Generic Models for the Integrated Design of Domestic and Global Supply Chain Networks with Remanufacturing

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ABSTRACT

Generic Models for the Integrated Design of Domestic and
Global Supply Chain Networks with Remanufacturing

Tieshan Wang

This research focuses on the modeling of strategic supply chain network design. Several comprehensive mixed-integer-programming models are developed for the strategic integrated design of domestic and global supply chain networks with remanufacturing capacity. The models allow simultaneous determination of supplier selection, manufacturing and distribution facility selection and allocation, production quantities, transportation flows, reverse distribution facility selection, and disassembly plant allocation. Additionally, our models incorporate bill of material (BOM) both in the manufacturing process and in disassembly process. Management policies are also considered in the model formulation so that specific management choices, such as multi-sourcing strategy or single sourcing strategy, can be fulfilled in the strategic supply chain network design. Global factors considered in the model include currency exchange rates, transfer prices, allocation of transportation costs, local content requirements, local income taxes, and tariffs. The models are verified by medium-sized numerical examples.

Compared to previous literature, the proposed models have two distinctive features. First, the corresponding integrated logistics problem of a global supply chain is formulated with a generalized mathematical form, and thus is not limited to applications for specific industries. Such a methodological measure is rare in previous literature, and has exhibited its potential advantages in addressing complicated global supply chain problems. Second, remanufacturing factors oriented from the enforcement of corresponding governmental regulations for environmental protection are considered in the proposed model. Thus, the corresponding effects may help to determine solution alternatives to improve the performance of a global supply chain with remanufacturing capacity.

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Chapter 1

Introduction

1.1. Remanufacturing

Remanufacturing is a process in which a used product or parts of the product are restored to like-new condition. The process involves disassembling the used product which called a "core" down to its constituent used parts. The parts will be cleaned, tested, sometimes repaired to make them fully functional like new. Some of the parts that cannot be restored or not worth to be restored will be scrapped. Then the restored parts along with new parts will be used to rebuild the product. Many firms among them General Electric, Caterpillar, Lockheed Martin, Pitney Bowes, and Cummins Engine have recognized that there are significant business opportunities in the market for remanufactured goods. In 1996, a research found that an estimated 73,000 firms in the U.S. are involved in remanufacturing, account for over $53 billion in sales and employing a half-million people (Lund 1996).

There are two primary factors that drive the growth of the remanufacturing industry. The number one reason is the cost of remanufactured goods is much lower than the traditionally manufactured goods, so the manufacturers can gain competitiveness in the market by lowering the sale prices of their products. Lund (1984) provides early research on remanufacturing demonstrating its financial and environmental benefits. Remanufacturing is profitable and efficient when a large fraction of materials used in a product, and the value added to it when it is made, can be recovered at a low cost compared with that of the original manufacture.

The second factor is the positive impact on the environment. In the age of increasing environmental awareness, governmental and consumer pressure have induced companies to consider carefully the environmental impacts of their products as well as their processes. This has become particularly evident in Europe in the form of environmental legislations. In the United States, environmental regulations have put increasing pressure on industries to reduce waste disposal. Companies are increasingly being held responsible for their products throughout their life cycle.

A research estimated worldwide energy savings of current remanufacturing in lieu of building new products is about 400 trillion BTUs of energy annually, which is equivalent of about 96 million barrels of crude oil, or enough gasoline to run 6 million cars for a year. Based on this estimate, remanufacturing avoids the generation of about 28 million tons of CO_2 annually, roughly the output of ten 500-megawatt coal-burning electrical plants.

Regardless of the driver, whether government regulations, consumer pressure, or economic advantages, remanufacturing has become part of many companies' long term strategy, gaining more momentum in many industries.

1.2. Supply Chain

A supply chain is the entire structure of key business activities undertaken by an enterprise, from procurement of raw material to the distribution of final products to customers. The supply chain is organized and managed with the goal of minimizing the overall cost while maintaining a satisfactory service level by providing the customers the right product in the right quality at the right time for the right price.

The current globalization of the economy is the driver for designing and managing efficient global supply chain, which contribute to the enterprise's competitive advantage. This competitive advantage is reflected by different business parameters such as product quality and cost, response time, as well as service cost and level, among other key performance indicators.

According to Simchi-Levi et al (2000), business enterprises have been forced to invest in and focus on their supply chains due to "fierce competition in today's global markets, the introduction of products with short life cycles, and the heightened expectations of customers." Simchi-Levi et al (2000) also interpret supply chain management as the next step to increase profit and market share from the 1980s manufacturing management technologies such as just-in-time (JIT), kanban, lean manufacturing and total quality control. From this interpretation, we observe that competition has forced enterprises first to improve internal processes at the plant level and then later to expand to the level of the entire enterprise. Now supply chain management has a much broader scope: integrating internal and external processes given in a supply chain network formed by multi-level suppliers, manufacturing/assembly plants, warehouses, distribution centers, retail outlets, and customers.

An example of a supply chain network is presented in Figure 1.1. As it can be observed, the complexity of a supply chain significantly increases as a function of levels in the supply chain, the number of production facilities and the product variety. In Figure 1.1, nodes represent facilities, while links represent transportation of components and products between facilities. The raw material, components and finished products flow throughout the supply chain network.

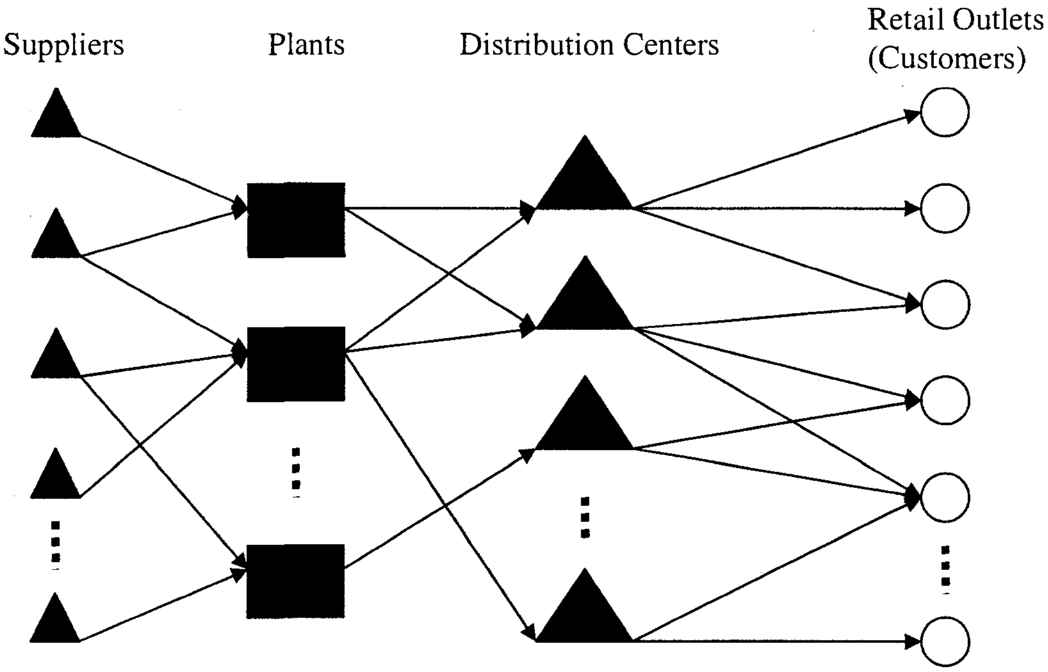


Figure 1.1. Typical Supply Chain Network

Typically, the decisions to be made in supply chain optimization can be categorized into three categories based on the horizons of their effects. They are strategic, tactical, and operational level decisions. The strategic decisions involve determining the number and location of facilities. Manufacturing plants, warehouses, and distribution centers may take several years to construct with significant investments and have a useful life of several decades. Consequently, strategic decisions have the most significant and lasting impact on the structure of supply chain and survival of a company. The tactical decisions are concerned with production and distribution network operating decisions such as transportation policies, and usually made yearly or quarterly. The decisions such as scheduling that are required to be made on a daily basis are the operational level decisions.

Our research is aimed at a strategic level issue: supply chain network design. An optimized supply chain network can lead to significant savings for the company by determining the least cost or most efficient supply chain strategy, including optimal facility locations, production capacity, and product mixing, etc.

1.3. Global Supply Chain Network Design

Based on the countries accessed by a supply chain, supply chain can be categorized into domestic and global supply chain. A domestic supply chain is a supply chain network where all of its members are located inside the borders of a single country.

A global supply chain is more complicated than domestic supply chain because international firms face issues like tariffs, currency exchange, tax zones, and economical grouping among nations. These are issues that cannot be considered in single-country models.

In a global supply chain, the company has to pay tariffs or export taxes for transporting goods cross borders, and currency exchange rate has to be used. A tariff is an import duty that assigns a fixed monetary tax per physical unit of good imported. An export tax is levied on home-produced goods that are destined for export and not for home consumption. Both tariff and export rates differ by country and type of goods. The currency exchange rate is the price of one currency in terms of another.

There are economic grouping among nations. The NAFTA (North American Free Trade Agreement) which was implemented in 1994 is a free trade agreement among the United States, Mexico, and Canada. The European Union is an integration for economical and political cooperation among its member countries. APEC (Asia-Pacific Economic Cooperation) which was established in 1989 is a group promoting open trade and practical economical cooperation among twenty-one member countries. These types of formations change the way trade takes place in the world.

There are many reasons that firms set up facilities in different countries and economical regions. Among them, the following are most common: accessing to lower labor costs; proximity to market; use of advanced technological resources; lowering income tax rates.

Because of the additional issues that a multi-national company has to face, the global supply chain network design is more complicated than domestic network, especially when remanufacturing is involved in the supply chain. Effective strategic planning and decision making is the key to the success of a global company.

1.4. Thesis Overview

The basic motivation of this research is to help multinational companies analyze and make strategic decisions about their forward and reverse supply chain networks and their interactions in the global business environment. The global factors and the reverse logistics for remanufacturing significantly increase the complexity of the supply chain structures. In order to support this decision making process, strategic supply chain network design models are developed in this thesis.

Two supply chain design models with remanufacturing capacities are developed in this thesis: one for domestic supply chain, one for multi-national supply chain. The objective of these models is to maximize the after-tax profitability of the corporation. The decisions considered in the models include:

1) Given a set of alternative locations and capacities, where to build the facilities;
2) Given a set of alternative market zones with demands, where to open the retail outlets;
3) Given a set of suppliers with capacities and costs of material and freight, which suppliers to buy from;
4) Given a set of alternative remanufacturing and processing facility locations, where to open them;
5) Given the options of new parts and remanufactured parts, which and how many to use;
6) Given a set of alternative used products and recoverable parts, which products and parts will be recovered.

In Chapter 2, the relevant literature is reviewed and discussed. Literature that pertains to "global supply chain network design model with remanufacturing" can be categorized into the following topics: remanufacturing, domestic supply chain modeling, international supply chain models, and supply chain models with reverse logistics and remanufacturing. This review is intended to provide information on the state of the art, determine what is lacking, and clarify the differences and similarities between the work in this thesis and the existing literature.

In Chapter 3, a mathematical model for a domestic supply chain design with remanufacturing capacity is developed. This design problem is defined on a network where the set of facilities correspond to the vertex set and the set of transportation channels correspond to the arc set. The problem consists of choosing the facilities to be opened such that: all customer demand can be met, total production does not exceed the capacity of the open facilities, the transportation does not exceed the capacity of the channels, and the total fixed cost and variable cost is minimized. The open-or-close decisions for the facilities are 0-1 binary decision variables and the production and transportation flow decisions are continuous decision variables. Consequently, this problem is a binary mixed integer linear programming problem.

In Chapter 4, a global supply chain design model with remanufacturing consideration is presented. The complexity of the model for designing global supply chain with remanufacturing is caused by the size of the problem, which is typically very large. In addition, the complexity is also caused by the international trading factors, such as taxes and duties, and regional protection trade barriers. The key differences between the global supply chain design and the domestic supply chain design models are the inclusion of global factors and the complexity of the problem.

Finally, in Chapter 5, conclusions are drawn and discussed, and suggestions for future research are presented.

Chapter 2

Literature Review

In this Chapter, the relevant literature is discussed. Literature that pertains to 'global supply chain network design model with remanufacturing' can be categorized into the following topics: remanufacturing, domestic supply chain modeling, international supply chain models, and supply chain models with reverse logistics and remanufacturing. This review is intended to provide information on the state of the art, determine what is lacking, and clarify the differences and similarities between the work in this thesis and the existing literature.

Section 2.1 reviews the area of remanufacturing, while section 2.2 covers domestic supply chain modeling. Section 2.3 covers the area of international supply chain models, and Section 2.4 overviews supply chain models with reverse logistics and remanufacturing. Section 2.5 presents a summary and a general outlook on what exists and what is lacking in current literature, and what the research in this thesis adds to the current literature.

2.1. Remanufacturing Literature

Probably the best known literature on remanufacturing research has been authored by Robert Lund in the late 1970s and early 1980s, and recently in his 1996 book called "The Remanufacturing Industry: Hidden Giant". Lund has identified remanufacturing as an important part of the United States' economy that has been largely overlooked by the general public. Remanufacturing, according to Lund, is a labor-intensive industry and an important source of training of people in industrial skills. He estimates the U.S. remanufacturing industry is a make of 73,000 firms with sales of $53 billion per year and direct employees of 500,000 people. Lund states that the largest sector of this industry is the automotive remanufacturing industry with sales of $36 billion per year (Lund, 1996).

Lund (1984) provides early research on remanufacturing demonstrating its financial and environmental benefits. Remanufacturing is profitable and efficient when a large fraction of materials used in a product, and the value added to it when it is made, can be recovered at a low cost compared with that of the original manufacture. Virtually any manufactured product, device, or mechanical system can be remanufactured. The major requirement is that the cost of salvaging the materials and the value added is much less than the market value of the remanufactured item. The range of commercial products identified by Lund as being remanufacturable is broad and be divided into four categories:

(1) Automotive. Replacement parts for automobile are the largest application of remanufacturing in the United States. These products range from simple starter solenoids to complete diesel engines.

(2) Industrial Equipment. These products include process valves, hydraulic equipment, heavy-duty diesel engines, production machinery, and oil-drilling equipment.

(3) Commercial Products. There products include office equipment, compressors for commercial refrigerators, vending machines, copiers, computers, and communication equipment.

(4) Residential Products. These products include kitchen appliances, power tools and gardening equipment.

Kerr and Ryan (2001) used Life-Cycle Analysis to compare the environmental impacts between a remanufactured and a non-remanufactured Xerox photocopier. They calculated material consumption, energy consumption, water consumption and green house gas emissions between the two products. Their findings demonstrated that the remanufactured photocopier can reduce resource consumption and waste generation by a factor of 3.

Giuntini and Gaudette (2003) estimated worldwide energy savings of current remanufacturing in lieu of building new products is an incredible 400 trillion BTUs of energy annually, which is equivalent of about 96 million barrels of crude oil, or enough gasoline to run 6 million cars for a year. Based on this estimate, remanufacturing avoids the generation of about 28 million tons of CO_2 annually, roughly the output of ten 500-megawatt coal-burning electrical plants. The authors also estimated that the savings in raw materials is equally compelling-the materials saved would fill 155,000 railway cars in a train spanning 1,100 miles.

2.2. Domestic Supply Chain Modeling

Formulating, and optimizing complex systems for integrated manufacturing and distribution systems have been a concern of many researchers who have modeled and analyzed the supply chain. There are several key papers in the modeling area. Different objectives are addressed in each paper, from efficiency to coordination. All of the approaches are built upon different models, many of Linear Programming (LP) or Mixed Integer Linear Programming structure. The researches achieve results such as cost savings or reduction in the number of facilities.

Chandra and Fisher (1994) conduct research on determining the value of coordinating production and distribution planning. Their multi-period model has production facilities, distribution centers, and customers. They consider setup, transportation and inventory costs, production capacity and vehicle capacity constraints. A local improvement heuristic is developed. They solve a large number of different problems by using both the coordinated approach and an uncoordinated one.

Dogan and Goetschalckx (1999) develop a multi-commodity, multi-stage production, multi-echelon, multi-period mixed integer programming model with piece-wise concave operating costs and seasonal demands, and solved using primal decomposition methodology. The model represents an integrated network including suppliers, production and warehousing facilities, and customers. Its objective is to locate manufacturing and warehouse facilities to configure a production-distribution network, which meets seasonal demand while minimizing production, transportation, and operating costs. The objective function includes supply costs, fixed and variable manufacturing costs, variable facility operating cost, warehousing costs, cycle inventory costs at facilities, pipeline inventory costs, inventory carrying costs, and transportation costs. The model constraints are customer demand, conservation of flows at facilities, suppliers, and machines, supplier capacity, facility capacity, machine capacity, single facility type at a site, and linkage constraints between machines and facilities.

Degraeve and Roodhooft (2000) describe a multi-period, multi-commodity, multi-vendor mixed integer programming model applied to an enterprise purchasing function in order to minimize all costs associated with the purchasing process. The model simultaneously determines the best combination of suppliers and an optimal ordering and inventory policy. The objective function is formed by three cost categories or hierarchical structure identified as (1) the supplier level activities, (2) the order level activities, and (3) the unit level activities. The model constraints are formed by customer demand, min/max purchasing requirements, bounds on the number of suppliers used, and discount purchasing. According to the authors, there are three main contributions of the model: a recognized hierarchy of activities, the mathematical programming model makes activity based costing to be operational in a purchasing environment, and the relationship between activity based costing and total cost of ownership is made clear.

Sery et al. (2001) present a multi-product, single-period, linear and mixed integer programming model applied at BASF North America's distribution system. The model defines the optimal number and location of warehouses as well as their product allocation to meet anticipated customer demand and required delivery service times that generate the minimum overall cost. The objective function includes production costs, transportation costs, handling and storage costs, as well as a penalty for not meeting demand requirements. The model constraints are customer demand, maximum inventory time, DC's storage capacity, balance constraints between special storage capacity and total capacity, and number of DC's. The authors utilized sensitivity analysis by relaxing constraints and modifying costs to evaluate the model's response under uncertainty. Although the authors define North America as the model's geographic region, detail is not provided to identify special conditions for Mexico and Canada as part of the NAFTA region.

Jayaraman and Pirkul (2001) develop a mixed integer program for locating production and distribution facilities in a multi-echelon environment. Their single-period model includes three major costs: fixed and variable production costs, transportation costs for the raw material from vendors to the plants, and the fixed and variable costs for distribution of the final product from the plants to the customers through warehouses. Their sample problems are too large to solve with standard optimization software, so they use a heuristic procedure based on Lagrangian relaxation.

Cheung et al. (2001) describe a multi-period mixed integer model to design a service network for the air express company DHL Hong Kong. The study was originated primarily due to the relocation of the international airport as well as to the intensified business and social activities between Hong Kong and the Chinese mainland since Hong Kong became part of the People's Republic of China in 1997. The objective function minimizes the sum of present-value costs of transportation and facility installation. The model constraints are demand for each zone, individual flow capacity, transportation time, location policy, and logical constraints. The model determines inbound and outbound flows between the international airport and the customer zones considering current and alternate locations for depots and service centers. Also, the model evaluates trade-offs between service coverage as a function of cutoffs time and service reliability for time delivery compliance.

Verter and Dasci (2002) describe a single-period, single-echelon, multi-commodity mixed integer program with concave costs. The model defines an uncapacitated plant location and flexible technology acquisition problem, balancing scale and scope economies with dedicated and flexible equipment respectively. The model objective function includes fixed costs of opening a plant, technology acquisition and operation costs, as well as transportation costs. The model constraints are customer demand, logic constraints allowing existing plants to produce and ship product, non-negativity, and binary restrictions over decision variables. The model minimizes costs determining the capacity to be built at a candidate location as well as the allocation of products and customers.

Melo at el. (2006) present a mixed integer programming model for strategic supply chain planning problem. They propose a general supply chain network where different products are delivered to satisfy several demand points (facilities and customers). The network accommodates different types of facilities, e.g. plants, distribution centers and warehouses. Commodities can be transported between any types of facilities. Candidate sites for the new facilities are known in advance, and the goal of the model is to determine which sites should be chosen for the optimal network design. They divided costs to two categories: the 'business costs' and the investment costs. The first category comprises time-dependent costs for the purchase of products from external suppliers, production costs, transportation costs, inventory holding costs, and fixed facility operating costs, e.g. fixed overhead and maintenance costs. The second category includes facility relocation cost, new facility setup cost and existing facility shutdown cost. They solved to optimality a number of randomly generated test problems using standard mathematical software in less than 5 hours.

2.3. Global Supply Chain Models

In this section some models applied to international supply chains' optimization are reviewed. These models basically incorporate modeling features observed for the domestic supply chain models and add specific international features such as differentiators for international sites, country regions, as well as tariff factors.

Arntzen et al. (1995) present a multi-period, multi-commodity international mixed integer programming model at Digital Equipment Corporation (DEC) that incorporates international features such as taxes and duties, offset requirements, and local content. This model, called Global Supply Chain Model, minimizes a weighted combination of total cost and activity days. Total cost is formed by production costs, inventory costs, facility material handling costs, taxes, facility fixed charges, production line fixed costs, transportation costs, fixed costs associated with particular methods of manufacturing, and duty costs less duty drawback and duty avoidance. The model constraints are customer demand, balance of materials, bill of materials, throughput capacity at each facility, production capacity at each facility, system configuration constraints, and bounds on decision variables.

Rao et al. (2000) develop an international rapid-response supply chain model for a spin-off product line. The researchers examine two study years: the second and sixth years of production. The first year is ignored because it is considered a "ramp-up" year. The two study years differ in volume of forecasted demand, price and cost parameters, and routing restrictions. The model includes a combination of new and existing facilities and dual suppliers, i.e. a low cost regular alternative and a high-speed expedited supplier. The researchers decompose the problem into dealer nodes and transshipment nodes so that the sub-problems can be solved as single-stage inventory systems. The model determines international transportation modes, delivery lead times, and the effect of the changes in demand volume between the two study years. The authors perform a sensitivity analysis on demand forecasts to address forecasting errors and uncertainty.

Vidal and Goetschalckx (2000) present a simple mixed integer programming model to illustrate how uncertainties affect the configuration of global logistics systems and the capabilities of mathematical programming formulations for analyzing these uncertainties. Their model illustrates the effect of exchange rate, changing demand, supplier reliability, and international transportation lead times on the optimal global supply chain network configuration. The authors confirm that the consideration of uncertainties makes mathematical programming models for global logistics systems intractable, and therefore, sensitivity analysis is probably the best way to analyze system variations.

Vidal (2001) describes the multi-product, multi-echelon, single-period, deterministic, international mixed integer programming model. This model offers transfer pricing and the allocation of transportation costs within the model as the distinguishing features. The objective function maximizes the global after-tax profit formed by after-tax profit of internal suppliers, after-tax profit of plants, and after-tax profit of distribution centers. The model constraints are expressions for the net income before taxes of internal suppliers, plants, and distribution centers; suppliers' capacity, production capacity at plants; customer demand constraints; bill of materials at plants and balance constraints at distribution centers; minimum profit for internal suppliers, plants; bounds on transfer prices and general bounds on decision variables.

