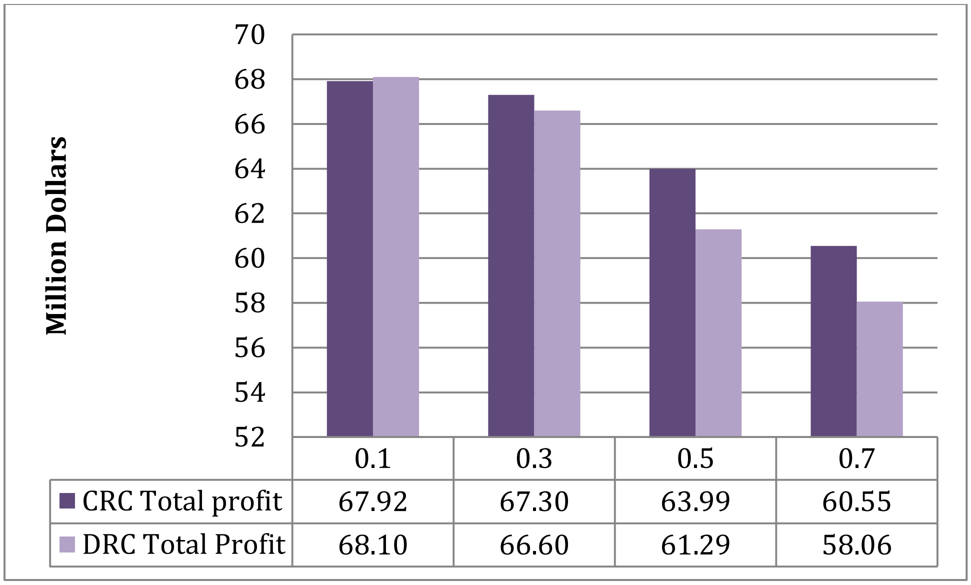
Figure 13. Case study “D”: Total profit for CRC and DRC networks



	0.1	0.3	0.5	0.7
■ CRC Total profit	67.21	67.94	67.69	65.96
■ DRC Total Profit	67.39	67.21	66.08	63.48

Figure 14. Case study “E”: Total profit for CRC and DRC networks

Case study “E” shows that the CRC model results in higher profit at almost all return rates, except for the 10 percent return rate. On average, approximately 2 percent more profit is gained by using CRC. It should be reiterated that for this case study, it was assumed that the product cannot be reused or repaired and thus, demands for the used products in the secondary market were set to zero. Therefore, no shortage costs or additional storage costs for overstocked return items are incurred. Therefore, the declining trend in total profit as return rates increase highlights the notion that the profitability of product recovery comes from secondary market sales to a large extent and when that is removed from the system, product recovery might start to become detrimental to the company as more products are returned.



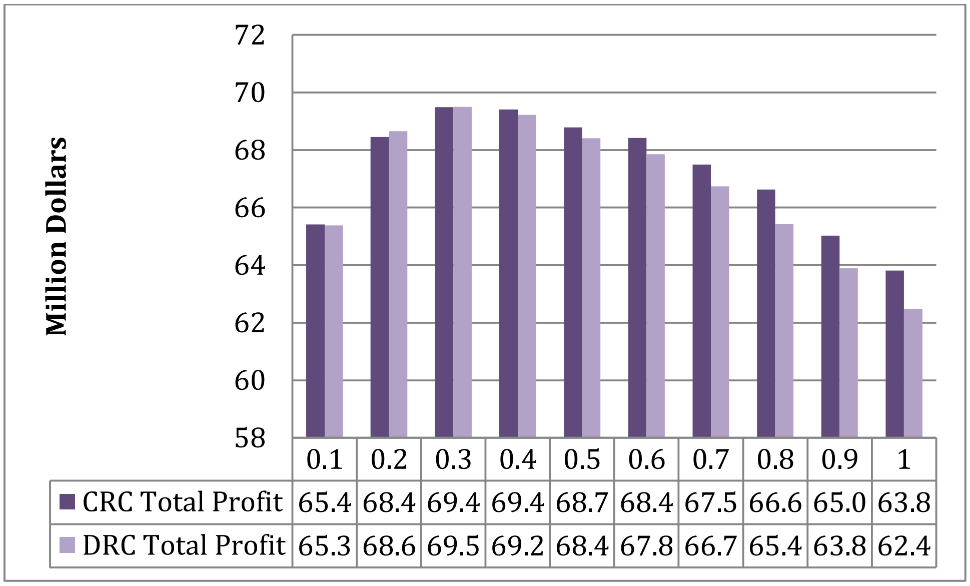
	0.1	0.3	0.5	0.7
■ CRC Total profit	67.92	67.30	63.99	60.55
■ DRC Total Profit	68.10	66.60	61.29	58.06

Figure 15. Case study "F": Total profit for CRC and DRC networks

Case study "F" represents the case in which a big portion of the returned products is reused either directly or indirectly. On average, the CRC model results in approximately 2.5 percent increase in profit. Again in this case, at return rate of 50 percent, more reusable products are returned than demanded in the secondary market, resulting in the high storage costs for stocked items. Therefore, although compared to other case studies, higher amounts of profit are observed at 10 percent and 30 percent, profit drops down drastically with an overstocking of reusable items at higher return rates.