Dhaenens-Flipo and Finke (2001) illustrate a multi-facility, multi-commodity, multi-period, mixed integer programming for a European manufacturer in the business of mass production of metal items. The authors explain that factories may be located in different countries, giving rise to variation in production costs. The model is composed of ten plants, eight aggregated products, twelve time periods, fifty warehouses and three hundred distribution points (customers). The objective function minimizes production costs, set up costs to model changes in production lines, transportation and storage costs. The model constraints are production sequencing, production capacity, balance flow constraints, customer demand and storage capacity.

Tsiakis et al. (2001) describe a multi-product, multi-echelon, single period, mixed integer programming model with deterministic and uncertain product demand. The model considers fixed manufacturing locations and customer zones. The decisions to be determined by the model are the number, location, and capacity of warehouses and distribution centers, as well as the network transportation links and the flows and production rates of materials. The objective function minimizes the facility establishment costs for a warehouse or distribution center at a potential location, variable production costs, variable material handling costs at warehouses and distribution centers, and piece-wise transportation costs reflecting economies of scale. The model constraints are logic constraints for facility existence, single distribution center sourcing from a warehouse, single-sourcing customer zones, logic transportation constraints, transportation links minimum flows, material balance constraints, production capacity, resource capacity, and warehouse storage and flow capacity. According to the authors, the primary contribution of this model is the integration of three distinct echelons within a single mathematical programming-based formulation including other model features such as multi-commodity, piece-wise transportation costs, and uncertain product demand. The authors also provide a small supply chain example to illustrate the deterministic and uncertain demand modeling alternatives. This example presents a manufacturer in Europe with three manufacturing plants producing 14 products, located in United Kingdom, Spain, and Italy. Product demand has eighteen customer zones located in sixteen different countries within Europe, and there are fifteen countries as an alternative for the location of distribution centers.

Goetschalckx et al. (2002) present a model that integrates strategic global supply chain networks with tactical production-distribution allocations and transfer prices. They consider the network design as part of the strategic planning and the product allocation within the tactical hierarchical planning level. Depending on the relative allocation flexibility of the product/process nature, a strategic or tactical criterion applies. In this case the authors assume this flexibility exists and categorize their model proposal as integrated strategic/tactical. The problem is defined as multi-product, multi-echelon, multi-period, deterministic mixed integer programming model integrated by a model and a sub-model: (1) the fist model maximizes after-tax profit of an international corporation focusing on setting transfer prices, and (2) the sub-model minimizes production and distribution costs within a single country with customer seasonal demands. The model optimization uses heuristics and primal decomposition methods. The authors also discuss data and solution times for a real life case study applied in the packaging industry.

Yan et al. (2003) introduce a strategic multi-commodity, multi-echelon, single-period mixed integer programming production-distribution problem where bills of material are considered. Their model concentrates on the role of bill of material in the selection of suppliers of a strategic supply chain design and determines the number, location, capacity, and type of production producers and distribution centers to be used. The objective function is to minimize total cost or maximize the after-tax profit of the supply chain. They also utilize a test problem and discuss results.

2.4. Supply Chain Models with Reverse Logistics and Remanufacturing

Fleischmann et al. (1997) provide a general framework for reverse distribution systems that includes both the forward flow from producer to user, and the reverse flow from user to producer. Reverse distribution refers to the collection and transportation of used products and materials. It can either take place in the original forward channel, through a separate reverse channel, or through a unified structure of the forward and reverse channel. In addition, the reverse distribution network can take several different forms depending on the ability of the individual components to perform different logistics tasks. In the classical forward channel, virgin materials are obtained from a supplier to be transformed by a producer into usable items through the use of several manufacturing processes. The end product is transported to the distributors, who will put the product on the market so the consumers can reach it. On the other hand, the reverse channel 'undo' these operations by collecting the end product from the consumers, sorting it and transporting it back to the original producer, a remanufacturer, or a recycler. Then the useful materials or components are recycled or remanufactured and re-enter the process again.

Realff et al. (2000) design a reverse production system intended for the recycling and remanufacturing of carpet by a major producer in the US. The objective of their mixed integer programming model was to maximize the overall network profit of the carpet manufacturer. Constraints include flow balances between sites; upper and lower bounds for storage, transportation and processing capacity; and logical constraints on sites such as the need to open a site before allowing tasks to be located there. In this article, profit was defined as the final material minus the processing and transportation costs, subject to conservation of flow, capacity of process and reuse, product requirements, and upper and lower bounds. The major influences for carpet recycling were the recovery of manufactured value, in a form in which the original carpet producer was able to re-use, and the avoidance of disposal costs. The reverse production system starts with the collection of used carpet at the collection points located throughout the US. Then the used carpet is transported to a sorting center where the carpet is separated to sorted nylon carpet and 'other' carpet. The two kinds of carpet are transported to different processing centers to recover raw materials. The authors investigated the impact of the volume of carpet collected on cost of collection, the impact of the volume of carpet collected on the sorting cost, the establishment of additional processing sites and raw material recycling plant.

Barros, et al. (1998) developed a mixed integer programming model for the sand problem. The reverse channel, in this problem, starts with the production of construction waste at the different supply points. Because of regulations, all construction waste must be first shipped to a sorting facility where it is separated into reusable and non-reusable materials. If the waste is mainly composed of stone materials, it is directly transported to a processing facility where the waste is crushed into recyclable sand. Otherwise, the waste is transported to sorting facilities to isolate recyclable materials from non-recyclable ones. The objective of the sand recycling network model is to minimize the total cost of the system, incurred by the recycling of the construction waste, and to determine the type and number of processing sites and their specific location in the network. In addition, the model determines the amount of waste to process to generate the correct amount of sand that minimizes the fixed and variable costs of the system.

Ammons et al. (1999) propose a mathematical programming approach to facilitate the determination of reverse production systems for electronics assemblies. The model includes issues such as the complexity in design, manufacturing, and materials content of the final products and their cycle frequency. The reverse production system includes demanufacturing and remanufacturing processes. The authors recognize that the basic features of the product assembled determine the structure of a reverse production system. Thus, their model of this specific network includes the determination of the reverse flow routes for products and materials to be processed by the system, the allocation of the remanufacturing and demanufacturing functions, the number and capacity of collection sites as well as processing sites. The model also determines the amount of materials to allocate to each potential manufacturing facilities, and the transportation modes that connect the different sites.

Lu and Bostel (2007) present a two-level location problem with three types of facility to be located in a specific reverse logistics system, named a Remanufacturing Network. For this problem, they propose a mixed integer programming model, in which they simultaneously consider "forward" and "reverse" flows and their mutual interactions.

In the remanufacturing system, they assume there are four kinds of participants i.e., customers, intermediate centers, remanufacturing centers and producers. At the customers, there are product demands and used products ready to be recovered. Intermediate reprocessing centers are only used in the reverse channel and are responsible for some processing activities, such as cleaning, disassembly, checking and sorting. Remanufacturing centers accept the returns from intermediate centers and remanufacture the products to their original function. Producers are only responsible for new product manufacturing, and together with the remanufacturing centers, to meet the demand of customers. The objective of the model is to minimize the total cost of the system, includes the fixed costs and the variable costs. Constraints include customer demand, conservation of flow, relationship between forward and return flows, integrality of location variables, and non-negative constraints. The authors solve the problem by an algorithm based on the Lagrangian heuristic approach. Through examples, they confirm that reverse flows influence the decisions about facility location and allocation, and the influence varies with the magnitude of the reverse flows, their distribution at demand sites and their correlation with forward flows.

Lebreton and Tuma (2006) propose a mixed integer programming model for assessing the profitability of car and truck tire remanufacturing. The authors estimated that over 600,000 tons of used tires are annually disposed of in Germany. Given the legal frame work and the limited landfill capacities, particular attention has been given to the environmental impacts of tire recycling. Dedicated life cycle assessments point out tire remanufacturing, also called retreading, as the most sustainable recovery alternative. Nevertheless, retreading still remains only one alternative among others with a fraction varying from 1% up to 80% market share depending on the tire type. The authors develop an OEM-centered decision model in order to analyze potential future scenarios concerning the ability to raise remanufacturing rates. The objective of the model is to maximize the margin for the producer, with a given selling price. Constraints include customer demand, market share, upper bond, conservation of flow. They find out that retreaded truck tires have exhausted their remanufacturing potential whereas a customer-sided bottleneck hinders further development in the car tire market. The question whether an OEM should add retreaded tires to his current product mix mostly depends on a product's nature, either functional or psycho-sociological. Only functional products have enough remanufacturing potential to justify an extension of supply chain planning towards recovery. To remove this demand bottleneck, one solution could be to underline the functional nature of tires and to reduce the role of psycho-sociological factors in the procurement process.

2.5. Summary

The literature cited in this chapter has covered the research work carried out under the area of remanufacturing, supply chain management and reverse logistics. Models have been developed in literature are abundant for

- domestic forward supply chain network design,
- global forward supply chain network design, and
- domestic forward supply chain design with reverse logistics.

One of the limitations in the current research is that comprehensive global supply chain design models with remanufacturing are rare. None of the reviewed literature covers both the international supply chain issues and remanufacturing process. Even for the domestic supply chain, it is also difficult to find a model that cover both forward supply chain and remanufacturing issues in a generic form that can be applied in different industries. With the development of remanufacturing industry and globalization, the integration of forward and reverse logistics flows and international issues are vital for global companies with remanufacturing capability, which are the focus of this thesis.

Chapter 3

Domestic Supply Chain Network Design Model with Remanufacturing Capacity

In this chapter, we present a mathematical formulation for the integrated domestic supply chain network design problem with remanufacturing capacity. This design problem is defined on a network where the set of facilities correspond to the vertex set and the set of transportation channels correspond to the arc set. The problem consists of choosing the facilities to be opened such that: total production does not exceed the capacity of the open facilities, the transportation does not exceed the capacity of the channels, and the total profit of the company is maximized. The open-or-not decisions for the facilities are 0-1 binary decision variables and the production and transportation flow decisions are continuous decision variables. Consequently, this problem is a binary mixed integer linear programming problem.

3.1. Model Description

The model formulated below is for a domestic company with manufacturing and remanufacturing capacity. The essential structure of the supply chain network is shown in Fig. 3.1. In the figure, the representation of the material flow is given, which starts from the procurement process through over the production, distribution, retail process to the collection and remanufacturing process and back to the production process.

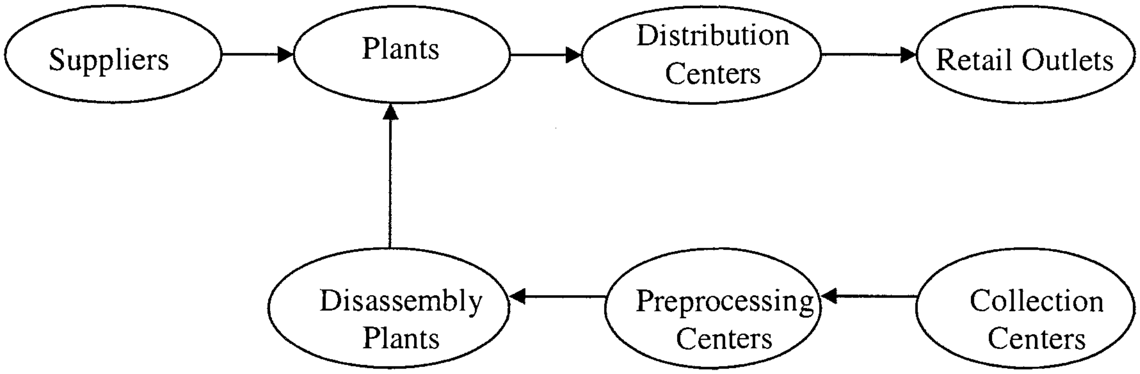


Figure 3.1. Supply Chain Structure with Remanufacturing

Note that plants not only manufacture finished products which are shipped to distribution centers, but also manufacture semi-products which will be supplied to other plants. So, there are three kinds of suppliers for a plant: external material suppliers, internal plants, and disassembly plants.

Each market zone has one and only one possible retail outlet and one possible collection center. So if an outlet is chosen to be built, then the demand of its market zone will be fulfilled or partially fulfilled, depending on the profitability of the entire network. If there is no outlet to be built, then all the demand of its market zone will not be fulfilled. A collection center may be built only when a retail outlet is chosen to be built in the same market zone.

Disassembly plants restore not only materials (as those supplied by external suppliers), but also restore semi-products as those produced by plants. Some parts that are not suitable to restore will be disposed with certain costs.

Preprocessing centers will test the used products shipped from collection centers, and then select those in good conditions to ship to disassembly plants to restore materials and semi-products. Other used products will go to disposal.

3.2. Model Assumptions and Verbal Formulation

3.2.1. Model Assumptions

(1) The model is based on a fixed period, i.e. one year, 3 years, or 5 years, etc. Each flow shown in the model is the total quantity which occurred in an arc of the network in the whole period.

(2) The model selects suppliers, manufacturing plants, distribution centers, retail outlets, collection centers, preprocessing centers, and disassembly plants from a given set of alternative locations. Therefore, locations that are not included in those sets will not be chosen.

(3) The retail outlets in the model are the representation of many types of channels to deliver the products to end customers, such department stores, super market, specialty stores, etc.

(4) Variable and fixed costs are given for all elements of the business processes. Fixed costs occur with the operation of a facility.

(5) Remanufactured materials and parts are used as new materials in the production process.

3.2.2. Verbal Formulation of the Model

Objective function:

Maximize total profit of the company:

Total sales – total costs

Subject to:

(1) Capacity limitations of all facilities and suppliers

(2) Customer demand constraints

(3) Bill-of- material at plants

(4) Bill-of-material at disassembly plants

(5) Conservation of flow

(6) Logical constraints for decision variables

(7) Bounds on decision variables

3.3. List of Notations

3.3.1. Indices

c	collection center
d	distribution center
i,j	material (or part), semi-product, finished product
p	plant
b	preprocessing center
r	disassembly plant

s	supplier
v	retail outlet (market zone) , one outlet corresponding to one market zone

3.3.2. Sets:

C	set of collection centers
D	set of distribution centers
B	set of preprocessing centers
M	set of materials or parts supplied by suppliers
M^s	set of materials available from supplier s
MP^j	set of materials or semi-products required to manufacture product j
P	set of plants
N	set of products
NF	set of finished products (to distribute through distribution centers and then sell at retail outlets)
NS	set of semi-products (to supply to other plants)
NR	set of semi-products or materials restored at disassembly centers
NP^p	set of products manufactured at plant p
BOM^i	set of materials or semi-products required to manufacture product (including semi-product) i
R	set of disassembly plants
S	set of suppliers
V	set of retail outlets

3.3.3. Cost, Price and Other Related Parameters

$DISCB_{b,i}$	disposal cost rate for used product i at preprocessing center b
$DISCR_{r,i}$	disposal cost rate for the un-restorable part of used product i at disassembly plant r
$FIXC_{c}$	fixed operating cost of collection center c
$FIXD_{d}$	fixed operating cost of distribution center d
$FIXP_{p}$	fixed operating cost of plant p
$FIXB_{b}$	fixed operating cost of preprocessing center b
$FIXR_{r}$	fixed operating cost of disassembly plant r
$FIXR_{v}$	fixed operating cost of retail outlet v
$FIXS_{s}$	fixed cost of using supplier s
$PRV_{v,i}$	retail price of product i at retail outlet v
$PRC_{c,i}$	price paid by collection center c for consumer to return used product i
$PRS_{s,i}$	procurement price of material i from supplier s
$TCCB_{c,b,i}$	variable transportation unit cost for transporting product i from collection center c to preprocessing center b
$TCBR_{b,r,i}$	variable transportation unit cost for transporting product i from preprocessing center l to disassembly plant r
$TCDV_{d,v,i}$	variable transportation unit cost for transporting product i from distribution center d to retail outlet v
$TCPD_{p,d,i}$	variable transportation unit cost for transporting product i from plant p to distribution center d
$TCPP_{p1,p2,i}$	variable transportation unit cost for transporting product i from plant $p1$ to

	plant $p2$
$TCRP_{r,p,i}$	variable transportation unit cost for transporting product (or material) i from disassembly center r to plant p
$TCSP_{s,p,i}$	variable transportation unit cost for transporting product i from supplier s to plant p
$VCC_{c,i}$	variable unit cost for collecting product i at collection center c, including handling and storage cost
$VCD_{d,i}$	variable unit cost for distributing product i at distribution center d, including handling and storage cost
$VCP_{p,i}$	variable unit cost for manufacturing product i at plant p, including production and storage cost
$VCB_{b,i}$	variable unit cost for processing product i at preprocessing center b, including processing, handling and storage cost
$VCRr,i$	variable unit cost for disassembling product (or material) i at disassembly plant r, including production, handling and storage cost
$VCV_{v,i}$	variable unit cost for selling product i at retail outlet v, including handling and storage cost
$OUTC_{v,i}$	out sourcing unit cost of product i at retail outlet v

3.3.4. Other Parameters

$DM_{v,i}$	demand for product i at retail outlet (market zone) v
$RV_{v,i}$	recycling rate of product i at market zone v
$RB_{b,i}$	preprocessing rate of product (used) i at preprocessing center b, un-preprocessed products (not suitable for remanufacturing) will

	go to disposal
RRr,i	restore rate of material (or semi-product) *i* at disassembly plant *r*
$BOM_{i,j}$	Bill-of-Material coefficient which indicates the units of the material or semi-product *i* required to manufacture a unit of product *j*
M	big number
$CAPS_{s,i}$	maximum capacity of supplier *s* for material *i*
$CAPP_{p,i}$	maximum capacity of plant *p* for product *i*
$CAPD_{d,i}$	maximum capacity of distribution center *d* for product *i*
$CAPB_{b,i}$	maximum capacity of preprocessing center *b* for (used) product *i*
$CAPR_{r,i}$	maximum capacity of disassembly center *r* for (used) product *i*
$SMAX_{p,i}$	maximum number of suppliers for material *i* at plant *p*

3.3.5. Decision Variables

$xp_{p,i}$	quantity of product *i* manufactured at plant *p*
$xv_{v,i}$	quantity of product *i* sold at retail outlet *v*
$xsp_{s,p,i}$	quantity of material *i* supplied by supplier *s* to plant *p*
$xpp_{p1,p2,i}$	quantity of semi-product *i* supplied by plant *p1* to plant *p2*
$xpd_{p,d,i}$	quantity of finished product *i* supplied by plant *p* to distribution center *d*
$xdv_{d,v,i}$	quantity of product *i* supplied by distribution center *d* to retail outlet *v*
$xcb_{c,b,i}$	quantity of used product *i* supplied by collection center *c* to preprocessing center *b*
$xbr_{b,r,i}$	quantity of used product *i* supplied by preprocessing center *b* to disassembly plant *r*
$xrp_{r,p,i}$	quantity of material or semi-product *i* supplied by disassembly plant *r* to

	plant p
$out_{v,i}$	outsourcing quantity of finished product i incurred when demand for finished product i from customers at outlet v area is not satisfied.
yp_p	binary variable, $yp_p = 1$ if plant p is built; otherwise, $yp_p = 0$
yd_d	binary variable, $yd_d = 1$ if distribution center d is built; otherwise, $yd_d = 0$
yv_v	binary variable, $yv_v = 1$ if retail outlet v is built; otherwise, $yv_v = 0$
yc_c	binary variable, $yc_c = 1$ if collection center c is built; otherwise, $yc_c = 0$
yb_b	binary variable, $yb_b = 1$ if preprocessing center b is built; otherwise, $yb_b = 0$
yr_r	binary variable, $yr_r = 1$ if disassembly plant r is built; otherwise, $yr_r = 0$
ys_s	binary variable, $ys_s = 1$ if supplier s is selected; otherwise, $ys_s = 0$
$zsp_{s,p,i}$	binary variable, $zsp_{s,p,i} = 1$ if supplier s supply material i to plant p; otherwise $zsp_{s,p,i} = 0$
$zdv_{d,v,i}$	binary variable, $zdv_{d,v,i} = 1$ if distribution center d supply product i to retail outlet v, otherwise $zsp_{s,p,i} = 0$
$zcb_{c,b,i}$	binary variable, $zcb_{c,b,i} = 1$ if collection center c supply used product i to preprocessing center b; otherwise $zcb_{c,b,i} = 0$

3.4. Model Formulation

3.4.1. Objective Function

In the model, two types of costs need to be considered: fixed cost and variable costs. The fixed costs are the costs that the corporations need to pay when they open a certain facility. The fixed cost does not depend on the volume of production or flow.

The variable costs are product-volume dependent costs. For example, the production cost and the transportation cost are calculated based on the unit product produced or transported. The production cost is the processing cost in a facility per unit product; the transportation cost is the transportation cost per unit product. In our model, total cost = total fixed cost + total variable cost.

In the calculation of the total fixed cost, only the open facilities need to consider. The status (binary decision variables) of a facility equals 1 when the facility is chosen to be open and 0 when it is not chosen. The total fixed cost is the sum of the fixed costs of all open facilities, including the fixed costs for opening manufacturing plants, distribution centers, retail outlets, collection centers, preprocessing centers, disassembly plants. The mathematical formulation of total fixed cost is as follows.

$$\begin{aligned}\textit{Total fixed cost} = {} & \sum_{p\in P}(FIXP_p \cdot yp_p) + \sum_{s\in S}(FIXS_s \cdot ys_s) + \sum_{d\in D}(FIXD_d \cdot yd_d) \\ & + \sum_{v\in V}(FIXV_v \cdot yv_v) + \sum_{c\in C}(FIXC_c \cdot yc_c) + \sum_{b\in B}(FIXB_b \cdot yb_b) + \sum_{r\in R}(FIXR_r \cdot yr_r) \qquad (3.1)\end{aligned}$$

In the model, six types of variable costs are considered: production cost, transportation cost, material cost, used product collection cost, used product processing cost, and disposal cost. The production cost is the cost incurred when a product is processed or handled in a facility. The transportation cost is the cost incurred when a product is transferred from one facility to another facility. Material cost is the material purchasing price. The used product collection cost is the buying-back price paid to the customer and the handling cost incurred in the collection centers. Used product processing cost includes cost incurred when a used product is preprocessed (sorting, cleaning, pre-disassembly for efficient transportation) in a preprocessing center, and the cost incurred when a used product is disassembled in a disassembly plant. The disposal cost is incurred when some used products are disposed. The total variable cost is the sum of the production cost, transportation cost, material cost, used product collection cost, used product processing cost and disposal cost.

The total production cost is the sum of manufacturing costs at all open manufacturing plants, and the processing and handling costs in distribution centers and retail outlets. The formulation of total production cost is as follows:

$$\textit{Total production cost} =$$

$$\sum_{p\in P}\Big(\sum_{p_1\in P, p\neq p}\sum_{i\in NS} VCP_{p,i}\,xpp_{p,p_1,i} + \sum_{d\in D}\sum_{i\in NF} VCP_{p,i}\,xpd_{p,d,i}\Big) + \sum_{d\in D}\sum_{i\in NF}\sum_{v\in V} VCD_{d,i}\,xdv_{d,v,i}$$

$$+\sum_{v\in V}\sum_{i\in NF}\sum_{d\in D} VCV_{v,i}\,xdv_{d,v,i} \qquad (3.2)$$

With a similar definition, the total transportation cost is the sum of transportation cost in all available transportation channels. The formulation of the total transportation cost is described in (3.3).

$$\textit{Total transportation cost} = \sum_{s\in S}\sum_{p\in P}\sum_{i\in M} TCSP_{s,p,i}\,xsp_{s,p,i} + \sum_{p\in P}\sum_{d\in D}\sum_{i\in NF} TCPD_{p,d,i}\,xpd_{p,d,i}$$

$$+\sum_{d\in D}\sum_{v\in V}\sum_{i\in NF} TCDV_{d,v,i}\,xdv_{d,v,i} + \sum_{c\in C}\sum_{b\in B}\sum_{i\in NF} TCCB_{c,b,i}\,xcb_{c,b,i} + \sum_{b\in B}\sum_{r\in R}\sum_{i\in NF} TCBR_{b,r,i}\,xbr_{b,r,i}$$

$$\sum_{r\in R}\sum_{p\in P}\sum_{i\in NR} TCRP_{r,p,i}\,xrp_{r,p,i} + \sum_{p\in P}\sum_{p_1\in P, p_1\neq p}\sum_{i\in NS} TCPP_{p,p_1,i}\,xpp_{p,p_1,i} \qquad (3.3)$$

The total material cost is the sum of material purchasing price paid to external suppliers. The formulation of the total material cost is described in (3.4).

$$\text{Total material cost} = \sum_{s\in S}\sum_{p\in P}\sum_{i\in M} PRS_{s,i}\,xsp_{s,p,i} \tag{3.4}$$

The total used product collection cost is the sum of buying-back price paid to end customers and the sum of handling cost incurred in all open collection centers. The formulation of the total used product collection cost is described in (3.5).

$$\text{Total used product collection cost} = \sum_{c\in C}\sum_{b\in B}\sum_{i\in NF}((VCC_{c,i} + PRC_{c,i})xcb_{c,b,i} \tag{3.5}$$

The total used product processing cost is the sum of preprocessing cost in all open preprocessing center, and the disassembly cost in all open disassembly plants. The formulation of the total used product processing cost is described in (3.6).

$$\text{Total product processing cost} = \sum_{b\in B}\sum_{r\in R}\sum_{i\in NF} VCB_{b,i}\,xbr_{b,r,i} + \sum_{r\in R}\sum_{p\in P}\sum_{i\in NR} VCR_{r,i}\,xrp_{r,p,i} \tag{3.6}$$

The total disposal cost is the sum of disposal cost in all preprocessing centers and disassembly plants. The formulation of the total disposal cost is described in (3.7).

$$\text{Total disposal cost} = \sum_{b\in B}\sum_{i\in NF}((1 - RB_{b,i})DISCB_{b,i}\sum_{c\in C} xcb_{c,b,i}) + \sum_{r\in R}\sum_{i\in NF}(DISCR_{r,i}\sum_{b\in B} xbr_{b,r,i})$$

(3.7)

The total variable cost is the combination of the total production costs, transportation costs, material costs, used product collection costs, used product processing cost, and disposal costs.

The objective function is formulated by combining total sales income of retail outlets, total fixed cost and total variable cost as below:

$$\text{Maximize:} \quad \sum_{v\in V}(\sum_{i\in NF}((PRV_{v,i} - VCV_{v,i})\cdot\sum_{d\in D} xdv_{d,v,i}) - FIXV_v \cdot yv_v)$$

$$-\sum_{s\in S}(FIXS_s ys_s + \sum_{p\in P}\sum_{i\in M}((PRS_{s,i} + TCSP_{s,p,i})xsp_{s,p,i}))$$

$$-\sum_{p\in P}(FIXP_p yp_p + \sum_{p_1\in P, p\neq p}\sum_{i\in NS}((VCP_{p,i} + TCPP_{p,p_1,i})xpp_{p,p_1,i}) + \sum_{d\in D}\sum_{i\in NF}((VCP_{p,i} + TCPD_{p,d,i})xpd_{p,d,i}))$$

$$-\sum_{d\in D}(FIXD_d yd_d + \sum_{v\in V}\sum_{i\in NF}((VCD_{d,i} + TCDV_{d,v,i})xdv_{d,v,i}))$$

$$-\sum_{c\in C}(FIXC_c yc_c + \sum_{b\in B}\sum_{i\in NF}((VCC_{c,i} + PRC_{c,i} + TCCB_{c,b,i})xcb_{c,b,i}))$$

$$-\sum_{b\in B}(FIXB_b yb_b + \sum_{r\in R}\sum_{i\in NF}((VCB_{b,i} + TCBR_{b,r,i})xbr_{b,r,i}) + \sum_{i\in NF}((1 - RB_{b,i})DISCB_{b,i}\sum_{c\in C} xcb_{c,b,i}))$$

$$-\sum_{r\in R}(FIXR_r yr_r + \sum_{p\in P}\sum_{i\in NF}(TCRP_{r,p,i}xrp_{r,p,i}) + \sum_{i\in NF}((VCR_{r,i} + DISCR_{r,i})\sum_{b\in B} xbr_{b,r,i}))$$

(3.8)

3.4.2. Constraints

3.4.2.1. Capacity Constraints

Capacity constraints ensure that the total production in a facility does not exceed its capacity. There exist two types of capacity: individual product capacity and joint product capacity. The individual product capacity is the capacity of a facility to produce a certain product. For instance, a plant has a capacity to produce 1000 of product A per week.

The joint capacity is the capacity of a facility to produce more than one type of products. It usually is refered as the joint resource capacity.

In our model, individual product capacity formulation is presented, but it is easy to extend the formulation to joint resource cases.

The capacity constraint for suppliers is formulated as (3.9). This constraint is to ensure that the total amount of material *i* supplied by supplier *s* does not exceed the supply capacity of supplier *s* for material *i*.

$$\sum_{p\in P} xsp_{s,p,i} \le CAPS_{s,i} \quad i\in M, s\in S \tag{3.9}$$

Capacity constraints for manufacturing plants are formulated as (3.10) and (3.11). Formulation (3.10) is to ensure that the total amount of semi-products supplied by plant p1 to other plants does not exceed its production capacity. Formulation (3.11) is to ensure that the total amount of finished products supplied by plant p to all distribution centers does not exceed its production capacity.

$$\sum_{p_2\in P, p_2\ne p_1} xpp_{p_1,p_2,i} \le CAPP_{p_1,i} \qquad i\in NS, p_1\in P \tag{3.10}$$

$$\sum_{d\in D} xpd_{p,d,i} \le CAPP_{p,i} \quad i\in NF, p\in P \tag{3.11}$$

The capacity constraint for distribution centers is formulated as (3.12). Formulation (3.12) is to ensure that the total amount of finished products shipped by all manufacturing plants to distribution center d does not exceed the distribution center's handling capacity.

$$\sum_{p \in P} xpd_{p,d,i} \leq CAPD_{d,i} \qquad i \in NF, d \in D \tag{3.12}$$

The capacity constraint for preprocessing centers is formulated as (3.13). Formulation (3.13) is to ensure that the total amount of used products shipped by all collection centers to preprocessing center b does not exceed the preprocessing center's processing capacity.

$$\sum_{c \in C} xcb_{c,b,i} \leq CAPB_{b,i} \quad i \in NF, b \in B \tag{3.13}$$

The capacity constraint for disassembly plants is formulated as (3.14). Formulation (3.14) is to ensure that the total amount of used products shipped by all preprocessing centers to disassembly plant r does not exceed its disassembly capacity.

$$\sum_{b \in B} xbr_{b,r,i} \leq CAPR_{r,i} \quad i \in NF, r \in R \tag{3.14}$$

3.4.2.2. Customer Demand Constraints

The demand constraints ensure the quantity of the products delivered to each retail outlet is no more than the customer demand of that region.

The demand constraint is formulated as bellow:

$$\sum_{d\in D} xdv_{d,v,i} \leq DM_{v,i} \qquad v\in V, i\in NF \tag{3.15}$$

3.4.2.3. Bill-of- Material at Plants

A bill of material (BOM) is a complete, formally structured list of the components that make up a product or assembly. The list contains the object number of each component, together with the quantity and unit of measure. In a real-life supply chain system, the BOM is commonly used in corporations involved in manufacturing or components assembly. However, some process industries such as paper or textile industry also use bill of material with a much simpler structure.

Next we present a simple bill of material structure that includes three product levels. Level 0 is finished product; level 1 is the intermediate product; level 2 is the basic parts. The production process has to follow the bill-of-material structure in order to produce finished products. The example bellow is a schematic diagram of a bill of material for men's racing bicycle (SAP R/3 Library, Release 4.70, 2004).

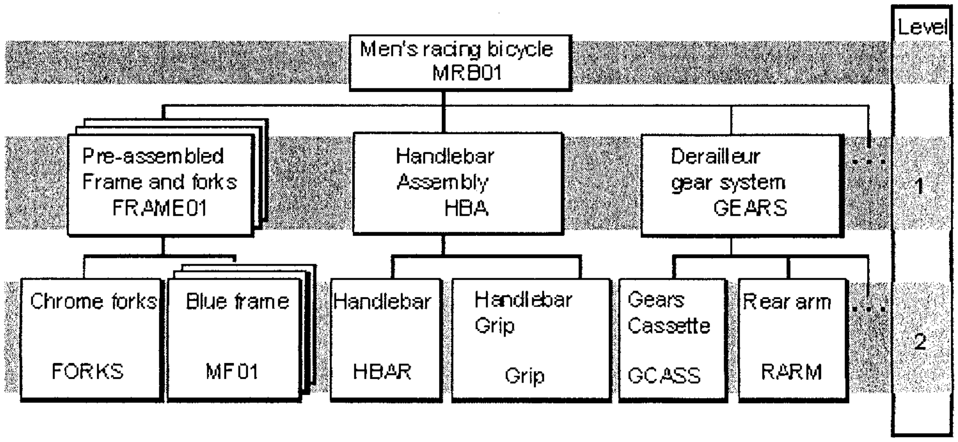
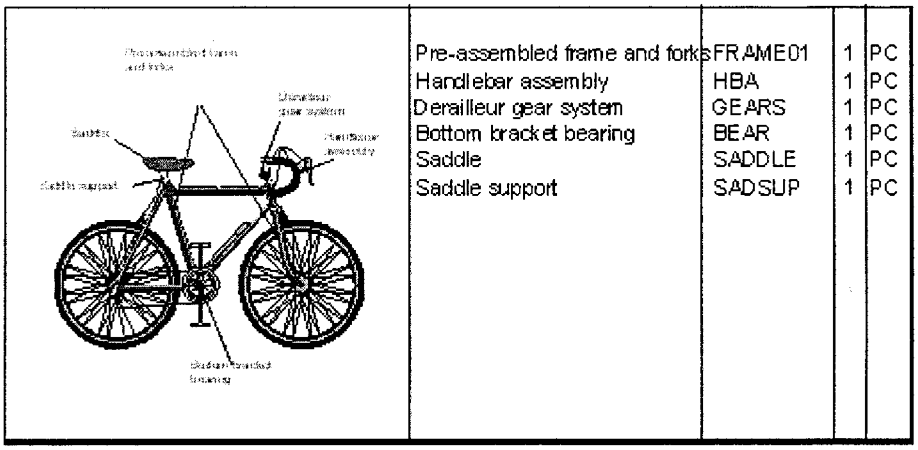


Figure 3.2. BOM Structure of a Bicycle



Pre-assembled frame and forks	FRAME01	1	PC
Handlebar assembly	HBA	1	PC
Derailleur gear system	GEARS	1	PC
Bottom bracket bearing	BEAR	1	PC
Saddle	SADDLE	1	PC
Saddle support	SADSUP	1	PC

Figure 3.3. BOM List of a Bicycle

The BOM presented in figure 3.2 includes intermediate products and basic parts. There are usually several levels in a BOM structure. The finished product is always marked as Level 0, and the immediate level bellow the finished product is marked as Level 1, and the next level will be Level 2, etc. Each finished product, intermediate product or basic part has a unique part number. In figure 3.2, the finished product, level 0, is a man's racing bicycle with a part number MRB01. The intermediate products, level 1 are sub-assemblies such as pre-assembled frame and forks (part number FR AME01), handlebar assembly (part number HBA), and Derailleur gear system (GEARS). In level 1, there are also some basic parts which are directly assembled to the finished product. These parts include bottom bracket bearing (part number BEAR), saddle (part SADDLE), and saddle support (part number SAD SUP). Parts in level 2 are directly assembled to subassemblies in level 1. For example, handlebar (HBAR) and handlebar grips (GRIP) are assembled to handlebar assembly (HBA).

A BOM can have many levels. From a BOM, we not only know which subassemblies or parts are needed for a finished product or a subassembly, we can also know how many parts or subassemblies are needed to make a finished product or an assembly. In our example, to assemble a bicycle, we need 1 piece of handlebar assembly. We can also know that to assemble each handlebar assembly, we need 2 pieces of handle grips.

To ensure that the production process follows the structure of the bill of material, we add BOM constraints to the model. The mathematical formulation of these constraints is as follows.

$$\sum_{s\in S} xsp_{s,p,i} + \sum_{p_1\in P, p_1\neq p} xpp_{p_1,p,i} + \sum_{r\in R} xrp_{r,p,i} = \sum_{j\in NP} BOM_{ij}\, xp_{p,j} \quad i\in NS\bigcup M, p\in P \qquad (3.16)$$

The left side of the formula is the sum of materials (or parts or subassemblies) *i* supplied by suppliers, other plants and disassembly plants to plant *p*. The right side of the formula is the total amount of materials *i* needed to produce all products in plant *p* according to bill of materials.

3.4.2.4. Reverse Bill-of-Material at Disassembly Plants

Similarly, the disassembly process has to be ensured by reverse BOM formulation as follows.

$$\sum_{j\in NF} (RR_{r,i} BOM_{i,j} \sum_{b\in B} xbr_{b,r,j}) \geq \sum_{p\in P} xrp_{r,p,i} \qquad i\in NR, r\in R \qquad (3.17)$$

The left side of the formulation is the amount of material i obtained by disassembling all products j in disassembly plant r. $RR_{r,j}$ is the restore rate of material i (parts or subassembly) in plant r. It is less than 1 because some of the material i cannot be restored, and will be disposed. The right side of the formulation is total amount of restored material i supplied to manufacturing plants.

3.4.2.5. Conservation of Flow Constraints

This set of constraints ensures the flow balance of the network. A network is balanced if the amount of products coming into a facility is equal to the amount of products departing from that facility.

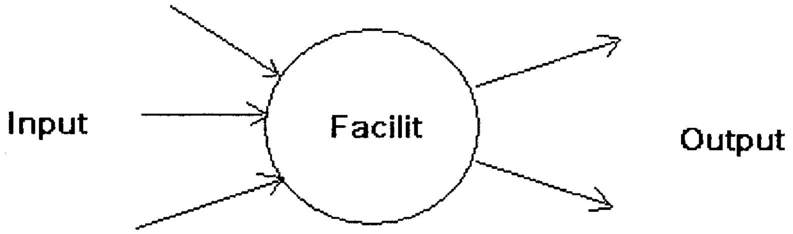


Figure 3.4. Balance Flow of a Network Node

In our network design problem the flow is balanced in all nodes. One of the conservation of flow constraints is as follows. The total amount of finished product i produced in plant p is equal to the amount of product i shipped from plant p to all distribution centers.

$$xp_{p,i} = \sum_{d \in D} xpd_{p,d,i} \qquad i \in NF, p \in P \qquad (3.18)$$

Similarly, the total amount of semi-product i produced in plant p is equal to the amount of product i shipped from plant p to all other plants for producing finished products. There is no semi-product is allowed to be shipped to distribution centers.

$$xp_{p,i} = \sum_{p_1 \in P, p_1 \neq p} xpp_{p,p_1,i} \qquad i \in NS, p \in P \qquad (3.19)$$

Conservation of flow constraints for distribution centers, preprocessing centers and disassembly plants are as bellow.

$$\sum_{p \in P} xpd_{p,d,i} = \sum_{v \in V} xdv_{d,v,i} \qquad d \in D, i \in NF \qquad (3.20)$$

$$\sum_{b \in B} xcb_{c,b,i} \le RV_{v,i} \sum_{d \in D} xdv_{d,v,i} \qquad i \in NF, c \in C, v \in V, c = v \qquad (3.21)$$

$$\sum_{r \in R} xbr_{b,r,i} = RB_{b,i} \sum_{c \in C} xcb_{c,b,i} \qquad i \in NF, b \in B \qquad (3.22)$$

3.4.2.6. Management Restrictions

For better management, the following restrictions are set in the network design:

1) Only allow limited number of suppliers to supply material i to plant p.

$$xsp_{s,p,i} \le BIG \cdot zsp_{s,p,i} \qquad s \in S, p \in P, i \in M \qquad (3.23)$$

$$\sum_{s \in S} zsp_{s,p,i} \le SMAX_{p,i} \qquad i \in M, p \in P \qquad (3.24)$$

2) Each outlet has only one distribution center to supply product i to it.

$$xdv_{d,v,i} \le BIG \cdot zdv_{d,v,i} \qquad d \in D, v \in V, i \in NS \qquad (3.25)$$

$$\sum_{d \in D} zdv_{d,v,i} = 1 \qquad v \in V, i \in NS \qquad (3.26)$$

3) For each kind of used product, each collection center supplies only one preprocessing center.

$$xcb_{c,b,i} \le BIG \cdot zcb_{c,b,i} \quad c \in C, b \in B, i \in NF \tag{3.27}$$

$$\sum_{b \in B} zcb_{c,b,i} = 1 \qquad c \in C, i \in NF \tag{3.28}$$

3.4.2.7. Logical Constraints for Decision Variables

Constraint (3.29) is to ensure $yp_p = 1$ when plant p is open. When plant p is not open, yp_p will be 0. So from the value of yp_p, we can know whether the candidate location for plant p is selected or not.

$$\sum_{d \in D} \sum_{i \in NF} xpd_{p,d,i} + \sum_{p_1 \in P, p_1 \ne p} \sum_{i \in NS} xpp_{p_1,p,i} \le BIG \cdot yp_p \qquad p \in P \tag{3.29}$$

Similarly, logical constraints are formulated for suppliers, distribution centers, retail outlets, collection centers, preprocessing centers, and disassembly centers as follows.

$$\sum_{p \in P} \sum_{i \in M} xsp_{s,p,i} \le BIG \cdot ys_s \qquad s \in S \tag{3.30}$$

$$\sum_{v \in V} \sum_{i \in M} xdv_{d,v,i} \le BIG \cdot yd_d \qquad d \in D \tag{3.31}$$

$$\sum_{d \in D} \sum_{i \in NF} xdv_{d,v,i} \le BIG \cdot yv_v \qquad v \in V \tag{3.32}$$

$$\sum_{b \in B} \sum_{i \in NF} xcb_{c,b,i} \le BIG \cdot yc_c \qquad c \in C \tag{3.33}$$

$$\sum_{r \in R} \sum_{i \in NF} xbr_{b,r,i} \le BIG \cdot yb_b \qquad b \in B \tag{3.34}$$

$$\sum_{p \in P} \sum_{i \in NS} xrp_{r,p,i} \le BIG \cdot yr_r \qquad r \in R \tag{3.35}$$

3.4.2.8. Bounds on Decision Variables

$$xp_{p,i}, xv_{v,i}, xsp_{s,p,i}, xpp_{p1,p2,i}, xpd_{p,d,i}, xdv_{d,v,i}, xcb_{c,b,i}, xbr_{b,r,i}, xrp_{r,p,i} \geq 0$$

$yp_p, yd_d, yv_v, yc_c, yb_b, yr_r, ys_s$ are binary

$zsp_{s,p}, zdv_{d,v,i}, zcb_{c,b,i}$ are binary

3.4.3. Complete Formulation of the Model

The complete formulation of the model is as follows.