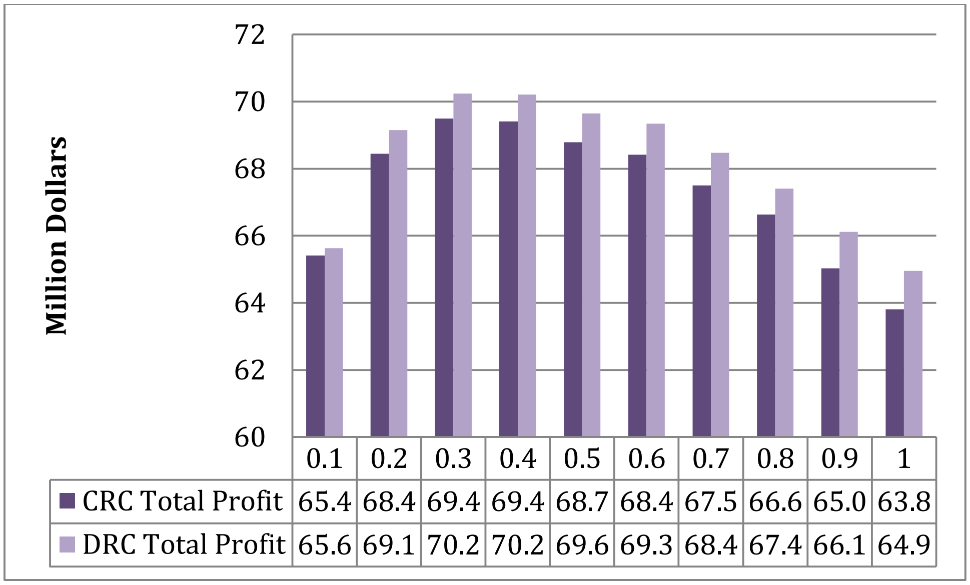
<u>Sensitivity of performance DRC network over CRC to processing cost</u>

Figure 10 showed the superior performance of CRC over DRC design for case study "B". The difference in CRC and DRC network costs is caused partially by the differences in the cost of transportation and network facilities, and partially by the additional cost that we assume will be incurred at retail centers for processing the returned items. While it is reasonable to include additional processing costs in the DRC model to account for lower efficiency and consistency in handling the returns, it is important to also investigate the extent to which this additional cost may affect the results. Figure 10 showed that the CRC model yields greater profits at all return ratios, assuming the unit processing cost to be 40 percent of the unit production cost. Of course this is just an assumption and does not necessarily reflect the real world cases. Figures 16 and 17 may be used as references in order to understand how the choice of this parameter affects the outcome.



	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
■ CRC Total Profit	65.4	68.4	69.4	69.4	68.7	68.4	67.5	66.6	65.0	63.8
■ DRC Total Profit	65.3	68.6	69.5	69.2	68.4	67.8	66.7	65.4	63.8	62.4

Figure 16. Total profit after 50 percent reduction in processing costs



	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
■ CRC Total Profit	65.4	68.4	69.4	69.4	68.7	68.4	67.5	66.6	65.0	63.8
■ DRC Total Profit	65.6	69.1	70.2	70.2	69.6	69.3	68.4	67.4	66.1	64.9

Figure 17. Total profit after 100% reduction in processing costs

The graphs in Figures 16 and 17 are prepared after reducing the processing cost by 50 percent and 100 percent respectively. Results show that after a 50 percent reduction, the CRC model still performs slightly better than DRC. However, if processing costs are completely removed, the DRC model becomes more profitable. This suggests that improving processing and handling of returns at collection points may remove the need for CRC.

Sensitivity of network structure to centralization of return facilities

It is important to investigate whether centralized return centers affect the structure of the forward and reverse logistics networks. In other words, do the two models select the same locations as the optimal facility locations or they result in different network structures?

Case studies “B” and “C” are used to perform the network structure analysis on networks with different sizes. Case study “A” is not considered in this analysis, because the size of the problem in terms of the number of candidate facilities is similar to case study “B”. The two cases are modeled by both CRC and DRC and under the return rate of 30 percent. All other model parameters are kept the same, as discussed in the previous sections.

Not surprisingly, the two models result in highly dissimilar network structures in both cases. In case study “B”, the forward channels comprised of the manufacturing and warehouse locations turn out to be identical in terms of number and location of the facilities for both models. However, the two models create dissimilar reverse networks. The reverse networks are similar in terms of the number of repair and recycling facilities, but different in terms of the location of these facilities. Both networks use two factories and two warehouses at the same locations, as well as one repair facility and two recycling facilities at different locations.

In case study “C”, the situation becomes different as the network grows in size. The forward networks also turn out different in structure. Both networks have three factories at different locations, and the CRC network has five warehouses, while DRC network has eight. The two reverse networks are similar in terms of the number of repair and recycling facilities, but they are different in terms of the location of these facilities. Both networks use three repair facilities and three recycling facilities at different locations.