Maximize:

$$\sum_{v\in V}(\sum_{i\in NF}((PRV_{v,i}-VCV_{v,i})\cdot\sum_{d\in D}xdv_{d,v,i})-FIXV_v\cdot yv_v)$$

$$-\sum_{s\in S}(FIXS_s ys_s+\sum_{p\in P}\sum_{i\in M}((PRS_{s,i}+TCSP_{s,p,i})xsp_{s,p,i}))$$

$$-\sum_{p\in P}(FIXP_p yp_p+\sum_{p_1\in P,p\neq p}\sum_{i\in NS}((VCP_{p,i}+TCPP_{p,p_1,i})xpp_{p,p_1,i})+\sum_{d\in D}\sum_{i\in NF}((VCP_{p,i}+TCPD_{p,d,i})xpd_{p,d,i}))$$

$$-\sum_{d\in D}(FIXD_d yd_d+\sum_{v\in V}\sum_{i\in NF}((VCD_{d,i}+TCDV_{d,v,i})xdv_{d,v,i}))$$

$$-\sum_{c\in C}(FIXC_c yc_c+\sum_{b\in B}\sum_{i\in NF}((VCC_{c,i}+PRC_{c,i}+TCCB_{c,b,i})xcb_{c,b,i}))$$

$$-\sum_{b\in B}(FIXB_b yb_b+\sum_{r\in R}\sum_{i\in NF}((VCB_{b,i}+TCBR_{b,r,i})xbr_{b,r,i})+\sum_{i\in NF}((1-RB_{b,i})DISCB_{b,i}\sum_{c\in C}xcb_{c,b,i}))$$

$$-\sum_{r\in R}(FIXR_r yr_r+\sum_{p\in P}\sum_{i\in NF}(TCRP_{r,p,i}xrp_{r,p,i})+\sum_{i\in NF}((VCR_{r,i}+DISCR_{r,i})\sum_{b\in B}xbr_{b,r,i}))$$

(3.8)

Subject to:

$$\sum_{p\in P} xsp_{s,p,i} \le CAPS_{s,i} \qquad i\in M, s\in S \tag{3.9}$$

$$\sum_{p_2\in P, p_2\ne p_1} xpp_{p_1,p_2,i} \le CAPP_{p_1,i} \qquad i\in NS, p_1\in P \tag{3.10}$$

$$\sum_{d\in D} xpd_{p,d,i} \le CAPP_{p,i} \qquad i\in NF, p\in P \tag{3.11}$$

$$\sum_{p\in P} xpd_{p,d,i} \le CAPD_{d,i} \qquad i\in NF, d\in D \tag{3.12}$$

$$\sum_{c\in C} xcb_{c,b,i} \le CAPB_{b,i} \qquad i\in NF, b\in B \tag{3.13}$$

$$\sum_{b\in B} xbr_{b,r,i} \le CAPR_{r,i} \qquad i\in NF, r\in R \tag{3.14}$$

$$\sum_{d\in D} xdv_{d,v,i} \le DM_{v,i} \qquad v\in V, i\in NF \tag{3.15}$$

$$\sum_{s\in S} xsp_{s,p,i} + \sum_{p_1\in P, p_1\ne p} xpp_{p_1,p,i} + \sum_{r\in R} xrp_{r,p,i} = \sum_{j\in NP} BOM_{ij} xp_{p,j} \qquad i\in NS\bigcup M, p\in P \tag{3.16}$$

$$\sum_{j\in NF} (RR_{r,i} BOM_{i,j} \sum_{b\in B} xbr_{b,r,j}) \ge \sum_{p\in P} xrp_{r,p,i} \qquad i\in NR, r\in R \tag{3.17}$$

$$xp_{p,i} = \sum_{d\in D} xpd_{p,d,i} \qquad i\in NF, p\in P \tag{3.18}$$

$$xp_{p,i} = \sum_{p_1\in P, p_1\ne p} xpp_{p,p_1,i} \qquad i\in NS, p\in P \tag{3.19}$$

$$\sum_{p\in P} xpd_{p,d,i} = \sum_{v\in V} xdv_{d,v,i} \qquad d\in D, i\in NF \tag{3.20}$$

$$\sum_{b\in B} xcb_{c,b,i} \le RV_{v,i} \sum_{d\in D} xdv_{d,v,i} \qquad c\in C, i\in NF \tag{3.21}$$

$$\sum_{r\in R} xbr_{b,r,i} = RB_{b,i} \sum_{c\in C} xcb_{c,b,i} \qquad b\in B, i\in NF \tag{3.22}$$

$$xsp_{s,p,i} \le BIG\cdot zsp_{s,p,i} \qquad s\in S, p\in P, i\in M \tag{3.23}$$

$$\sum_{s\in S} zsp_{s,p,i} \le SMAX_{p,i} \qquad i\in M, p\in P \tag{3.24}$$

$$xdv_{d,v,i} \le BIG \cdot zdv_{d,v,i} \qquad d\in D, v\in V, i\in NS \tag{3.25}$$

$$\sum_{d\in D} zdv_{d,v,i} = 1 \quad v\in V, i\in NS \tag{3.26}$$

$$xcb_{c,b,i} \le BIG \cdot zcb_{c,b,i} \quad c\in C, b\in B, i\in NF \tag{3.27}$$

$$\sum_{b\in B} zcb_{c,b,i} = 1 \quad c\in C, i\in NF \tag{3.28}$$

$$\sum_{d\in D}\sum_{i\in NF} xpd_{p,d,i} + \sum_{p_1\in P, p_1\ne p}\ \sum_{i\in NS} xpp_{p_1,p,i} \le BIG \cdot yp_p \qquad p\in P \tag{3.29}$$

$$\sum_{p\in P}\sum_{i\in M} xsp_{s,p,i} \le BIG \cdot yS_s \qquad s\in S \tag{3.30}$$

$$\sum_{v\in V}\sum_{i\in M} xdv_{d,v,i} \le BIG \cdot yd_d \qquad d\in D \tag{3.31}$$

$$\sum_{d\in D}\sum_{i\in NF} xdv_{d,v,i} \le BIG \cdot yv_v \qquad v\in V \tag{3.32}$$

$$\sum_{b\in B}\sum_{i\in NF} xcb_{c,b,i} \le BIG \cdot yc_c \qquad c\in C \tag{3.33}$$

$$\sum_{r\in R}\sum_{i\in NF} xbr_{b,r,i} \le BIG \cdot yb_b \qquad b\in B \tag{3.34}$$

$$\sum_{p\in P}\sum_{i\in NS} xrp_{r,p,i} \le BIG \cdot yr_r \qquad r\in R \tag{3.35}$$

and

$xp_{p,i}, xv_{v,i}, xsp_{s,p,i}, xpp_{p1,p2,i}, xpd_{p,d,i}, xdv_{d,v,i}, xcb_{c,b,i}, xbr_{b,r,i}, xrp_{r,p,i} out_{v,i} \ge 0$

$yp_p, yd_d, yv_v, yc_c, yb_b, yr_r, ys_s$ are binary

$zsp_{s,p}, zdv_{d,v,i}, zcb_{c,b,i}$ are binary

3.5. A Numerical Example for the Domestic Model

3.5.1. The Size and Objective of the Example

For validation and verification purposes, a numerical example is created and some analyses are conducted. The size of the supply chain in the example is summarized as below:

Table 3.1. The Size of the Supply Chain Model in the Example

Members of the supply chain	**Total**
Product types	7
Total facilities	48
Total suppliers	6
Manufacturing plants	2
Distribution centers	4
Retail outlets	10
Market zones	10
Collection centers	10
Preprocessing centers	4
Disassembly plants	2
Counties	1
Total Supply chain arcs	312
Total parameters	696

The objective of the model is to maximize the profitability of the domestic company. The decisions considered in the models include:

1) Given a set of alternative locations and capacities, where to build the facilities;
2) Given a set of alternative market zones with demands, where to open the retail outlets;
3) Given a set of suppliers with capacities and costs of material and freight, which suppliers to buy from;
4) Given a set of alternative remanufacturing and processing facility locations, where to open them;
5) Given the options of new parts and remanufactured parts, which and how many to use;
6) Given a set of alternative used products and recoverable parts, which products and parts will be remanufactured.

The company is a domestic company with manufacturing plants, distribution channels and suppliers in Canada. The products are sold to Canadian customers through retail outlets. Used products are collected by the collection centers, and shipped to preprocessing centers for sorting, cleaning, testing and repacking, and the restorable ones are shipped to disassembly plants located in Canada. Restored parts are sent back to the manufacturing plants and partially replacing new parts to build new products.

3.5.2. The Structure of the Example Model

We develop the supply chain design model as a multi-commodity mixed integer linear program. The model is built in and solved by Lingo software. The data are managed by Microsoft Excel and linked to the model in Lingo. The data and model Lingo codes are presented in Appendix A.

We include many cost factors and product/material prices in the model: facility setup costs; new material buying prices; used products prices paid to end customers; transportation costs between suppliers, manufacturing plants, distribution centers and retail outlets; between collection centers, preprocessing centers, disassembly plants and manufacturing plants; manufacturing and operation costs for all facilities; disposal costs.

We also include special factors such as Bills of material (BOM), used product collection rates, material and semi-products recover rates.

The run time for solving the model is about two minutes when we set the product quantity for each type of the products as continuous variables. But if we set the product quantities as integer variables, it takes about 3 hours to get global optimal solution.

3.5.3. The Effects of Some Remanufacturing Factors on Profitability

In the example, we also tested the effects of some key remanufacturing factors on the profitability of the company. The results show that the restore rates and used product collection rates can significantly affect the profitability of the company in the case.

3.5.3.1. The Effects of Restore Rates at Disassembly Plants

The tables below show the results of the company's profitability in different levels of used part restore rates at disassembly plants.

Table 3.2. The Effects of Restore Rates on Profitability

Scenarios	Scenario 1	Scenario 2	Scenario 3
Recovery Rates	Low (Table 3.3)	Original (Table 3.4)	High (Table 3.5)
After Tax Net Profit	$15,210,610	$27,448,700	$37,054,710

Table 3.3. Scenario 1: Low Restore Rates at Disassembly Plants

Disassembly Plant	Material#3	Material#4	Material#5	Material#6	Material#7
1	0.6	0.5	0.5	0.4	0.5
2	0.6	0.5	0.5	0.4	0.5

Table 3.4. Scenario 2: Original Restore Rates at Disassembly Plants

Disassembly Plant	Material#3	Material#4	Material#5	Material#6	Material#7
1	0.8	0.7	0.7	0.6	0.7
2	0.8	0.7	0.7	0.6	0.7

Table 3.5. Scenario 3: High Restore Rates at Disassembly Plants

Disassembly Plant	Material#3	Material#4	Material#5	Material#6	Material#7
1	0.9	0.9	0.9	0.8	0.9
2	0.9	0.9	0.9	0.8	0.9

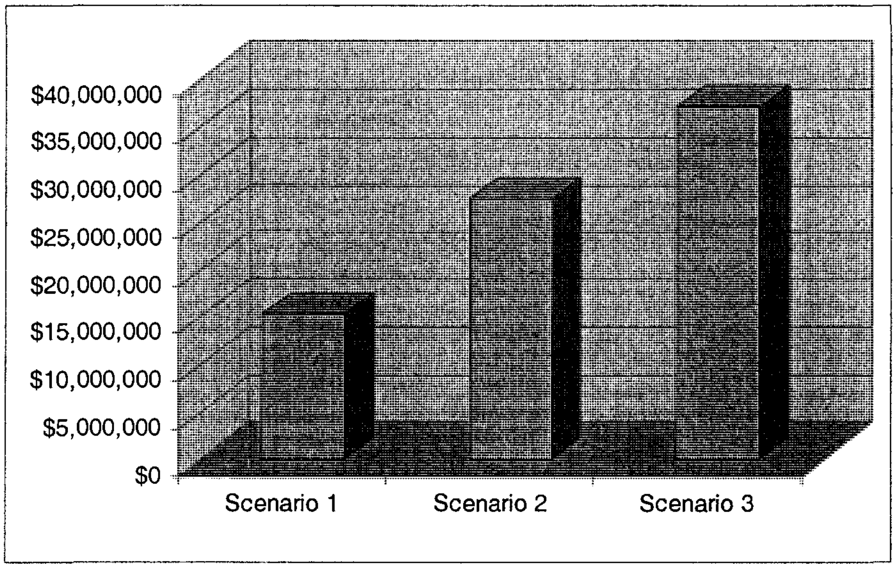


Figure 3.5. Net Profit in Three Scenarios of Restore Rates

3.5.3.2. The Effects of Used-Product Collection Rates

The tables below show the results of the company's profitability in different levels of used-product collection rates from end customers.

Table 3.6. The Effects of Used-Product Collection Rates on Profitability

Scenarios	**Scenario 4**	**Scenario 5**	**Scenario 6**
Recovery Rates	Low (Table 3.7)	Original (Table 3.8)	High (Table 3.9)
After Tax Net Profit	$18,324,620	$27,448,700	$37,047,050

Table 3.7. Scenario 4: Low Used-Product Collection Rates

Market Zone#	Product #1	Product #2
1	0.20	0.25
2	0.20	0.25
3	0.20	0.25
4	0.20	0.30
5	0.25	0.35
6	0.25	0.35
7	0.30	0.25
8	0.30	0.25
9	0.25	0.30
10	0.25	0.30

Table 3.8. Scenario 5: Original Used-Product Collection Rates

Market Zone#	Product #1	Product #2
1	0.35	0.40
2	0.35	0.40
3	0.35	0.40
4	0.35	0.45
5	0.40	0.50
6	0.40	0.50
7	0.45	0.40
8	0.45	0.40
9	0.40	0.45
10	0.40	0.45

Table 3.9. Scenario 6: High Used-Product Collection Rates

Market Zone#	Product #1	Product #2
1	0.50	0.55
2	0.50	0.55
3	0.50	0.55
4	0.50	0.60
5	0.55	0.65
6	0.55	0.65
7	0.60	0.55
8	0.60	0.55
9	0.55	0.60
10	0.55	0.60

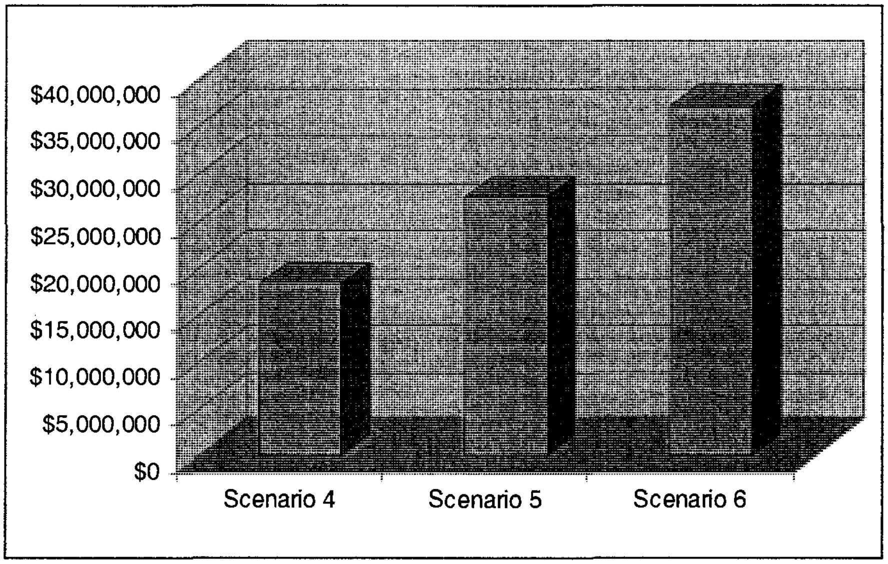


Figure 3.6. Net Profit in Three Scenarios of Collection Rates

The above results show that the effects of some remanufacturing factors on profitability are significant in this case, so the company should make efforts to improve those factors to gain competitiveness in the market place.

3.6. Summary

In this chapter, a comprehensive model for the strategic integrated design of a domestic supply chain network is developed. The model allows simultaneous determination of supplier selection, manufacturing and distribution facility selection and allocation, production quantities, transportation flows, used product collection and reverse distribution facility selection, disassembly plant allocation. Additionally, our model incorporates Bill of Material both in manufacturing process and in disassembly process. Management policies are also considered in the model formulation so that specific management choices can be fulfilled in the strategic supply chain network design.

The model was tested with a medium-sized numerical example which includes 173 constraints and 314 variables (38 integers). The model is successfully solved by Lingo. The run time for solving the model varies depending on the values of the parameters, but it is less than 3 minutes in most of the cases. Six scenarios are used to verify the model and also serve as sensitivity analysis for some parameters.

This model is useful for companies which operate in one country or one free trade region, i.e. European Union, but it is not appropriate for companies with international operations because it does not address global factors such as tariffs, local income tax regulations, currency exchange rates, etc. In next chapter, we will address these global factors in our strategic supply chain network model which is specially designed for companies with international operations.

Chapter 4

Global Supply Chain Network Design Model with Remanufacturing Capacity

The development of globalization makes many corporations realize the importance of global supply chain design. Globalization creates new opportunity to increase the efficiency of the supply chain operations. However, it also increases the scope and complexity of the supply chain design problem.

The complexity of the model for designing global supply chain with remanufacturing is caused by the size of the problem, which is typically very large. In addition, the complexity is also caused by the international trading factors, such as taxes and duties, and regional protection trade barriers.

A comprehensive model for the design of global supply chain with remanufacturing capability is developed. The key differences between the global supply chain design and the domestic supply chain design models are the inclusion of global factors and the complexity of the problem. The major global factors are summarized in Section 4.1, then we overview the model, including assumption and verbal description of the model, in Section 4.2. List of notations used to develop the model is provided in Section 4.3. The explanations of how the objective function and constraints of the model are developed and the model formulation are presented in Section 4.4. We test the model by a medium-sized numerical example in Section 4.5 and summarize the model in Section 4.6.

4.1. International Trade Factors in the Global Supply Chain Design

In multinational firm's supply chain, the material, semi-products and finished goods usually need to be transported among multiple countries before their products reach the end customers. The transfer of goods among the facilities of a multinational company involves currency exchange rate risk, trade barriers, transfer pricing, transportation cost allocation, local content regulations, and local tax systems. Many researchers discuss the types and effects of global factors in international economics as well as global logistics. Appleyard and Field (2001), for example, explored the impact of different types of international trade barriers among countries. In the global supply chain model, we incorporate many global factors including tariff, currency exchange rate, transfer price, local content requirement, local income tax, and allocation of transportation cost.

4.1.1. Tariff

A tariff is a tax on goods upon importation. When a ship arrives in port a customs officer inspects the contents and charges a tax according to the tariff formula. Appleyard and Field (2001) classified the tariff calculation methods into the ad-valorem and the specific method:

- An ad-valorem tariff is a fixed percentage of the value of the good that is being imported.
- A specific tariff is a tariff of a specific amount of money that does not vary with the price of the good.

Romer (1998) classified tariff barriers in three different types: by country, by product, and by country and product. They find that a tariff barrier is a product and country specific barrier. The same products from the same country can be imposed with significantly different import tax rates by importing countries.

4.1.2. Currency Exchange Rate

The Currency exchange rate (also known as the foreign-exchange rate) between two currencies specifies how much one currency is worth in terms of the other. For example, an exchange rate of 7.15 Chinese yuan to the Canadian dollar means that 7.15 Chinese yuan is worth the same as CDN 1. The foreign exchange market is one of the largest markets in the world. By some estimates, about 2 trillion USD worth of currency changes hands every day.

Many researchers discussed the impact of the currency exchange rates on the supply chain. Kouvelis at el. (2001) find that currency exchange rate risk is one of the most important global factors in the design of global logistics systems. Huchzermeier and Cohen (1996) developed a model to evaluate the flexibility of the supply chain design in which the currency exchange rate risk is considered. They generated a set of scenarios based on exchange rate variance. Then they evaluated the value of each scenario using a mixed integer linear model.

Riitta and Toppinnen (1999) incorporated currency exchange rate in their model for the global pricing strategy of a specific pulp and paper company in Europe. The authors assessed the effects of the currency exchange rate on the competitiveness of the company which has to decide their product price based on the currency exchange rate, local competitor's prices, and the competition level. In the model, the currency exchange rate was used as a deterministic global factor in their formulation.

4.1.3. Transfer Price

Transfer pricing refers to the pricing of goods or assets transferred within an organization. For example, goods from the production division may be sold to the marketing division, or goods from a parent company may be sold to a foreign subsidiary. O'Connor (1997) defined the transfer price as the selling price given from one division in a particular country to another division in the same or different country. Both divisions are parts of the same corporation.

Since the prices are set within an organization, the typical market mechanisms that establish prices for such transactions between third parties may not apply. The choice of the transfer price will affect the allocation of the total profit among the parts of the company. This is a major concern for fiscal authorities who worry that multi-national entities may set transfer prices on cross-border transactions to reduce taxable profits in their jurisdiction. This has led to the rise of transfer pricing regulations and enforcement, making transfer pricing a major tax compliance issue for multi-national companies.

Vidal and Goetschalckx (2001) studied the impact of transfer price in their global supply chain design model. They claimed that the impact of transfer price decisions on taxable income and management performance was significant. Additionally, they also observed that the problem with transfer pricing decisions more complicated because the global supply chain design problem became a bilinear problem, and thus it was even more difficult to solve.

4.1.4. Local Content Requirement

In order to fully realize the employment and technology-transfer benefit, developing countries commonly impose local content requirement on multinational firms. This kind of policy requires the multinational firms to use a certain proportion of locally made parts and components, so that the employment in the local parts industries can be improved. Furthermore, to maintain the quality of their final products, it is also necessary for the multinational firms to transfer technology to the local parts industries. Thus, local content requirement becomes a popular government regulation in developing countries.

Artntzen et al. (1995) conducted some research on this issue. They defined local content regulations as the minimum percentage of the total value of a product that is locally manufactured. They find that this regulation is commonly applied in many developing countries to protect their local industries. This protection is generally applied to assembly production corporations where the percentage of the content can be calculated and be imposed easily.

4.1.5. Local Income Tax

Local income tax is also an important factor in the global supply chain network design problem. The local income tax regulation is an income tax bracket system that is applied and regulated for a particular country. An international firm needs to determine the corporate income tax system of the countries where it will build the facilities. Vidal and Goetschalckx (2001) include the corporate income tax in their global supply chain model. They find that international firms generally are at the highest income tax bracket, so they build their model by assuming a constant local income tax rate for each country. Therefore, the corporate income tax was calculated as a constant fraction of the taxable income of the corporation. With this simplification, their model is very easy to solve.

4.1.6. Allocation of Transportation Cost

Allocation of transportation cost is another factor related to international trade. The effect of the allocation of transportation cost on after-tax net profit is similar to transfer price. Allocating more transportation cost to the divisions with higher income tax rate can decrease the total income tax paid by the corporation, so increase the total after-tax net profit of the corporation.

Vidal and Goetschalckx (2001) conducted some research on the transportation cost allocation problem. They incorporate this cost into a global supply chain design model as a decision variable in order to understand how this factor can affect the total after-tax profit of the corporation. The model is able to determine the best allocation strategy to maximize the overall after-tax profit of the corporation.

There exists a standard list of terms for international trade, called Incoterms (International Commercial Terms) and are defined by the International Chamber of Commerce. The choice of incoterms in a purchase order or contract affects the allocation of transportation cost, insurance premium, and duties for the sellers and the buyers. Consequently, it also affects the configuration decisions for the design of global supply chains.

4.2. Model Description and Assumptions

4.2.1. Model Description

The model formulated below is for a global company with manufacturing and remanufacturing facilities. The essential structure of the supply chain network is shown in Figure 4.1. In the figure, the representation of the material flow is given, which starts from the procurement process through over the production, distribution, retail process to the collection and remanufacturing process and back to the production process. The facilities are built in multiple countries.

Note that plants not only manufacture finished products which are shipped to distribution centers, but also manufacture semi-products which will be supplied to other plants. So, there are three kinds of suppliers for a plant: external material suppliers, internal plants, and disassembly plants, and they are located in different countries.

Each market zone has one and only one possible retail outlet and one possible collection center. So if an outlet is chosen to be built, then the demand of its market zone will be fulfilled or partially fulfilled, depending on the profitability of the entire network. If there is no outlet to be built, then all the demand of its market zone will not be fulfilled. A collection center may be built only when a retail outlet is chosen to be built in the same market zone.

Disassembly plants restore not only materials (as those supplied by external suppliers), but also restore semi-products as those produced by plants. Some parts that are not suitable to restore will be disposed with certain costs.

Preprocessing centers will test the used products shipped from collection centers, and then select those in good conditions to ship to disassembly plants to restore materials and semi-products. Other used products will go to disposal.

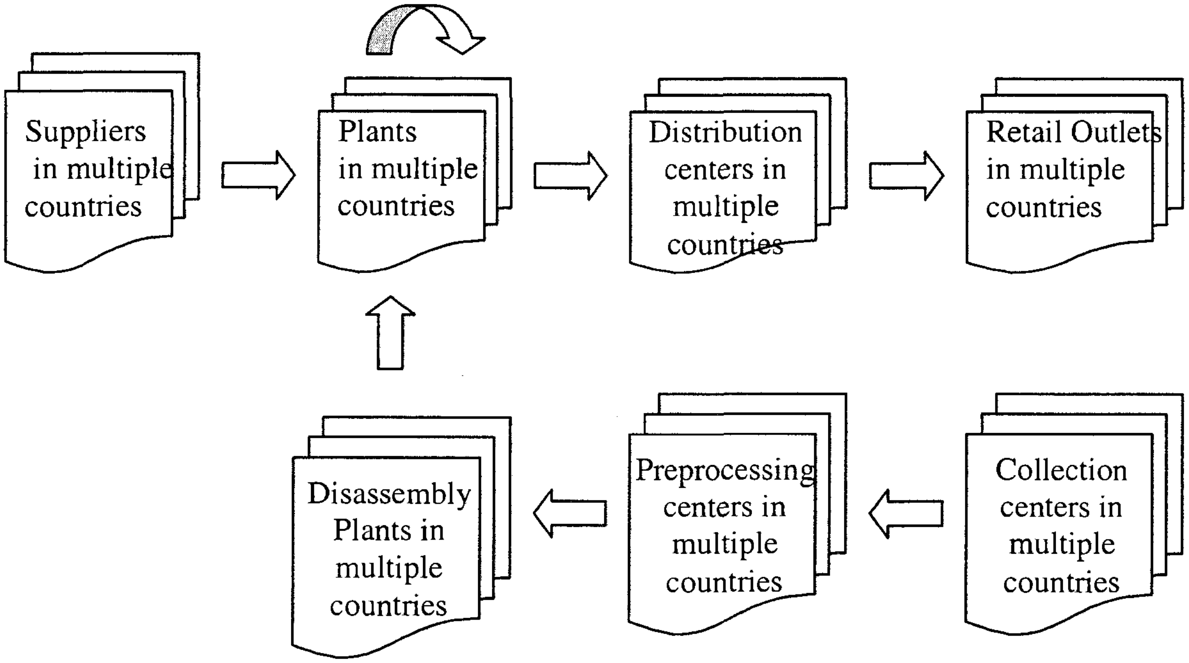


Figure 4.1. Global Supply Chain Structure with Remanufacturing

4.2.2. Model Assumptions

(1) The model is based on a fiscal year (one year for calculating income tax). Each flow shown in the model is the total quantity which occurred in an arc of the network in the whole period.

(2) Transfer prices are predetermined (if transfer prices become decision variables, the model will become a quadratic programming model). Currency exchange rates are fixed in the entire period.

(3) Variable and fixed costs are given for all elements of the business processes. Fixed costs occur with the operation of a facility.

(4) Remanufactured materials and parts are used as new materials in the production process.

(5) The prices and costs shown for all elements are in the currency of the country of the facility. In the model they will be standardized to one currency through an exchange rate.

4.2.3. Verbal Formulation of the Model

Objective function:

Maximize the global after-tax profit in a standardized currency.

Subject to:

(1) Expressions of the net income before tax of plants, distribution centers, retail outlets, collection centers, preprocessing centers, and disassembly centers in every country

(2) Capacity restrictions of all facilities and suppliers

(3) Customer demand constraints

(4) Conservation of flow

(5) Bill-of- material at plants

(6) Bill-of-material at disassembly plants

(7) Local content requirements

(8) Management restrictions

(9) Logical constraints for decision variables

(10) Bounds on decision variables

4.3. List of Notations

4.3.1. Indices:

c	collection center
d	distribution center
i,j	material(or part), semi-product, finished product
k,	country
p	plant
b	preprocessing center
r	disassembly plant
s	supplier
v	retail outlet (market zone) , one outlet corresponding to one market zone

4.3.2. Sets:

C	set of collection centers
C^k	set of collection centers in country k
D	set of distribution centers

D^k	set of distribution centers in country k
K	set of countries
B	set of preprocessing centers
B^k	set of preprocessing centers in country k
M	set of materials or parts supplied by suppliers
M^s	set of materials available from supplier s
MP^j	set of materials or semi-products required to manufacture product j
P	set of plants
P^k	set of plants in country k
N	set of products
NF	set of finished products (to distribute though distribution centers and then sell at retail outlets)
NS	set of semi-products (to supply to other plants)
NR	set of semi-products or materials restored at disassembly centers
NP^p	set of products manufactured at plant p
BOM^i	set of materials or semi-products required to manufacture product (including semi-product) i
R	set of disassembly plants
R^k	set of disassembly plants in country k

S	set of suppliers
S^k	set of suppliers in country k
V	set of retail outlets
V^k	set of retail outlets in country k

4.3.3. Cost, Price and Other Related Parameters

$DISCB_{b,i}$	disposal cost rate for used product i at preprocessing center b
$DISCR_{r,i}$	disposal cost rate for the un-restorable part of used product i at disassembly plant r
$DUTY_{k1,k2}$	total duty for transporting goods from coutry $k1$ to $k2$ which including export duty from country $k1$ and import duty to country $k2$
$DUTYCB_{c,b,i}$	duty rate for shipping product i from collection center c to preprocessing center b
$DUTYBR_{b,r,i}$	duty rate for shipping product i from preprocessing center b to disassembly plant r
$DUTYDV_{d,v,i}$	duty rate for shipping product i from distribution center d to retail outlet v
$DUTYPD_{p,d,i}$	duty rate for shipping product i from plant p to distribution center d
$DUTYPP_{p1,p2,i}$	duty rate for shipping product i from plant $p1$ to plant $p2$

$DUTYRP_{r,p,i}$	duty rate for shipping product i from disassembly plant r to plant p
$DUTYSP_{s,p,i}$	duty rate for shipping product i from supplier s to plant p
EC_c	exchange rate of the country of collection center c (regarding the mother company's home currency)
ED_d	exchange rate of the country of distribution center d
EP_p	exchange rate of the country of plant p
ES_s	exchange rate of the country of supplier s
EV_v	exchange rate of the country of retail outlet v
EB_b	exchange rate of the country of preprocessing center b
ER_r	exchange rate of the country of disassembly plant r
$FIXC_c$	fixed operating cost of collection center c
$FIXD_d$	fixed operating cost of distribution center d
$FIXP_p$	fixed operating cost of plant p
$FIXB_b$	fixed operating cost of preprocessing center b
$FIXR_r$	fixed operating cost of disassembly plant r
$FIXR_v$	fixed operating cost of retail outlet v
$FIXS_s$	fixed cost of using supplier s
$PRV_{v,i}$	retail price of product i at retail outlet v
$PRC_{c,i}$	price paid by collection center c for consumer to return used product i
$PRS_{s,i}$	procurement price of material i from supplier s

TAX_k	income tax rate in country k
$TCCB_{c,b,i}$	variable transportation unit cost for transporting product i from collection center c to preprocessing center b
$TCBR_{b,r,i}$	variable transportation unit cost for transporting product i from preprocessing center l to disassembly plant r
$TCDV_{d,v,i}$	variable transportation unit cost for transporting product i from distribution center d to retail outlet v
$TCPD_{p,d,i}$	variable transportation unit cost for transporting product i from plant p to distribution center d
$TCPP_{p1,p2,i}$	variable transportation unit cost for transporting product i from plant $p1$ to plant 2
$TCRP_{r,p,i}$	variable transportation unit cost for transporting product (or material) i from disassembly center r to plant p
$TCSP_{s,p,i}$	variable transportation unit cost for transporting product i from supplier s to plant p
$TPC_{c,i}$	transfer price (per unit) of the product i distributed from collection center c
$TPD_{d,i}$	transfer price (per unit) of the product i distributed from distribution center d
$TPP_{p,i}$	transfer price (per unit) of the product i manufactured at plant p

$TPB_{b,i}$	transfer price (per unit) of the product i processed at preprocessing center b
$TPR_{r,i}$	transfer price (per unit) of the product (or material) i distributed from disassembly plant l
$VCC_{c,i}$	variable unit cost for collecting product i at collection center c, including handling and storage cost
$VCD_{d,i}$	variable unit cost for distributing product i at distribution center d, including handling and storage cost
$VCP_{p,i}$	variable unit cost for manufacturing product i at plant p, including production and storage cost
$VCB_{b,i}$	variable unit cost for processing product i at preprocessing center b, including processing, handling and storage cost
$VCRr,i$	variable unit cost for disassembling product i at disassembly plant r, including production, handling and storage cost
$VCV_{v,i}$	variable unit cost for selling product i at retail outlet v, including handling and storage cost

4.3.4. Other Parameters

$CONT_k$	local content coeffecient.
$DM_{v,i}$	demand for product i at retail outlet (market zone) v

$RV_{v,i}$	recycling rate of product i at market zone v
$RB_{b,i}$	preprocessing rate of product (used) i at preprocessing center b, un-preprocessed products (not suitable for remanufacturing) will go to disposal
RRr,i	restore rate of material (or semi-product) i at disassembly plant r
$BOM_{i,j}$	Bill of Material coefficient which indicates the units of the material or semi-product i required to manufacture a unit of product j
M	big number
$CAPS_{s,i}$	maximum capacity of supplier s for material i
$CAPP_{p,i}$	maximum capacity of plant p for product i
$CAPD_{d,i}$	maximum capacity of distribution center d for product i
$CAPB_{b,i}$	maximum capacity of preprocessing center b for (used) product i
$CAPR_{r,i}$	maximum capacity of disassembly center r for (used) product i
$SMAX_{p,i}$	maximum number of suppliers for material i at plant p

4.3.5. Decision Variables

$nibt_k$	net income before tax of all facilities in country k
$nibtd_k$	net income before tax of all distribution centers in country k
$nibtp_k$	net income before tax of all plants in country k

$nibtv_k$	net income before tax of all retail outlets in country k
$nibtc_k$	net income before tax of all collection centers in country k
$nibtb_k$	net income before tax of all preprocessing centers in country k
$nibtr_k$	net income before tax of all disassembly plants in country k
$xp_{p,i}$	quantity of product i manufactured at plant p
$xv_{v,i}$	quantity of product i sold at retail outlet v
$xsp_{s,p,i}$	quantity of material i supplied by supplier s to plant p
$xpp_{p1,p2,i}$	quantity of semi-product i supplied by plant $p1$ to plant $p2$
$xpd_{p,d,i}$	quantity of finished product i supplied by plant p to distribution center d
$xdv_{d,v,i}$	quantity of product i supplied by distribution center d to retail outlet v
$xcb_{c,b,i}$	quantity of used product i supplied by collection center c to preprocessing center b
$xbr_{b,r,i}$	quantity of used product i supplied by preprocessing center b to disassembly plant r
$xrp_{r,p,i}$	quantity of material or semi-product i supplied by disassembly plant r to plant p
yp_p	binary variable, $yp_p = 1$ if plant p is built; otherwise, $yp_p = 0$
yd_d	binary variable, $yd_d = 1$ if distribution center d is built; otherwise, $yd_d = 0$

yv_v	binary variable, $yv_v = 1$ if retail outlet v is built; otherwise, $yv_v = 0$
yc_c	binary variable, $yc_c = 1$ if collection center c is built; otherwise, $yc_c = 0$
yb_b	binary variable, $yb_b = 1$ if preprocessing center b is built; otherwise, $yb_b = 0$
yr_r	binary variable, $yr_r = 1$ if disassembly plant r is built; otherwise, $yr_r = 0$
ys_s	binary variable, $ys_s = 1$ if supplier s is selected; otherwise, $ys_s = 0$
$zsp_{s,p,i}$	binary variable, $zsp_{s,p,i} = 1$ if supplier s supply material i to plant p; otherwise $zsp_{s,p,i} = 0$
$zdv_{d,v,i}$	binary variable, $zdv_{d,v,i} = 1$ if distribution center d supply product i to retail outlet v ;otherwise $zdv_{d,v,i} = 0$
$zcb_{c,b,i}$	binary variable, $zcb_{c,b,i} = 1$ if collection center c supply used product i to preprocessing center b; otherwise $zcb_{c,b,i} = 0$

4.4. Model Formulation

4.4.1. Objective Function

The net income variables are free variables, since the net income before tax may be negative, zero, or positive. Therefore, each of these variables is replaced by the difference between a ``plus" non-negative variable (profit variable) and a ``minus" non-negative variable (loss variable).

The net income after tax is calculated among countries. The local income tax rates are based on the local income tax regulations in the country where the facilities are located. We assume that the global company groups together its all facilities that located in the same country as one tax-payer. So, if the net income before tax of all facilities in one country is positive, the income tax is applicable. If the net income before tax is negative, the company does not need to pay income tax in that country. So the income after tax in country k is:

$$[(1-TAX_k)nibt_k^+ - nibt_k^-] \tag{4.1}$$

Then the total net income after tax of the global company (objective function) is

$$\sum_{k\in K}[(1-TAX_k)nibt_k^+ - nibt_k^-] \tag{4.2}$$

4.4.2. Constraints

4.4.2.1. Expressions of Net Income before Tax for Facilities in Each Country

The net income before tax of the global company in each country is the sum of the net income before tax of all its facilities in that country. These facilities include plants, distribution centers, retail outlets, collection centers, preprocessing centers, and disassembly plants.

For each facility,

Net income before tax (NIBT) = total income – fixed cost – procurement cost –

variable operation cost – transportation cost –

disposal cost

(1) NIBT of all plants in country k:

$$nibtp_k^+ - nibtp_k^- =$$

$$\sum_{p\in P^k}(\frac{1}{EP_p}\sum_{i\in NP^p}(TPP_{p,i}-VCP_{p,i})xp_{p,i}-\frac{1}{EP_p}FIXP_p\cdot yP_p$$

$$-\sum_{s\in S}\sum_{i\in M}(\frac{1}{ES_s}((1+DUTYSP_{s,p,i})PRS_{s,i}+TCSP_{s,p,i})xsp_{s,p,i})$$

$$-\sum_{p_1\in P,p_1\neq p}\sum_{i\in NS}\frac{1}{EP_{p_1}}((1+DUTYPP_{p_1,p,i})TPP_{p_1,i}+TCPP_{p_1,p,i})xpp_{p_1,p,i})$$

$$-\sum_{r\in R}\sum_{i\in NR}(\frac{1}{ER_r}((1+DUTYRP_{r,p,i})TPR_{r,i}+TCRP_{r,p,i})xrp_{r,p,i}) \tag{4.3}$$

(2) NIBT of all distribution centers in country k:

$$nibtd_k^+ - nibtd_k^- =$$

$$\sum_{d\in D^k}(\frac{1}{ED_d}\sum_{i\in NF}((TPD_{d,i}-VCD_{d,i})\sum_{v\in V}xdv_{d,v,i})-\frac{1}{ED_d}FIXD_d\,yd_d$$

$$-\sum_{p\in P}\sum_{i\in NF}(\frac{1}{EP_p}((1+DUTYPD_{p,d,i})TPP_{p,i}+TCPD_{p,d,i})\,xpd_{p,d,i})) \tag{4.4}$$

(3) NIBT of all retail outlets in country k:

$$nibtv_k^+ - nibtv_k^- =$$

$$\sum_{v\in V}(\frac{1}{EV_v}\sum_{i\in NF}((PRV_{v,i} - VCV_{v,i})\cdot\sum_{d\in D} xdv_{d,v,i}) - \frac{1}{EV_v} FIXV_v \cdot yv_v$$

$$-\sum_{d\in D}\sum_{i\in NF}(\frac{1}{ED_d}((1+DUTYDV_{d,v,i})TPD_{d,i} + TCDV_{d,v,i})xdv_{d,v,i})) \tag{4.5}$$

(4) NIBT of all collection centers in country *k*:

$$nibtc_k^+ - nibtc_k^- =$$

$$\sum_{c\in C^k}(\frac{1}{EC_c}\sum_{i\in NF}((TPC_{c,i} - PRC_{c,i} - VCC_{c,i})\sum_{b\in B} xcb_{c,b,i}) - \frac{1}{EC_c}FIXC_c \cdot yc_c) \tag{4.6}$$

(5) NIBT of all preprocessing centers in country *k*:

$$nibtB_k^+ - nibtB_k^- =$$

$$\sum_{b\in B^k}(\frac{1}{EB_b}\sum_{i\in NF}((TPB_{b,i} - VCB_{b,i})\sum_{r\in R} xbr_{b,r,i}) - \frac{1}{EB_b}FIXB_b \cdot yb_b$$

$$-\sum_{c\in C}\sum_{i\in NF}(\frac{1}{EC_c}((1+DUTYCB_{c,b,i})TPC_{c,i} + TCCB_{c,b,i})xcb_{c,b,i})$$

$$-\frac{1}{EB_b}\sum_{i\in NF}((1-RB_{b,i})DISCB_{b,i}\sum_{c\in C} xcb_{c,b,i})) \tag{4.7}$$

(6) NIBT of all disassembly plants in country *k*:

$$nibtr_k^+ - nibtr_k^- =$$

$$\sum_{r\in R^k}((\frac{1}{ER_r}\sum_{i\in NR}(TPR_{r,i}\sum_{p\in P} xrp_{r,p,i}) - \frac{1}{ER_r}FIXR_r \cdot yr_r$$

$$-\sum_{b\in B}\sum_{i\in NF}(\frac{1}{EB_b}((1+DUTYBR_{b,r,i})TPB_{b,i} + TCBR_{b,r,i})xbr_{b,r,i})$$

$$-\frac{1}{ER_r}\sum_{i\in NF}((VCR_{r,i}+DISCR_{r,i})\sum_{b\in B}xbr_{b,r,i})) \tag{4.8}$$

(7) NIBT of all facilities in country *k*:

$$nibtd_k^+ + nibtp_k^+ + nibtv_k^+ + nibtc_k^+ + nibtb_k^+ + nibtr_k^+ - nibtd_k^- - nibtp_k^-$$
$$- nibtv_k^- - nibtc_k^- - nibtb_k^- - nibtr_k^- = nibt_k^+ - nibt_k^- \qquad k\in K \tag{4.9}$$

4.4.2.2. Capacity Restrictions of All Facilities and Suppliers

1) $\sum_{p\in P} xsp_{s,p,i} \le CAPS_{s,i} \qquad i\in M, s\in S$ (4.10)

2) $\sum_{p_2\in P, p_2\neq p_1} xpp_{p_1,p_2,i} \le CAPP_{p_1,i} \quad i\in NS, p_1\in P$ (4.11)

3) $\sum_{d\in D} xpd_{p,d,i} \le CAPP_{p,i} \qquad i\in NF, p\in P$ (4.12)

4) $\sum_{p\in P} xpd_{p,d,i} \le CAPD_{d,i} \qquad i\in NF, d\in D$ (4.13)

5) $\sum_{c\in C} xcb_{c,b,i} \le CAPB_{b,i} \qquad i\in NF, b\in B$ (4.14)

6) $\sum_{b\in B} xbr_{b,r,i} \le CAPR_{r,i} \qquad i\in NF, r\in R$ (4.15)

4.4.2.3. Customer Demand Constraints

$$\sum_{d\in D} xdv_{d,v,i} \le DM_{v,i} \qquad v\in V, i\in NF \tag{4.16}$$

4.4.2.4. Bill-of- Material at Plants

$$\sum_{s\in S} xsp_{s,p,i} + \sum_{p_1\in P, p_1\neq p} xpp_{p_1,p,i} + \sum_{r\in R} xrp_{r,p,i} = \sum_{j\in NP} BOM_{ij}\, xp_{p,i} \qquad i\in NS\bigcup M, p\in P \qquad (4.17)$$

4.4.2.5. Reverse Bill-of-Material at Disassembly Plants

$$\sum_{j\in NF} (RR_{r,i} BOM_{i,j} \sum_{b\in B} xbr_{b,r,j}) \geq \sum_{p\in P} xrp_{r,p,i} \qquad i\in NR, r\in R \qquad (4.18)$$

4.4.2.6. Conservation of Flow

1) $$xp_{p,i} = \sum_{p_1\in P, p_1\neq p} xpp_{p,p_1,i} + \sum_{d\in D} xpd_{p,d,i} \qquad i\in NP^{P}, p\in P \qquad (4.19)$$

2) $$\sum_{p\in P} xpd_{p,d,i} = \sum_{v\in V} xdv_{d,v,i} \qquad d\in D, i\in NF \qquad (4.20)$$

3) $$\sum_{b\in B} xcb_{c,b,i} \leq RV_{v,i} \sum_{d\in D} xdv_{d,v,i} \qquad c\in C, i\in NF \qquad (4.21)$$

4) $$\sum_{r\in R} xbr_{b,r,i} = RB_{b,i} \sum_{c\in C} xcb_{c,b,i} \qquad b\in B, i\in NF \qquad (4.22)$$

4.4.2.7. Local Content Requirements

Local (domestic) value or cost is no less than certain percentage of the total product value (total cost) in a manufacturing facility (plant). Only plants have to obey this requirement

Local value = material and semi-product (supplied by domestic suppliers, plants, and disassembly plants) procurement and transportation costs + fixed cost + operation cost.