Chapter 6: Summary and Discussion

According to statistics, logistics activities account for a considerable portion of the economy in the U.S. and around the globe. As environmental concerns grow fast among nations, product recovery has become a necessity for logistics providers. Although product recovery and recycling in its broad sense has already been around and practiced in some industries, there has not yet been a consensus on how a product recovery network should be designed for maximum efficiency.

This document attempts to provide a general framework for modeling an integrated forward and reverse logistics network for the industries involved in product manufacturing and recovery. An attempt is made to consider and include as many general recovery processes so as to increase model applicability to various industries. In addition, this thesis contributes to the existing literature by providing an assessment of the performance of centralized return center (CRC) compared to the conventional decentralized return centers. Recent studies suggest that CRCs result in significant savings, and big companies are starting to incorporate CRCs into their logistics networks. However, no supporting evidence was found in the literature.

Two optimizations models are developed to configure the optimum location for logistics network facilities. One of the models follows the concept of centralized return center and is referred to as the CRC model. The other model follows a conventional approach, using retail centers as collection points for returned products and is referred to as the DRC model.

The performance and structure of the two network models are compared for several different scenarios, and sensitivity of the profitability of the models to various model parameters are tested.

The findings suggest that on average, CRC model results in approximately a two percent to three percent increase in profitability when compared to the DRC model. It was found that the two networks perform similarly when product return rates are not high, and the difference in profitability becomes more significant as more products are returned. The findings also suggest that the profitability of the two networks not only depends on return ratios, but also on other recovery (i.e. disposition) ratios.

Another important finding is the impact of centralization of the return centers on network structure. It was found that centralization affects not only the structure of reverse channels, but also the structure of the forward channel as the two channels are highly integrated and share some of their facilities.

It is important to keep in mind the underlying assumption about the CRC in this analysis, which is that the returns are processed faster and more efficiently at the CRC than at the conventional return centers, creating a gain in savings during processing and handling of the products. In all studied cases, transportation costs slightly increased for the CRC network. However, the additional processing charge in the DRC network was still greater than the additional transportation cost of the CRC network, hence the profitability of the CRC over the DRC model. In fact, as also discussed in Chapter 5, the extent to which CRCs succeed in providing savings in labor and space determines the superiority of one model over the other.

Clearly, the proposed models can be improved in several ways in order to better reflect and highlight the difference in performance of the two models. The following section provides several recommendations for future research.

Model limitations and recommendations for future work

The proposed models are based on the assumption that all returned products are collected. However, in reality, different return policies may exist on different products. Government regulations and obligations could also impact the producer's return collection strategies. Therefore, various return policies may be incorporated in the models to investigate the effect of product recovery on profitability and structure of the network in a more realistic manner.

The proposed models are based on the assumptions that demands and returns for all products are known at all times. This assumption simplifies the problem to a large extent and may not represent realistic conditions. Incorporating uncertainty in product demand and return provides a better representation of the real world scenarios.

Another simplifying assumption in the modeling is the assumption that the quality and the state in which products are returned are known beforehand. In reality, products are returned with varying levels of damage and wear that only become known after they arrived at the return centers. Therefore, assuming deterministic ratios for different recovery processes may not be very realistic. In the presence of historic data, estimations may be made about these ratios. However, in absence of data, it is advised to incorporate uncertainty in quality of returned products.

This analysis overlooks the fraction of product returns that result from customer dissatisfaction with the product and/or the product not meeting the buyer's expectations. In these cases, the product re-enters the network and the purchase is fully or partially refunded. Also, several companies compensate customers for the returned products, especially products that are reusable, such as bottles and containers, highly recyclable such as paper, or remanufacturable such as smartphones and other electronics. In fact, whether the company compensates the returns may increase the costs in the short run. However, over the long run, the company may experience more savings in production and raw materials by attracting more returns. Moreover, improved customer service and return policies may increase future sales and revenues. Therefore, the model would better represent the reality if compensating the returns is considered and if product demands and return ratios are considered functions of the compensation amount and return policies.

Another limitation of the proposed models comes from the assumption of fixed capacities for the logistics facilities. As a result, when additional products enter the network, new facilities are established to handle the excess shipments. Establishing additional facilities may be a good solution in many cases. However, in some instances, it might be more economical to allow for expanding the capacity of the existing facilities instead of establishing whole new facilities, which might result in a large unused capacity. Therefore, allowing for facility expansion in the model could possibly improve space and capacity utilization and lower facility costs.

Lastly, it is important to note that comparison of the CRC and the DRC models in this thesis is performed at a planning level, which focuses on facility locations and network structure. The difference in the performance of the two models might become more significant at an operational level, when timeliness of the product delivery and collection becomes a major priority. It is at the operational level that one of the major benefits of CRC becomes highlighted. Specifically, it occurs when returned items can be consolidated in larger shipments and sent to their destinations at lower cost and with shorter delivery times. Although additional processing cost considered in this study accounts for these savings to some extent, the analysis becomes more realistic if done at a more detailed level.

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