Total cost = all material and semi-product procurement and transportation costs + fixed cost + operation cost

$$\sum_{s\in S^k}\sum_{i\in M}(PS_{s,i}+TCSP_{s,p,i})xsp_{s,p,i} + \sum_{p_1\in P^k, p_1\neq p}\sum_{i\in NS}(TPP_{p_1,i}+TCPP_{p_1,p})xpp_{p_1,p}$$

$$\sum_{r\in R^k}\sum_{i\in NR}(TPR_{r,i}+TCRP_{r,p,i})xrp_{r,p,i} + FIXP + \sum_{i\in NP^p}VCP_{p,i}xp_{p,i}$$

$$\geq CONT_k \cdot EP_p(\frac{1}{EP_p}FIXP_p + \frac{1}{EP_p}\sum_{i\in NP^p}VCP_{p,i}xp_{p,i}$$

$$+\sum_{s\in S}\sum_{i\in M}\frac{1}{ES_s}((1+DUTYSP_{s,p,i})PS_{s,i}+TCSP_{s,p,i})xsp_{s,p,i}$$

$$+\sum_{p_1\in P, p_1\neq p}\sum_{i\in NS}\frac{1}{EP_{p_1}}((1+DUTYPP_{p_1,p,i})TPP_{p_1,i}+TCPP_{p_1,p,i})xpp_{p_1,p,i}$$

$$+\sum_{r\in R}\sum_{i\in NR}\frac{1}{ER_r}((1+DUTYRP_{r,p,i})TPR_{r,i}+TCRP_{r,p,i})xrp_{r,p,i})$$

$$k\in K, p\in P \qquad (4.23)$$

4.4.2.8. Management Restrictions

For better management, we set following restrictions in the network design:

1) Only allow limited number of suppliers to supply material i to plant p.

$$xsp_{s,p,i} \le BIG \cdot zsp_{s,p,i} \qquad s \in S, p \in P, i \in M \tag{4.24}$$

$$\sum_{s \in S} zsp_{s,p,i} \le SMAX_{p,i} \qquad i \in M, p \in P \tag{4.25}$$

2) Each outlet has only one distribution center to supply product i to it.

$$xdv_{d,v,i} \le BIG \cdot zdv_{d,v,i} \qquad d \in D, v \in V, i \in NS \tag{4.26}$$

$$\sum_{d \in D} zdv_{d,v,i} = 1 \qquad v \in V, i \in NS \tag{4.27}$$

3) For each kind of used product, each collection center supplies only one preprocessing center.

$$xcb_{c,b,i} \le BIG \cdot zcb_{c,b,i} \qquad c \in C, b \in B, i \in NF \tag{4.28}$$

$$\sum_{b \in B} zcb_{c,b,i} = 1 \qquad c \in C, i \in NF \tag{4.29}$$

4.4.2.9. Logical Constraints for Decision Variables

1) $$\sum_{d \in D} \sum_{i \in NF} xpd_{p,d,i} + \sum_{p_1 \in P, p_1 \ne p} \sum_{i \in NS} xpp_{p_1,p,i} \le BIG \cdot yp_p \qquad p \in P \tag{4.30}$$

2) $$\sum_{p \in P} \sum_{i \in M} xsp_{s,p,i} \le BIG \cdot yS_s \qquad s \in S \tag{4.31}$$

3) $$\sum_{v \in V} \sum_{i \in NF} xdv_{d,v,i} \le BIG \cdot yd_d \qquad d \in D \tag{4.32}$$

4) $\sum_{d\in D}\sum_{i\in NF} xdv_{d,v,i} \le BIG \cdot yv_v \quad v \in V$ (4.33)

5) $\sum_{b\in B}\sum_{i\in NF} xcb_{c,b,i} \le BIG \cdot yc_c \quad c \in C$ (4.34)

6) $\sum_{r\in R}\sum_{i\in NF} xbr_{b,r,i} \le BIG \cdot yb_b \quad b \in B$ (4.35)

7) $\sum_{p\in P}\sum_{i\in NS} xrp_{r,p,i} \le BIG \cdot yr_r \quad r \in R$ (4.36)

4.4.2.10. Bounds on Decision Variables

$nibtd_k^+, nibtp_k^+, nibtv_k^+, nibtc_k^+, nibtb_k^+, nibtr_k^+, nibtd_k^-, nibtp_k^-,$
$nibtv_k^-, nibtc_k^-, nibtb_k^-, nibtr_k^-, nibt_k^+, nibt_k^- \ge 0$

$xp_{p,i}, xv_{v,i}, xsp_{s,p,i}, xpp_{p1,p2,i}, xpd_{p,d,i}, xdv_{d,v,i}, xcb_{c,b,i}, xbr_{b,r,i}, xrp_{r,p,i} \ge 0$

$yp_p, yd_d, yv_v, yc_c, yb_b, yr_r, ys_s$ are binary

$zsp_{s,p}, zdv_{d,v,i}, zcb_{c,b,i}$ are binary

4.4.3. Formulation of the Model

The complete formulation of the model is as follows:

Maximize:

$$\sum_{k\in K}[(1-TAX_k)nibt_k^+ - nibt_k^-] \qquad (4.2)$$

Subject to:

$$nibtp_k^+ - nibtp_k^- =$$

$$\sum_{p\in P^k}(\frac{1}{EP_p}\sum_{i\in NP^p}(TPP_{p,i}-VCP_{p,i})xp_{p,i}-\frac{1}{EP_p}FIXP_p\cdot yp_p$$

$$-\sum_{s\in S}\sum_{i\in M}(\frac{1}{ES_s}((1+DUTYSP_{s,p,i})PRS_{s,i}+TCSP_{s,p,i})xsp_{s,p,i})$$

$$-\sum_{p_1\in P,\,p_1\neq p}\ \sum_{i\in NS}\frac{1}{EP_{p_1}}((1+DUTYPP_{p_1,p,i})TPP_{p_1,i}+TCPP_{p_1,p,i})xpp_{p_1,p,i})$$

$$-\sum_{r\in R}\sum_{i\in NR}(\frac{1}{ER_r}((1+DUTYRP_{r,p,i})TPR_{r,i}+TCRP_{r,p,i})xrp_{r,p,i})$$

$k\in K$ (4.3)

$$nibtd_k^+ - nibtd_k^- =$$

$$\sum_{d\in D^k}(\frac{1}{ED_d}\sum_{i\in NF}(\,(TPD_{d,i}-VCD_{d,i})\sum_{v\in V} xdv_{d,v,i}\,)-\frac{1}{ED_d}\,FIXD_d\,yd_d$$

$$-\sum_{p\in P}\sum_{i\in NF}(\frac{1}{EP_p}\,xpd_{p,d,i}(\,(1+DUTYPD_{p,d,i})\,TPP_{p,i}+TCPD_{p,d,i})\,))$$

$k\in K$ (4.4)

$$nibtv_k^+ - nibtv_k^- =$$

$$\sum_{v\in V}(\frac{1}{EV_v}\sum_{i\in NF}((PRV_{v,i}-VCV_{v,i})\cdot\sum_{d\in D}xdv_{d,v,i})-\frac{1}{EV_v}FIXV_v\cdot yv_v$$

$$-\sum_{d\in D}\sum_{i\in NF}(\frac{1}{ED_d}((1+DUTYDV_{d,v,i})TPD_{d,i}+TCDV_{d,v,i})xdv_{d,v,i}))$$

$k\in K$ (4.5)

$$nibtc_k^+ - nibtc_k^- =$$

$$\sum_{c\in C^k}(\frac{1}{EC_c}\sum_{i\in NF}((TPC_{c,i} - PRC_{c,i} - VCC_{c,i})\sum_{b\in B} xcb_{c,b,i}) - \frac{1}{EC_c} FIXC_c \cdot yc_c)$$

$$k\in K \qquad (4.6)$$

$$nibtb_k^+ - nibtb_k^- =$$

$$\sum_{b\in B^k}(\frac{1}{EB_b}\sum_{i\in NF}((TPB_{b,i} - VCB_{b,i})\sum_{r\in R} xbr_{b,r,i}) - \frac{1}{EB_b} FIXB_b \cdot yb_b$$

$$-\sum_{c\in C}\sum_{i\in NF}(\frac{1}{EC_c}((1 + DUTYCB_{c,b,i})TPC_{c,i} + TCCB_{c,b,i})xcb_{c,b,i})$$

$$-\frac{1}{EB_b}\sum_{i\in NF}((1 - RB_{b,i})DISCB_{b,i}\sum_{c\in C} xcb_{c,b,i})) \qquad k\in K \qquad (4.7)$$

$$nibtr_k^+ - nibtr_k^- =$$

$$\sum_{r\in R^k}((\frac{1}{ER_r}\sum_{i\in NR}(TPR_{r,i}\sum_{p\in P} xrp_{r,p,i}) - \frac{1}{ER_r} FIXR_r \cdot yr_r$$

$$-\sum_{b\in B}\sum_{i\in NF}(\frac{1}{EB_b}((1 + DUTYBR_{b,r,i})TPB_{b,i} + TCBR_{b,r,i})xbr_{b,r,i})$$

$$-\frac{1}{ER_r}\sum_{i\in NF}((VCR_{r,i} + DISCR_{r,i})\sum_{b\in B} xbr_{b,r,i})) \qquad k\in K \qquad (4.8)$$

$$nibtd_k^+ + nibtp_k^+ + nibtv_k^+ + nibtc_k^+ + nibtb_k^+ + nibtr_k^+ - nibtd_k^- - nibtp_k^-$$
$$- nibtv_k^- - nibtc_k^- - nibtb_k^- - nibtr_k^- = nibt_k^+ - nibt_k^-$$

$$k\in K \qquad (4.9)$$

$$\sum_{p\in P} xsp_{s,p,i} \le CAPS_{s,i} \quad i\in M, s\in S \qquad (4.10)$$

$$\sum_{p_2 \in P, p_2 \neq p_1} xpp_{p_1,p_2,i} \leq CAPP_{p_1,i} \qquad i \in NS, p_1 \in P \tag{4.11}$$

$$\sum_{d \in D} xpd_{p,d,i} \leq CAPP_{p,i} \quad i \in NF, p \in P \tag{4.12}$$

$$\sum_{p \in P} xpd_{p,d,i} \leq CAPD_{d,i} \qquad i \in NF, d \in D \tag{4.13}$$

$$\sum_{c \in C} xcb_{c,b,i} \leq CAPB_{b,i} \quad i \in NF, b \in B \tag{4.14}$$

$$\sum_{b \in B} xbr_{b,r,i} \leq CAPR_{r,i} \quad i \in NF, r \in R \tag{4.15}$$

$$\sum_{d \in D} xdv_{d,v,i} \leq DM_{v,i} \qquad v \in V, i \in NF \tag{4.16}$$

$$\sum_{s \in S} xsp_{s,p,i} + \sum_{p_1 \in P, p_1 \neq p} xpp_{p_1,p,i} + \sum_{r \in R} xrp_{r,p,i} = \sum_{j \in NP} BOM_{ij} xp_{p,i}$$

$$i \in NS \bigcup M, p \in P \tag{4.17}$$

$$xp_{p,i} = \sum_{p_1 \in P, p_1 \neq p} xpp_{p,p_1,i} + \sum_{d \in D} xpd_{p,d,i} \quad i \in NP^p, p \in P \tag{4.18}$$

$$\sum_{j \in NF} (RR_{r,i} BOM_{i,j} \sum_{b \in B} xbr_{b,r,j}) \geq \sum_{p \in P} xrp_{r,p,i} \quad i \in NR, r \in R \tag{4.19}$$

$$\sum_{p \in P} xpd_{p,d,i} = \sum_{v \in V} xdv_{d,v,i} \quad d \in D, i \in NF \tag{4.20}$$

$$\sum_{b \in B} xcb_{c,b,i} \leq RV_{v,i} \sum_{d \in D} xdv_{d,v,i} \qquad c \in C, i \in NF \tag{4.21}$$

$$\sum_{r \in R} xbr_{b,r,i} = RB_{b,i} \sum_{c \in C} xcb_{c,b,i} \qquad b \in B, i \in NF \tag{4.22}$$

$$\sum_{s \in S^k} \sum_{i \in M} (PS_{s,i} + TCSP_{s,p,i}) xsp_{s,p,i} + \sum_{p_1 \in P^k, p_1 \neq p} \sum_{i \in NS} (TPP_{p_1,i} + TCPP_{p_1,p}) xpp_{p_1,p}$$

$$\begin{aligned}
&\sum_{r\in R^k}\sum_{i\in NR}(TPR_{r,i}+TCRP_{r,p,i})xrp_{r,p,i}+FIXP+\sum_{i\in NP^p}VCP_{p,i}xp_{p,i}\\
&\geq CONT_k\cdot EP_p\Big(\frac{1}{EP_p}FIXP_p+\frac{1}{EP_p}\sum_{i\in NP^p}VCP_{p,i}xp_{p,i}\\
&+\sum_{s\in S}\sum_{i\in M}\frac{1}{ES_s}((1+DUTYSP_{s,p,i})PS_{s,i}+TCSP_{s,p,i})xsp_{s,p,i}\\
&+\sum_{p_1\in P,p_1\neq p}\sum_{i\in NS}\frac{1}{EP_{p_1}}((1+DUTYPP_{p_1,p,i})TPP_{p_1,i}+TCPP_{p_1,p,i})xpp_{p_1,p,i}\\
&+\sum_{r\in R}\sum_{i\in NR}\frac{1}{ER_r}((1+DUTYRP_{r,p,i})TPR_{r,i}+TCRP_{r,p,i})xrp_{r,p,i}\Big)\\
&\qquad\qquad k\in K,p\in P \qquad (4.23)
\end{aligned}$$

$$xsp_{s,p,i}\leq BIG\cdot zsp_{s,p,i} \qquad s\in S,p\in P,i\in M \qquad (4.24)$$

$$\sum_{s\in S}zsp_{s,p,i}\leq SMAX_{p,i} \qquad i\in M,p\in P \qquad (4.25)$$

$$xdv_{d,v,i}\leq BIG\cdot zdv_{d,v,i} \qquad d\in D,v\in V,i\in NS \qquad (4.26)$$

$$\sum_{d\in D}zdv_{d,v,i}=1 \qquad v\in V,i\in NS \qquad (4.27)$$

$$xcb_{c,b,i}\leq BIG\cdot zcb_{c,b,i} \qquad c\in C,b\in B,i\in NF \qquad (4.28)$$

$$\sum_{b\in B}zcb_{c,b,i}=1 \qquad c\in C,i\in NF \qquad (4.29)$$

$$\sum_{d\in D}\sum_{i\in NF}xpd_{p,d,i}+\sum_{p_1\in P,p_1\neq p}\sum_{i\in NS}xpp_{p_1,p,i}\leq BIG\cdot yp_p \qquad p\in P \qquad (4.30)$$

$$\sum_{p\in P}\sum_{i\in M}xsp_{s,p,i}\leq BIG\cdot yS_s \qquad s\in S \qquad (4.31)$$

$$\sum_{v\in V}\sum_{i\in NF} xdv_{d,v,i} \le BIG \cdot yd_d \qquad d\in D \qquad (4.32)$$

$$\sum_{d\in D}\sum_{i\in NF} xdv_{d,v,i} \le BIG \cdot yv_v \qquad v\in V \qquad (4.33)$$

$$\sum_{b\in B}\sum_{i\in NF} xcb_{c,b,i} \le BIG \cdot yc_c \qquad c\in C \qquad (4.34)$$

$$\sum_{r\in R}\sum_{i\in NF} xbr_{b,r,i} \le BIG \cdot yb_b \qquad b\in B \qquad (4.35)$$

$$\sum_{p\in P}\sum_{i\in NS} xrp_{r,p,i} \le BIG \cdot yr_r \qquad r\in R \qquad (4.36)$$

and

$$nibtd_k^+, nibtp_k^+, nibtv_k^+, nibtc_k^+, nibtb_k^+, nibtr_k^+, nibtd_k^-, nibtp_k^-,$$
$$nibtv_k^-, nibtc_k^-, nibtb_k^-, nibtr_k^-, nibt_k^+, nibt_k^- \ge 0$$

$$xp_{p,i}, xv_{v,i}, xsp_{s,p,i}, xpp_{p1,p2,i}, xpd_{p,d,i}, xdv_{d,v,i}, xcb_{c,b,i}, xbr_{b,r,i}, xrp_{r,p,i} \ge 0$$

$yp_p, yd_d, yv_v, yc_c, yb_b, yr_r, ys_s$ are binary

$zsp_{s,p}, zdv_{d,v,i}, zcb_{c,b,i}$ are binary

4.5. Numerical Example

4.5.1. The Example Overview

For validation and verification purposes, a numerical example is presented for this global supply chain model. The size of the supply chain in our case study is summarized as below:

Table 4.1. The Size of the Example Model

Members of the Supply Chain	Total
Product types	7
Total facilities	48
Total suppliers	6
Manufacturing plants	2
Distribution centers	4
Retail outlets	10
Market zones	10
Collection centers	10
Preprocessing centers	4
Disassembly plants	2
Counties	3
Total Supply chain arcs	312
Total parameters	773

The objective of the model is to maximize the after-tax profitability of the corporation. The home country of the company is Canada, with manufacturing plants, distribution channels and suppliers in Canada and China. The products are sold to Canadian and European customers through retail outlets. Used products are collected by the collection centers, and shipped to preprocessing centers for sorting, cleaning, testing and repacking, and the restorable ones are shipped to disassembly plants located in Canada and China. Restored parts are sent back to the manufacturing plants and partially replacing new parts to build new products.

4.5.2. Computational Results

We develop the supply chain design model as a multi-commodity mixed integer linear program. The model is built in and solved by Lingo software. The data are managed by Microsoft Excel and linked to the model in Lingo. Partial data and model formulation are presented in Appendix B.

We include many global factors in the model: currency exchange rates, transfer prices, allocation of transportation costs, local income taxes, and tariffs.

The run time for solving the model is about three minutes when setting the product quantity for each type of the products as continuous variables. But if we the product quantities are set as integer variables, it takes about 4 hours to get global optimal solution.

4.5.3. The Effects of Some Global Factors on the Supply Chain Structure

In a global supply chain, some global factors can have significant effects on the structure of the supply chain. In this case study, we tested the effects of some key global factors on the configuration of the company's supply chain.

4.5.3.1. The Effects of Currency Exchange Rates

In the case study, we changed the exchange rate between Chinese Yuan and Canadian dollar from 7:1 (1 CAD = 7.0 Yuan) to 5:1(1 CAD = 5.5 Yuan), and keep other parameters unchanged. The tables below show the structure of supply chain before and after the change.

Table 4.2. The Supply Chain Structure in the Original Model (1 CAD =7 Yuan)

Canada	Suppliers	#1, #2, #3
	Plants	No
	Distribution Centers	#1,
	Retail Outlets	#1, #2, #3, #4, #5, #6
	Collection Centers	#1, #2, #3, #4, #5, #6
	Preprocessing Centers	#1
	Disassembly Plants	No
China	Suppliers	#4, #5, #6
	Plants	#2
	Disassembly Plants	#2
Europe	Distribution Centers	#4,
	Retail Outlets	#7, #8, #9, #10
	Collection Centers	#7, #8, #9, #10
	Preprocessing Centers	#3

Table 4.3. The Supply Chain Structure after the Currency Exchange Rate Change (1 CAD = 5.5 Yuan)

Canada	Suppliers	#1, #2, #3
	Plants	#1 (the plant in Canada is chosen)
	Distribution Centers	#1, #2
	Retail Outlets	#1, #2, #3, #4, #5, #6
	Collection Centers	#1, #2, #3, #4, #5, #6
	Preprocessing Centers	#1
	Disassembly Plants	#1 (the disassembly plant is moved from China to Canada)
China	Suppliers	#4, #5, #6
	Plants	No (the plant in China is deselected)
	Disassembly Plants	No
Europe	Distribution Centers	#3 (#4 is deselected),
	Retail Outlets	#7, #8, #10 (#9 is deselected)
	Collection Centers	#7, #8, #10 (#9 is deselected)
	Preprocessing Centers	#3

4.5.3.2. The Effects of Tariffs

The level of tariffs can also have significant effects on the choices of facility locations in the supply chain. The table 4.4 shows the structural change of the company's supply chain when the duty rates from China to Canada are increased for material from 2% to 20% and finished products from 8% to 20%.

Table 4.4. The Supply Chain Structure after the Duty Rate Increase

Canada	Suppliers	#1, #2, #3
	Plants	#1 (the plant in Canada is also chosen)
	Distribution Centers	#1,
	Retail Outlets	#1, #2, #3, #4, #5, #6
	Collection Centers	#1, #2, #3, #4, #5, #6
	Preprocessing Centers	#1
	Disassembly Plants	No
China	Suppliers	#4, #5, #6
	Plants	#2 (the plant in China is selected)
	Disassembly Plants	#2
Europe	Distribution Centers	#4,
	Retail Outlets	#7, #8, #9, #10
	Collection Centers	#7, #8, #9, #10
	Preprocessing Centers	#3

The above results show that the effects of some global factors on the supply chain structure are significant in this case. Companies should carefully assess the risks imposed by those factors, and make more informed decisions based on solid analysis of international trade environment.

4.6. Summary

The optimization model developed above involves forward supply chain decisions, reverse supply decisions, remanufacturing process decisions, and international issues for multinational companies. For the forward supply chain, the model includes external suppliers, manufacturing facilities, distribution centers, retail outlets, and end customers.

The forward arcs include arcs from suppliers to manufacturing facilities, from manufacturing facilities to manufacturing facilities, from manufacturing facilities to distribution centers, from distribution centers to retail outlets, from retail outlets to end customers. The reverse and remanufacturing arcs include arcs from end customers to collection centers, from collection centers to preprocessing centers, from preprocessing centers to disposal, from preprocessing centers to disassembly plants, from disassembly plants to disposal, from disassembly plants to manufacturing plants.

The products considered include materials supplied by external suppliers, semi-products supplied from manufacturing plants to manufacturing plants, end products manufactured by plants, used products collected by collection centers, recovered materials partially replacing new materials from external suppliers, recovered semi-products partially replacing semi-products supplied by manufacturing plants.

Cost factors considered in this model include facility setup costs; new material buying prices; used products prices paid to end customers; transfer prices for semi-products between manufacturing plants; transfer prices for end products between manufacturing plants, distribution centers and retail outlets; transfer prices for recovered materials, semi-products between disassembly plants and manufacturing plants; transfer prices for used products among collection centers, preprocessing centers, and disassembly plants; transportation costs between all notes; manufacturing and operation costs for all facilities; disposal costs.

Global factors considered in this model include currency exchange rates, transfer prices, allocation of transportation costs, local content requirements, local income taxes, and tariffs.

Other special factors include Bills of material (BOM), used product collection rates, material and semi-products recover rates. And this model also considers some supply chain management choices such as multi-sourcing strategy or single sourcing strategy.

The model is verified by a medium-sized numerical example which includes 188 constraints and 338 decision variables (including 38 integer variables). The run time for the model in the example is less than 4 minutes, which shows that it can be solved efficiently by currently available tools.

Chapter 5

Conclusion and Future Research

5.1. Conclusion

Comprehensive models for the integrated design of domestic and global supply chain networks with remanufacturing are developed in this thesis. The models allow simultaneous determination of supplier selection, manufacturing and distribution facility selection and allocation, production quantities, transportation flows, used product collection and reverse distribution facility selection, disassembly plant allocation. Additionally, the models incorporate BOM (Bill of Material) both in manufacturing process and in disassembly process. Management policies are also considered in the model formulation so that specific management choices, such as multi-sourcing strategy or single sourcing strategy, can be fulfilled in the strategic supply chain network design.

The domestic model is useful for companies which operate in one country or one free trade region, i.e. European Union, but it is not appropriate for companies with international operations because it does not address global factors such as tariffs, local income tax regulations, currency exchange rates, etc. So these global factors are addressed by developing a strategic global supply chain network model which is specially designed for companies with international operations.

The global supply chain model developed in this thesis involves forward supply chain decisions, reverse supply decisions, remanufacturing process decisions, and international issues for multinational companies. For the forward supply chain, the model includes external suppliers, manufacturing facilities, distribution centers, retail outlets, and end customers. The forward arcs include arcs from suppliers to manufacturing facilities, from manufacturing facilities to manufacturing facilities, from manufacturing facilities to distribution centers, from distribution centers to retail outlets, from retail outlets to end customers. The reverse and remanufacturing arcs include arcs from end customers to collection centers, from collection centers to preprocessing centers, from preprocessing centers to disposal, from preprocessing centers to disassembly plants, from disassembly plants to disposal, from disassembly plants to manufacturing plants.

The products considered include materials supplied by external suppliers, semi-products supplied from manufacturing plants to manufacturing plants, end products manufactured by plants, used products collected by collection centers, recovered materials partially replacing new materials from external suppliers, recovered semi-products partially replacing semi-products supplied by manufacturing plants.

Cost factors considered in the models include facility setup costs; new material buying prices; used products prices paid to end customers; transfer prices for semi-products between manufacturing plants; transfer prices for end products between manufacturing plants, distribution centers and retail outlets; transfer prices for recovered materials, semi-products between disassembly plants and manufacturing plants; transfer prices for used products among collection centers, preprocessing centers, and disassembly plants; transportation costs between all notes; manufacturing and operation costs for all facilities; disposal costs.

Global factors considered in this model include currency exchange rates, transfer prices, allocation of transportation costs, local content requirements, local income taxes, and tariffs.

The main contributions of this research are the two distinctive features in the model compared to previous literature. First, the corresponding integrated logistics operational problem in a global supply chain is formulated with a generalized mathematical form, and thus is not limited to applications for specific industries. Such a methodological measure is rare in previous literature, and has exhibited its potential advantages in addressing complicated global supply chain problems. Second, remanufacturing factors for environmental protection concerns are considered in the proposed model. Thus, the corresponding effects may help to determine solution alternatives to improve the performance of a global supply chain with remanufacturing capacity.

The applications of this model framework are manifold. One main industry with interest in an extended supply chain management perspective is the automotive industry. Car manufacturers became global companies with a global development, sourcing, manufacturing and selling. From 2007 onwards, car manufacturers are forced by European Union law to recycle the new cars sold within the European Union. Therefore, these firms have a rising interest in optimizing their supply chain network from the developing up to the recycling and remanufacturing process.

On the whole, the global supply chain design models represent a new perspective in strategic planning which will become increasingly important for globally active companies. Current advances in information technology allow the calculation of even extensive optimization models. For this reason, the capability to set up and solve models of strategic supply chain management will develop into an important task of strategic planning.

5.2. Future Research

There are wide-ranging options for extensions of this model framework, whereby the most important ones are found below:

- Multiple time periods can be incorporated into the models to reflect the incremental investments of the company and the development of its supply chain network.
- Some of the model's components can also be developed further, such as the detailed modeling of taxes and customs duties and of the transport system.
- An extension of the basic framework to include separate production of refurbished products using restored parts is also conceivable.
- Risk issues like political risks and retail price risks are another important part for the practical use of global strategic supply chain design models.

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Appendix A

Data and Lingo Code Utilized in Presenting the Numerical Example for the Domestic Model

Table A1: Disposal Cost Rate at Preprocessing Centers and Disassembly Plants

Facilities	Product #1 ($/each)	product #2 ($/each)
Preprocess Center #1	18.00	29.00
Preprocess Center #2	18.00	29.00
Preprocess Center #3	15.00	26.00
Preprocess Center #4	15.00	26.00
Manufacture Plant #1	30.00	50.00
Manufacture Plant #2	28.00	48.00

Table A2: Fixed Costs for Production and Distribution Facilities

Facility Sequence Numbers	Manufacture Plant	Disassembly Plant	Distribution Center	Preprocess Center
#1	23,000,000	1,100,000	900,000	600,000
#2	25,000,000	1,170,000	1,100,000	650,000
#3	x	x	1,020,000	760,000
#4	x	x	980,000	670,000

Table A3: Fixed Costs for Suppliers, Retail Outlets and Collection Centers

Facility Sequence Numbers	Supplier	Retail Outlet	Collection Center
#1	31,000	430,000	140,000
#2	24,000	450,000	143,000
#3	29,000	410,000	140,000
#4	18,000	450,000	125,000
#5	19,000	430,000	138,000
#6	27,000	450,000	140,000
#7	x	420,000	120,000
#8	x	410,000	130,000
#9	x	370,000	120,000
#10	x	410,000	120,000

Table A4: Final Product Retail Prices at Each Retail Outlet

Retail Outlet #	Product #1 ($/each)	product #2 ($/each)
#1	1,820	2,190
#2	1,820	2,190
#3	1,820	2,190
#4	1,820	2,190
#5	1,810	2,170
#6	1,820	2,180
#7	1,760	2,050
#8	1,790	2,020
#9	1,730	2,040
#10	1,748	2,070

Table A5: Used Product Collect Prices at Each Collection Center

Collection Center #	Product #1 ($/each)	product #2 ($/each)
#1	45	80
#2	45	80
#3	45	80
#4	45	80
#5	45	80
#6	45	80
#7	40	75
#8	40	75
#9	40	75
#10	40	75

Table A6: Material Prices from Each Supplier

Supplier #	Material #3 ($/each)	Material #4 ($/each)	Material #5 ($/each)	Material #6 ($/each)	Material #7 ($/each)
#1	190	170	221	140	170
#2	210	175	231	150	180
#3	203	177	227	150	190
#4	198	179	233	152	182
#5	191	184	231	142	175
#6	197	181	219	147	178

Table A7: Transportation Cost from Supplier to Manufacturing Plant

Supplier #	Plant #1 ($/each)					Plant #2 ($/each)				
	Material #3	Material #4	Material #5	Material #6	Material #7	Material #3	Material #4	Material #5	Material #6	Material #7
#1	5.00	3.00	6.00	3.00	5.00	4.00	5.00	4.00	5.00	6.00
#2	4.00	3.00	6.00	3.00	3.00	4.00	4.00	5.00	5.00	6.00
#3	3.00	3.00	4.00	3.00	3.00	5.00	5.00	6.00	5.00	5.00
#4	4.00	5.00	5.00	4.00	5.00	5.00	6.00	5.00	5.00	5.00
#5	5.00	5.00	6.00	5.00	4.00	5.00	4.00	5.00	6.00	4.00
#6	5.00	5.00	4.00	6.00	5.00	6.00	6.00	4.00	5.00	4.00

Table A8: Transportation Cost from Plant to Distribution Center

Plant #	Distribution Center #1 ($/each)		Distribution Center #2 ($/each)		Distribution Center #3 ($/each)		Distribution Center #4 ($/each)	
	Product #1	Product #2	Product #1	Product #2	Product #1	Product #2	Product #1	Product #2
#1	4.00	4.00	4.00	4.00	6.00	6.00	6.00	6.00
#2	5.00	5.00	5.00	5.00	4.00	4.00	3.00	3.00

Table A9: Transportation Cost from Distribution Center to Retail Outlet

Distribution Center #	Retail Outlet #1 ($/each)		Retail Outlet #2 ($/each)		Retail Outlet #3 ($/each)		Retail Outlet #4 ($/each)		Retail Outlet #4 ($/each)	
	Product #1	Product #2	Product #1	Product #2	Product #1	Product #2	Product #1	Product #2	Product #1	Product #2
#1	14.00	14.00	14.00	14.00	15.00	15.00	15.00	15.00	18.00	18.00
#2	16.00	16.00	15.00	15.00	15.00	15.00	14.00	14.00	16.00	16.00
#3	19.00	19.00	19.00	19.00	18.00	18.00	17.00	17.00	15.00	15.00
#4	29.00	29.00	26.00	26.00	22.00	22.00	22.00	22.00	18.00	18.00

Table A9: Transportation Cost from Distribution Center to Retail Outlet (Continue)

Distribution Center #	Retail Outlet #6 ($/each)		Retail Outlet #7 ($/each)		Retail Outlet #8 ($/each)		Retail Outlet #9 ($/each)		Retail Outlet #10 ($/each)	
	Product #1	Product #2	Product #1	Product #2	Product #1	Product #2	Product #1	Product #2	Product #1	Product #2
#1	19.00	19.00	19.00	19.00	20.00	20.00	21.00	21.00	23.00	23.00
#2	16.00	16.00	18.00	18.00	19.00	19.00	21.00	21.00	24.00	24.00
#3	16.00	16.00	16.00	16.00	18.00	18.00	18.00	18.00	20.00	20.00
#4	17.00	17.00	17.00	17.00	17.00	17.00	14.00	14.00	13.00	13.00

Table A10: Transportation Cost from Collection Center to Preprocess Center

Collection Center #	Preprocess Center #1 ($/each)		Preprocess Center #2 ($/each)		Preprocess Center #3 ($/each)		Preprocess Center #4 ($/each)	
	Product #1	Product #2	Product #1	Product #2	Product #1	Product #2	Product #1	Product #2
#1	6.00	6.00	10.00	11.00	11.00	11.00	12.00	12.00
#2	6.00	6.00	10.00	11.00	11.00	11.00	12.00	12.00
#3	7.00	7.00	10.00	11.00	11.00	11.00	12.00	12.00
#4	8.00	8.00	5.00	4.00	10.00	10.00	10.00	10.00
#5	8.00	8.00	6.00	7.00	10.00	10.00	10.00	10.00
#6	7.00	6.00	6.00	6.00	9.00	9.00	10.00	10.00
#7	11.00	10.00	9.00	9.00	8.00	9.00	6.00	7.00
#8	11.00	10.00	10.00	10.00	9.00	10.00	7.00	9.00
#9	12.00	11.00	10.00	10.00	9.00	10.00	7.00	7.00
#10	13.00	12.00	9.00	9.00	9.00	9.00	6.00	6.00

Table A11: Transportation Cost from Preprocessing Center to Disassembly Plant

Preprocess Center #	Disassembly Plant #1 ($/each)		Disassembly Plant #2 ($/each)	
	Product #1	Product #2	Product #1	Product #2
#1	5.00	5.00	9.00	9.00
#2	6.00	6.00	9.00	9.00
#3	8.00	8.00	7.00	7.00
#4	9.00	9.00	6.00	6.00

Table A12: Transportation Cost from Disassembly Plant to Manufacturing Plant

Disassembly Plant #	Plant #1 ($/each)					Plant #2 ($/each)				
	Material #3	Material #4	Material #5	Material #6	Material #7	Material #3	Material #4	Material #5	Material #6	Material #7
#1	4.00	4.00	3.00	4.00	6.00	4.00	5.00	5.00	4.00	4.00
#2	4.00	4.00	5.00	5.00	4.00	5.00	6.00	5.00	6.00	6.00

Table A13: Variable Unit Cost for Production and Distribution Facilities

Facility Sequence Numbers	Plant ($/each)		Disassembly Plant ($/each)		Distribution Center ($/each)		Preprocess Center ($/each)	
	Product #1	Product #2	Product #1	Product #2	Product #1	Product #2	Product #1	Product #2
#1	180	290	130	255	28	40	12	28
#2	170	293	141	249	28	40	12	28
#3	x	x	x	x	22	32	10	23
#4	x	x	x	x	22	32	10	23

Table A14: Variable Unit Cost for Retail Outlets and Collection Centers

Facility Sequence Numbers	Retail Outlet ($/each)		Collection Center ($/each)	
	Product #1	Product #2	Product #1	Product #2
#1	45.00	68.00	5.00	16.00
#2	45.00	68.00	5.00	16.00
#3	45.00	68.00	5.00	16.00
#4	45.00	68.00	5.00	16.00
#5	45.00	68.00	5.00	16.00
#6	45.00	68.00	5.00	16.00
#7	43.00	64.00	5.00	16.00
#8	41.00	65.00	5.00	16.00
#9	41.00	64.00	5.00	16.00
#10	38.00	67.00	5.00	16.00

Table A15: End Customer Demand at Each Retail Outlets (Market Zone)

Retail Outlet #	Product #1 (each)	Product #2 (each)
#1	9100	8900
#2	8400	9200
#3	9900	9700
#4	9600	9200
#5	8300	7300
#6	8500	8100
#7	10200	8900
#8	8700	9700
#9	7900	7400
#10	7700	8300

Table A16: Used Product Collection Rate at Each Market Zones

Market Zone #	Product #1	Product #2
#1	0.35	0.40
#2	0.35	0.40
#3	0.35	0.40
#4	0.35	0.45
#5	0.40	0.50
#6	0.40	0.50
#7	0.45	0.40
#8	0.45	0.40
#9	0.40	0.45
#10	0.40	0.45

Table A17: Used Product Preprocess Rate at Preprocess Centers

Preprocess Center #	Product #1	Product #2
#1	0.70	0.50
#2	0.70	0.50
#3	0.70	0.50
#4	0.70	0.50

Table A18: Used Parts Restore Rate at Disassembly Plants

Disassembly Plant #	Material #3	Material #4	Material #5	Material #6	Material #7
#1	0.80	0.70	0.70	0.60	0.70
#2	0.80	0.70	0.70	0.60	0.70

Table A19: Bill-of-Material (BOM) Coefficient

Material Number	Product #1	Product #2
#3	2	0
#4	1	0
#5	3	1
#6	0	2
#7	0	6

Table A20: Maximum Capacity of Suppliers

Supplier #	Material #3	Material #4	Material #5	Material #6	Material #7
#1	128300	88000	89000	67000	180000
#2	94000	47000	97000	56000	160000
#3	87000	56000	91000	59000	155000
#4	77000	110000	23000	72000	210000
#5	98000	39000	33000	53000	122000
#6	132000	61000	69000	44000	57000

Table A21: Maximum Capacity of Production and Distribution Facilities

Facility Sequence Numbers	Plant		Disassembly Plant		Distribution Center		Preprocess Center	
	Product #1	Product #2	Product #1	Product #2	Product #1	Product #2	Product #1	Product #2
#1	120000	120000	60000	50000	50000	45000	30000	30000
#2	120000	120000	60000	50000	45000	48000	30000	30000
#3	x	x	x	x	48000	46000	20000	20000
#4	x	x	x	x	51000	52000	20000	20000

Lingo Code for the Domestic Example Model

```
SETS:
!primary sets, fixed cost, binary variable y;
COLLECTION_CENTER /COLLECT1..COLLECT10/: FIXC, yc;
RETAIL_OUTLET /RETAIL1..RETAIL10/: FIXV, yv;
DISTRIBUTION_CENTER /DISTRIB1..DISTRIB4/: FIXD, yd;
PLANT /PLANT1, PLANT2/: FIXP, yp;
PREPROCESS_CENTER /PREPR1..PREPR4/: FIXB, yb;
DISASSEMBLY_PLANT /DISAS1, DISAS2/: FIXR, yr;
SUPPLIER /SUPPLIER1..SUPPLIER6/: FIXS, ys;
PRODUCT /PRODUCT1..PRODUCT2/;
MATERIAL /MATERIAL3..MATERIAL7/;
!2-dimension sets, disposal cost rate, collection price, retail price, variable unite cost,
retail demand, recycling rate, preprocessing rate, ,restore rate, maximum capacity;
COLLECTION_PRODUCT (COLLECTION_CENTER, PRODUCT): PRC, VCC;
DISTRIBUTION_PRODUCT (DISTRIBUTION_CENTER, PRODUCT): VCD, CAPD;
PLANT_PRODUCT (PLANT, PRODUCT): VCP, CAPP, xp;
PREPROCESS_PRODUCT (PREPROCESS_CENTER, PRODUCT): DISCB, VCB, RB,
CAPB;
```

```
RETAIL_PRODUCT (RETAIL_OUTLET, PRODUCT): PRV, VCV, DM, RV;
DISASSEMBLY_PRODUCT (DISASSEMBLY_PLANT, PRODUCT): DISCR, VCR,
CAPR;
DISASSEMBLY_MATERIAL (DISASSEMBLY_PLANT, MATERIAL): RR;
SUPPLIER_MATERIAL (SUPPLIER, MATERIAL): PRS, CAPS;
!bill of material coefficient;
MATERIAL_PRODUCT (MATERIAL, PRODUCT): BOM;
!3-dimension sets, transportation costs, production flow variables;
COLLECT_PREPRO_PRODUCT (COLLECTION_CENTER,
PREPROCESS_CENTER, PRODUCT): TCCB, xcb;
PREPRO_DISA_PRODUCT (PREPROCESS_CENTER, DISASSEMBLY_PLANT,
PRODUCT):TCBR, xbr;
DISTR_RETAIL_PRODUCT (DISTRIBUTION_CENTER, RETAIL_OUTLET,
PRODUCT): TCDV, xdv;
PLANT_DISTR_PRODUCT (PLANT, DISTRIBUTION_CENTER, PRODUCT):
TCPD, xpd;
DISA_PLANT_MATERIAL (DISASSEMBLY_PLANT, PLANT, MATERIAL): TCRP,
xrp;
SUPPLY_PLANT_MATERIAL (SUPPLIER, PLANT, MATERIAL): TCSP, xsp;
```

```
ENDSETS
DATA:
!Import data from Excel;
  DISCB, DISCR, FIXS, FIXC, FIXD, FIXP, FIXB, FIXR, FIXV, PRV, PRC, PRS,
TCCB, TCBR, TCDV, TCPD, TCRP, TCSP, VCC, VCD, VCP, VCB, VCR, VCV, DM,
RV, RB, RR, BOM, CAPS, CAPP, CAPD, CAPB, CAPR, BIG =
   @OLE( 'C:\Documents and Settings\Terry\My Documents\Thesis\case for chapter
3\casedata3.xls');
!Export solutions back to Excel;
   @OLE( 'C:\Documents and Settings\Terry\My Documents\Thesis\case for chapter
3\case result3.xls') = ys, yp, yd, yv, yc, yb, yr, xsp, xpd, xdv, xcb, xbr, xrp;
ENDDATA
!The objective;
  (Profit) MAX = @SUM(RETAIL_OUTLET(v): - FIXV(v) * yv(v) +
@SUM(PRODUCT(i):(PRV(v,i) - VCV(v,i))*
@SUM(DISTRIBUTION_CENTER(d):xdv(d,v,i))))
-@SUM(SUPPLIER(s):FIXS(s) * ys(s)+
@SUM(PLANT(p):@SUM(MATERIAL(m):(PRS(s,m)+TCSP(s,p,m))*xsp(s,p,m))))
-@SUM(PLANT(p): FIXP(p) * yp(p) +
@SUM(DISTRIBUTION_CENTER(d):@SUM(PRODUCT(i):(VCP(p,i) +
TCPD(p,d,i))* xpd(p,d,i))))
```

```
-@SUM(DISTRIBUTION_CENTER(d): FIXD(d) * yd(d) +
@SUM(RETAIL_OUTLET(v):@SUM(PRODUCT(i):(VCD(d,i)+ TCDV(d,v,i))*
xdv(d,v,i))))
-@SUM(COLLECTION_CENTER(c): FIXC(c) * yc(c) +
@SUM(PREPROCESS_CENTER(b):@SUM(PRODUCT(i):(VCC(c,i)+ PRC(c,i)+
TCCB(c,b,i))* xcb(c,b,i))))
-@SUM(PREPROCESS_CENTER(b): FIXB(b) * yb(b) +
@SUM(DISASSEMBLY_PLANT(r):@SUM(PRODUCT(i):(VCB(b,i)+ TCBR(b,r,i))*
xbr(b,r,i)))+@SUM(PRODUCT(i):(1.0-
RB(b,i))*DISCB(b,i)*@SUM(COLLECTION_CENTER(c):xcb(c,b,i))))
-@SUM(DISASSEMBLY_PLANT(r): FIXR(r) * yr(r) +
@SUM(PLANT(p):@SUM(PRODUCT(i):TCRP(r,p,i)*
xrp(r,p,i)))+@SUM(PRODUCT(i):(VCR(r,i)+
DISCR(R,i))*@SUM(PREPROCESS_CENTER(b):xbr(b,r,i))));
 ! Capacity constrains of all suppliers;
@FOR(SUPPLIER(s):
   @FOR(MATERIAL(m):
      @SUM(PLANT(p): xsp(s,p,m))<= CAPS(s,m)
));
! Capacity constrains of all PLANTS;
@FOR(PLANT(p):
```

```
    @FOR(PRODUCT(i):

        @SUM(DISTRIBUTION_CENTER(d): xpd(p,d,i))<= CAPP(p,i)

));

! Capacity constrains of all distribution centers;

@FOR(DISTRIBUTION_CENTER(d):

    @FOR(PRODUCT(i):

        @SUM(PLANT(p): xpd(p,d,i))<= CAPD(d,i)

));

! Capacity constrains of all preprocess center;

@FOR(PREPROCESS_CENTER(b):

    @FOR(PRODUCT(i):

        @SUM(COLLECTION_CENTER(c): xcb(c,b,i))<= CAPB(b,i)

));

! Capacity constrains of all disassembly plants;

@FOR(DISASSEMBLY_PLANT(r):

    @FOR(PRODUCT(i):

        @SUM(PREPROCESS_CENTER(b): xbr(b,r,i))<= CAPR(r,i)

));

! Customer demand constraints;
```

```
@FOR(RETAIL_OUTLET(v):

    @FOR(PRODUCT(i):

        @SUM(DISTRIBUTION_CENTER(d): xdv(d,v,i))<= DM(v,i)

));

! Bill-of-Material at plants;

@FOR(PLANT(p):

    @FOR(MATERIAL(m):

        @SUM(SUPPLIER(s): xsp(s,p,m)) + @SUM(DISASSEMBLY_PLANT(r):

xrp(r,p,m)) = @SUM(PRODUCT(i):BOM(m,i)* xp(p,i))

));

! Reverse Bill of Material at disassembly plants;

@FOR(DISASSEMBLY_PLANT(r):

    @FOR(MATERIAL(m):

        @SUM(PRODUCT(i): RR(r,m)* BOM(m,i)*

@SUM(PREPROCESS_CENTER(b): xbr(b,r,i)))>= @SUM(PLANT(p): xrp(r,p,m))

));

! Conservation of flow - plant;

@FOR(PLANT(p):

    @FOR(PRODUCT(i):

        xp(p,i)= @SUM(DISTRIBUTION_CENTER(d): xpd(p,d,i))
```

```
));

! - Distribution Center;

@FOR(DISTRIBUTION_CENTER(d):

     @FOR(PRODUCT(i):

        @SUM(PLANT(p):xpd(p,d,i))= @SUM(RETAIL_OUTLET(v): xdv(d,v,i))

));

! - Collection Center;

@FOR(COLLECTION_CENTER(c):

     @FOR(PRODUCT(i):

        @SUM(PREPROCESS_CENTER(b):xcb(c,b,i))<=

RV(c,i)*@SUM(DISTRIBUTION_CENTER(d): xdv(d,c,i))

));

! - Preprocessing Center;

@FOR(PREPROCESS_CENTER(b):

     @FOR(PRODUCT(i):

        @SUM(DISASSEMBLY_PLANT(r):xbr(b,r,i))= RB(b,i)*

@SUM(COLLECTION_CENTER(c): xcb(c,b,i))

));

! Logical Constraints for decision variables;

@FOR(PLANT(p):
```

```
  @SUM(DISTRIBUTION_CENTER(d): @SUM(PRODUCT(i): xpd(p,d,i)))<=BIG*
yp(p));
@FOR(SUPPLIER(s):
  @SUM(PLANT(p): @SUM(MATERIAL(m): xsp(s,p,m)))<=BIG* ys(s));
@FOR(DISTRIBUTION_CENTER(d):
  @SUM(RETAIL_OUTLET(v): @SUM(PRODUCT(i): xdv(d,v,i)))<=BIG* yd(d)
);
@FOR(RETAIL_OUTLET(v):
  @SUM(DISTRIBUTION_CENTER(d): @SUM(PRODUCT(i): xdv(d,v,i)))<=BIG*
yv(v)
);
@FOR(COLLECTION_CENTER(c):
  @SUM(PREPROCESS_CENTER(b): @SUM(PRODUCT(i): xcb(c,b,i)))<=BIG*
yc(c)
);
@FOR(PREPROCESS_CENTER(b):
  @SUM(DISASSEMBLY_PLANT(r): @SUM(PRODUCT(i): xbr(b,r,i)))<=BIG*
yb(b)
);
@FOR(DISASSEMBLY_PLANT(r):
```

```
   @SUM(PLANT(p): @SUM(MATERIAL(m): xrp(r,p,m)))<=BIG* yr(r)
);
! Bounds on decision variables;
@FOR(PLANT(p): @BIN(yp(p)));
@FOR(DISTRIBUTION_CENTER(d): @BIN(yd(d)));
@FOR(RETAIL_OUTLET(v): @BIN(yv(v)));
@FOR(COLLECTION_CENTER(c): @BIN(yc(c)));
@FOR(PREPROCESS_CENTER(b): @BIN(yb(b)));
@FOR(DISASSEMBLY_PLANT(r): @BIN(yr(r)));
@FOR(SUPPLIER: @BIN(ys));
! Integer variables
@FOR(PLANT_PRODUCT: @GIN(xp))
@FOR(COLLECT_PREPRO_PRODUCT: @GIN(xcb))
@FOR(PREPRO_DISA_PRODUCT: @GIN(xbr))
@FOR(DISTR_RETAIL_PRODUCT: @GIN(xdv))
@FOR(PLANT_DISTR_PRODUCT: @GIN(xpd))
@FOR(DISA_PLANT_MATERIAL: @GIN(xrp))
@FOR(SUPPLY_PLANT_MATERIAL: @GIN(xsp));
END
```

Appendix B

Partial Data and Lingo Code Utilized in Presenting the Numerical Example for the Global Model

Table B1: Transfer Prices from Production and Distribution Facilities in Local Currency

Facility Sequence Numbers	Plant (/each)		Distribution Center (/each)		Preprocess Center (/each)	
	Product #1	Product #2	Product #1	Product #2	Product #1	Product #2
#1	$1,560	$1,895	$1,700	$2,050	$120	$190
#2	￥10,700	￥12,700	$1,700	$2,050	$120	$190
#3	x	x	€ 1,210	€ 1,490	€ 140	€ 170
#4	x	x	€ 1,200	€ 1,480	€ 140	€ 170

Table B2: Transfer Prices of Used Products from Collection Centers in Local Currency

Collection Center #	Product #1 ($/each)	product #2 ($/each)
#1	$128	$160
#2	$128	$160
#3	$128	$160
#4	$128	$160
#5	$128	$160
#6	$128	$160
#7	€ 105	€ 138
#8	€ 105	€ 138
#9	€ 105	€ 138
#10	€ 105	€ 138

Table B3: Transfer Prices of Used Parts from Disassembly Plants in Local Currency

Disassembly Plant #	Material #3 (/each)	Material #4 (/each)	Material #5 (/each)	Material #6 (/each)	Material #7 (/each)
#1	$170	$150	$200	$120	$140
#2	￥880	￥780	￥1,180	￥620	￥770

Table B4: Exchange Rates between Canadian Dollars, Chinese Yuan and Euro

Currency	Canadian Dollar	Chinese Yuan	Euro
Canadian Dollar	x	7.00	0.700
Chinese Yuan	0.143	x	0.100
Euro	1.429	10.000	x

Table B5: Duty Rate from Plant to Distribution Center

Plant #	Distribution Center #1		Distribution Center #2		Distribution Center #3		Distribution Center #4	
	Product #1	Product #2	Product #1	Product #2	Product #1	Product #2	Product #1	Product #2
#1	0	0	0	0	5.0%	5.0%	5.0%	5.0%
#2	2.0%	2.0%	2.0%	2.0%	6.0%	6.0%	6.0%	6.0%

Table B6: Income Tax Rate in Three Regions

Country/Region	Income Tax Rate
Canada	30%
EU	28%
China	33%

Table B7: Material Prices from Suppliers in Local Currency

Supplier #	Material #3 (/each)	Material #4 (/each)	Material #5 (/each)	Material #6 (/each)	Material #7 (/each)
#1	$200	$180	$250	$140	$170
#2	$220	$195	$240	$150	$180
#3	$220	$190	$250	$150	$190
#4	￥1,100	￥1,000	￥1,400	￥820	￥1,020
#5	￥1,200	￥950	￥1,450	￥840	￥1,080
#6	￥1,200	￥1,040	￥1,370	￥830	￥1,000

Table B8: Transportation Cost from Supplier to Manufacturing Plant in Local Currency

Supplier #	Plant #1 (/each)					Plant #2 (/each)				
	Material #3	Material #4	Material #5	Material #6	Material #7	Material #3	Material #4	Material #5	Material #6	Material #7
#1	$6.00	$3.00	$6.00	$3.00	$5.00	$21.00	$17.00	$18.00	$17.00	$17.00
#2	$4.00	$3.00	$6.00	$3.00	$3.00	$20.00	$17.00	$18.00	$17.00	$17.00
#3	$2.00	$3.00	$4.00	$3.00	$3.00	$21.00	$17.00	$18.00	$17.00	$17.00
#4	￥105.00	￥105.00	￥105.00	￥105.00	￥105.00	￥12.00	￥12.00	￥12.00	￥12.00	￥12.00
#5	￥110.00	￥110.00	￥110.00	￥110.00	￥110.00	￥15.00	￥15.00	￥15.00	￥15.00	￥15.00
#6	￥110.00	￥110.00	￥110.00	￥110.00	￥110.00	￥15.00	￥15.00	￥15.00	￥15.00	￥15.00

Table B9: Transportation Cost from Plant to Distribution Center in Local Currency

Plant #	Distribution Center #1 (/each)		Distribution Center #2 (/each)		Distribution Center #3 (/each)		Distribution Center #4 (/each)	
	Product #1	Product #2	Product #1	Product #2	Product #1	Product #2	Product #1	Product #2
#1	$4.00	$4.00	$4.00	$4.00	$35.00	$35.00	$35.00	$35.00
#2	￥110.00	￥110.00	￥110.00	￥110.00	￥120.00	￥120.00	￥120.00	￥120.00

Table B10: Transportation Cost from Disassembly Plant to Manufacturing Plant

Disassembly Plant #	Plant #1 (/each)					Plant #2 (/each)				
	Material #3	Material #4	Material #5	Material #6	Material #7	Material #3	Material #4	Material #5	Material #6	Material #7
#1	$4.00	$4.00	$6.00	$6.00	$7.00	$21.00	$18.00	$18.00	$21.00	$21.00
#2	¥80.00	¥85.00	¥86.00	¥89.00	¥97.00	¥15.00	¥13.00	¥12.00	¥10.00	¥10.00

Table B11: Variable Unit Cost for Production and Distribution Facilities In Local Currency

Facility Sequence Numbers	Plant ($/each)		Disassembly Plant (/each)		Distribution Center (/each)		Preprocess Center (/each)	
	Product #1	Product #2	Product #1	Product #2	Product #1	Product #2	Product #1	Product #2
#1	$220	$320	$120	$220	$28	$40	$12	$28
#2	¥1,190	¥1,820	¥600	¥1,100	$28	$40	$12	$28
#3	x	x	x	x	€ 22	€ 32	€ 10	€ 23
#4	x	x	x	x	€ 22	€ 32	€ 10	€ 23

Lingo Code for the Global Example Model

```
SETS:

!primary sets, fixed cost, binary variable y;

COLLECTION_CENTER /COLLECT1..COLLECT10/: EC, FIXC, yc;

RETAIL_OUTLET /RETAIL1..RETAIL10/: EV, FIXV, yv;
```

```
DISTRIBUTION_CENTER /DISTRIB1..DISTRIB4/: ED, FIXD, yd;
PLANT /PLANT1, PLANT2/: EP, FIXP, yp;
PREPROCESS_CENTER /PREPR1..PREPR4/: EB, FIXB, yb;
DISASSEMBLY_PLANT /DISAS1, DISAS2/: ER, FIXR, yr;
SUPPLIER /SUPPLIER1..SUPPLIER6/: ES, FIXS, ys;
COUNTRY /CANADA, EU, CHINA/: TAX, nibtplus, nibtminus, nibtd, nibtp, nibtv,
nibtc, nibtb, nibtr;
PRODUCT /PRODUCT1..PRODUCT2/;
MATERIAL /MATERIAL3..MATERIAL7/;
!2-dimension sets, disposal cost rate, transfer price, collection price, retail price, variable
unite cost, retail demand, recycling rate, preprocessing rate, maximum capacity;
COLLECTION_PRODUCT (COLLECTION_CENTER, PRODUCT): TPC, PRC, VCC;
DISTRIBUTION_PRODUCT (DISTRIBUTION_CENTER, PRODUCT): TPD, VCD,
CAPD;
PLANT_PRODUCT (PLANT, PRODUCT): TPP, VCP, CAPP, xp;
PREPROCESS_PRODUCT (PREPROCESS_CENTER, PRODUCT): DISCB, TPB,
VCB, RB, CAPB;
RETAIL_PRODUCT (RETAIL_OUTLET, PRODUCT): PRV, VCV, DM, RV;
DISASSEMBLY_PRODUCT (DISASSEMBLY_PLANT, PRODUCT): DISCR, VCR,
CAPR;
```

```
DISASSEMBLY_MATERIAL (DISASSEMBLY_PLANT, MATERIAL): TPR, RR;
SUPPLIER_MATERIAL (SUPPLIER, MATERIAL): PRS, CAPS;
!Bill of material coefficient;
MATERIAL_PRODUCT (MATERIAL, PRODUCT): BOM;
!duty rate;
COLLECTION_PREPROCESS (COLLECTION_CENTER, PREPROCESS_CENTER):
DUTYCB;
PREPROCESS_DISASSEMBLY (PREPROCESS_CENTER,
DISASSEMBLY_PLANT): DUTYBR;
DISTRIBUTION_RETAIL (DISTRIBUTION_CENTER, RETAIL_OUTLET):
DUTYDV;
PLANT_DISTRIBUTION (PLANT, DISTRIBUTION_CENTER): DUTYPD;
DISASSEMBLY_PRODUCTPLANT (DISASSEMBLY_PLANT, PLANT): DUTYRP;
SUPPLIER_PLANT (SUPPLIER, PLANT): DUTYSP;
!3-dimension sets, transportation costs, production flow variables;
COLLECT_PREPRO_PRODUCT (COLLECTION_CENTER,
PREPROCESS_CENTER, PRODUCT): TCCB, xcb;
PREPRO_DISA_PRODUCT (PREPROCESS_CENTER, DISASSEMBLY_PLANT,
PRODUCT):TCBR, xbr;
```

```
DISTR_RETAIL_PRODUCT (DISTRIBUTION_CENTER, RETAIL_OUTLET,
PRODUCT): TCDV, xdv;
PLANT_DISTR_PRODUCT (PLANT, DISTRIBUTION_CENTER, PRODUCT):
TCPD, xpd;
DISA_PLANT_MATERIAL (DISASSEMBLY_PLANT, PLANT, MATERIAL): TCRP,
xrp;
SUPPLY_PLANT_MATERIAL (SUPPLIER, PLANT, MATERIAL): TCSP, xsp;
!Sets by county;
COLLECTION_CANADA (COLLECTION_CENTER)/COLLECT1, COLLECT2,
COLLECT3, COLLECT4, COLLECT5, COLLECT6/;
COLLECTION_EU (COLLECTION_CENTER)/COLLECT7, COLLECT8, COLLECT9,
COLLECT10/;
RETAIL_CANADA (RETAIL_OUTLET)/RETAIL1, RETAIL2, RETAIL3, RETAIL4,
RETAIL5, RETAIL6/;
RETAIL_EU (RETAIL_OUTLET)/RETAIL7, RETAIL8, RETAIL9, RETAIL10/;
DISTRIBUTION_CANADA (DISTRIBUTION_CENTER) /DISTRIB1, DISTRIB2/;
DISTRIBUTION_EU (DISTRIBUTION_CENTER) /DISTRIB3, DISTRIB4/;
PLANT_CANADA (PLANT) /PLANT1/;
PLANT_CHINA (PLANT) /PLANT2/;
PREPROCESS_CANADA (PREPROCESS_CENTER) /PREPR1, PREPR2/;
```

```
PREPROCESS_EU (PREPROCESS_CENTER) /PREPR3, PREPR4/;
DISASSEMBLY_CANADA (DISASSEMBLY_PLANT) /DISAS1/;
DISASSEMBLY_CHINA (DISASSEMBLY_PLANT) /DISAS2/;
SUPPLIER_CANADA (SUPPLIER) /SUPPLIER1, SUPPLIER2, SUPPLIER3/;
SUPPLIER_CHINA (SUPPLIER) /SUPPLIER4, SUPPLIER5, SUPPLIER6/;
ENDSETS
DATA:
! Import the data from Excel;
  DISCB, DISCR, DUTYCB, DUTYBR, DUTYDV, DUTYPD, DUTYRP, DUTYSP,
ED, EC, EP, ES, EV, EB, ER, FIXC, FIXD, FIXP, FIXB, FIXR, FIXV, PRV, PRC, PRS,
TAX, TCCB, TCBR, TCDV, TCPD, TCRP, TCSP, TPC, TPD, TPP, TPB, TPR, VCC,
VCD, VCP, VCB, VCR, VCV, DM, RV, RB, RR, BOM, CAPS, CAPP, CAPD, CAPB,
CAPR, BIG =
   @OLE( 'C:\Documents and Settings\Terry\My Documents\Thesis\case\casedata2.xls');
! Export the solution back to Excel;
    @OLE( 'C:\Documents and Settings\Terry\My Documents\Thesis\case\case result.xls')
= ys, yp, yd, yv, yc, yb, yr, xsp, xpd, xdv, xcb, xbr, xrp;
ENDDATA
! The objective;
  MAX = @SUM( COUNTRY:
```

```
        (1-TAX) * nibtplus - nibtminus);

  ! The net income before tax;

  @FOR( COUNTRY: nibtd + nibtp + nibtv + nibtc + nibtb + nibtr = nibtplus -
nibtminus);

 ! The net income before tax - distribution centers - Canada;

  nibtd(1)= @SUM(DISTRIBUTION_CANADA(d): - FIXD(d) * yd(d) +
@SUM(PRODUCT(i):( TPD(d,i) - VCD(d,i))* @SUM(RETAIL_OUTLET(v):
xdv(d,v,i)))- @SUM(PLANT(p): @SUM(PRODUCT(i):
xpd(p,d,i)*((1+DUTYPD(p,d))*TPP(p,i) + TCPD(p,d,i)))/ EP(p)));

! The net income before tax - distribution centers - EU;

  nibtd(2)= @SUM( DISTRIBUTION_EU(d): - FIXD(d) * yd(d)/ED(d) +
@SUM(PRODUCT(i):( TPD(d,i) - VCD(d,i))* @SUM(RETAIL_OUTLET(v):
xdv(d,v,i)))/ED(d)- @SUM(PLANT(p): @SUM(PRODUCT(i):
xpd(p,d,i)*((1+DUTYPD(p,d))*TPP(p,i) + TCPD(p,d,i)))/ EP(p)));

! The net income before tax - distribution centers - China;

   nibtd(3)= 0;

! The net income before tax - Retail outlets - Canada;

 nibtv(1) = @SUM(RETAIL_CANADA(v): - FIXV(v) * yv(v) +
@SUM(PRODUCT(i):(PRV(v,i) - VCV(v,i))*
@SUM(DISTRIBUTION_CENTER(d):xdv(d,v,i)))-
```

```
@SUM(DISTRIBUTION_CENTER(d): @SUM(PRODUCT(i): ((1+ DUTYDV(d,v))*
TPD(d,i) + TCDV(d,v,i))* xdv(d,v,i))/ ED(d)));
! The net income before tax - Retail outlets - EU;
 nibtv(2)= @SUM(RETAIL_EU(v):  - FIXV(v) * yv(v)/EV(v) +
@SUM(PRODUCT(i):(PRV(v,i) - VCV(v,i))*
@SUM(DISTRIBUTION_CENTER(d):xdv(d,v,i)))/EV(v)-
@SUM(DISTRIBUTION_CENTER(d): @SUM(PRODUCT(i): ((1+ DUTYDV(d,v))*
TPD(d,i) + TCDV(d,v,i))* xdv(d,v,i))/ ED(d)));
! The net income before tax - Retail outlet - China;
  nibtv(3)= 0;
! The net income before tax - collection center - Canada;
  nibtc(1)= @SUM(COLLECTION_CANADA(c): - FIXC(c) * yc(c) +
@SUM(PRODUCT(i):(TPC(c,i) - PRC(c,i) -
VCC(c,i))*@SUM(PREPROCESS_CENTER(b): xcb(c,b,i))));
! The net income before tax - collection center - EU;
  nibtc(2)= @SUM(COLLECTION_EU(c): - FIXC(c) * yc(c)/EC(c) +
@SUM(PRODUCT(i):(TPC(c,i) - PRC(c,i) -
VCC(c,i))*@SUM(PREPROCESS_CENTER(b): xcb(c,b,i)))/EC(c));
! The net income before tax - collection center - China;
  nibtc(3)= 0;
! The net income before tax - preprocess center - Canada;
```

```
 nibtb(1)= @SUM(PREPROCESS_CANADA(b): - FIXB(b)* yb(b) +
@SUM(PRODUCT(i):(TPB(b,i)-VCB(b,i))* @SUM(DISASSEMBLY_PLANT(r):
xbr(b,r,i)))- @SUM(COLLECTION_CENTER(c): @SUM(PRODUCT(i): ((1+
DUTYCB(c,b))* TPC(c,i)+ TCCB(c,b,i))* xcb(c,b,i)/EC(c)))- @SUM(PRODUCT(i): (1-
RB(b,i))* DISCB(b,i)* @SUM(COLLECTION_CENTER(c): xcb(c,b,i))));
! The net income before tax - preprocess center - EU;
 nibtb(2)= @SUM(PREPROCESS_EU(b): - FIXB(b)* yb(b)/EB(b) +
@SUM(PRODUCT(i):(TPB(b,i)-VCB(b,i))* @SUM(DISASSEMBLY_PLANT(r):
xbr(b,r,i)))/EB(b)- @SUM(COLLECTION_CENTER(c): @SUM(PRODUCT(i): ((1+
DUTYCB(c,b))* TPC(c,i)+ TCCB(c,b,i))* xcb(c,b,i)/EC(c)))- @SUM(PRODUCT(i): (1-
RB(b,i))* DISCB(b,i)* @SUM(COLLECTION_CENTER(c): xcb(c,b,i)))/EB(b));
! The net income before tax - preprocess center - China;
 nibtb(3)= 0;
! The net income before tax - Plant - Canada;
 nibtp(1)= @SUM(PLANT_CANADA(p): - FIXP(p) * yp(p) + @SUM(PRODUCT(i):
(TPP(p,i)- VCP(p,i))* xp(p,i))- @SUM(SUPPLIER(s): @SUM(MATERIAL(m): ((1+
DUTYSP(s,p))* PRS(s,m)+ TCSP(s,p,m))* xsp(s,p,m))/ES(s))-
@SUM(DISASSEMBLY_PLANT(r): @SUM(MATERIAL(m): ((1+ DUTYRP(r,p))*
TPR(r,m) + TCRP(r,p,m))* xrp(r,p,m))/ER(r)));
! The net income before tax - plant - EU;
 nibtp(2)= 0;
! The net income before tax - Plant - China;
```

```
  nibtp(3)= @SUM(PLANT_CHINA(p): - FIXP(p) * yp(p)/EP(p) +
@SUM(PRODUCT(i): (TPP(p,i)- VCP(p,i))* xp(p,i))/EP(p)- @SUM(SUPPLIER(s):
@SUM(MATERIAL(m): ((1+ DUTYSP(s,p))* PRS(s,m)+ TCSP(s,p,m))*
xsp(s,p,m))/ES(s))- @SUM(DISASSEMBLY_PLANT(r): @SUM(MATERIAL(m): ((1+
DUTYRP(r,p))* TPR(r,m) + TCRP(r,p,m))* xrp(r,p,m))/ER(r)));
! The net income before tax - Disassembly plant - Canada;
  nibtr(1)= @SUM(DISASSEMBLY_CANADA(r): - FIXR(r)* yr(r)+
@SUM(MATERIAL(m): TPR(r,m)* @SUM(PLANT(p): xrp(r,p,m)))-
@SUM(PREPROCESS_CENTER(b): @SUM(PRODUCT(i): ((1+ DUTYBR(b,r))*
TPB(b,i)+ TCBR(b,r,i))* xbr(b,r,i))/EB(b))- @SUM(PRODUCT(i):(VCR(r,i)+
DISCR(r,i))* @SUM(PREPROCESS_CENTER(b): xbr(b,r,i))));
! The net income before tax - disassembly plant - EU;
  nibtr(2)= 0;
! The net income before tax - Disassembly plant - China;
  nibtr(3)= @SUM(DISASSEMBLY_CHINA(r): - FIXR(r)* yr(r)/ER(r)+
@SUM(MATERIAL(m): TPR(r,m)* @SUM(PLANT(p): xrp(r,p,m)))/ER(r)-
@SUM(PREPROCESS_CENTER(b): @SUM(PRODUCT(i): ((1+ DUTYBR(b,r))*
TPB(b,i)+ TCBR(b,r,i))* xbr(b,r,i))/EB(b))- @SUM(PRODUCT(i):(VCR(r,i)+
DISCR(r,i))* @SUM(PREPROCESS_CENTER(b): xbr(b,r,i)))/ER(r));
! Capacity constrains of all suppliers;
@FOR(SUPPLIER(s):
   @FOR(MATERIAL(m):
```

```
        @SUM(PLANT(p): xsp(s,p,m))<= CAPS(s,m)

));

! Capacity constrains of all PLANTS;

@FOR(PLANT(p):

    @FOR(PRODUCT(i):

        @SUM(DISTRIBUTION_CENTER(d): xpd(p,d,i))<= CAPP(p,i)

));

! Capacity constrains of all distribution centers;

@FOR(DISTRIBUTION_CENTER(d):

    @FOR(PRODUCT(i):

        @SUM(PLANT(p): xpd(p,d,i))<= CAPD(d,i)

));

! Capacity constrains of all preprocess center;

@FOR(PREPROCESS_CENTER(b):

    @FOR(PRODUCT(i):

        @SUM(COLLECTION_CENTER(c): xcb(c,b,i))<= CAPB(b,i)

));

! Capacity constrains of all disassembly plants;

@FOR(DISASSEMBLY_PLANT(r):
```

```
    @FOR(PRODUCT(i):

        @SUM(PREPROCESS_CENTER(b): xbr(b,r,i))<= CAPR(r,i)

));

! Customer demand constraints;

@FOR(RETAIL_OUTLET(v):

      @FOR(PRODUCT(i):

          @SUM(DISTRIBUTION_CENTER(d): xdv(d,v,i))<= DM(v,i)

));

! Bill-of-Material at plants;

@FOR(PLANT(p):

      @FOR(MATERIAL(m):

          @SUM(SUPPLIER(s): xsp(s,p,m)) + @SUM(DISASSEMBLY_PLANT(r):

xrp(r,p,m)) = @SUM(PRODUCT(i):BOM(m,i)* xp(p,i))

));

! Reverse Bill of Material at disassembly plants;

@FOR(DISASSEMBLY_PLANT(r):

      @FOR(MATERIAL(m):

          @SUM(PRODUCT(i): RR(r,m)* BOM(m,i)*

@SUM(PREPROCESS_CENTER(b): xbr(b,r,i)))>= @SUM(PLANT(p): xrp(r,p,m))

));
```

```
! Conservation of flow;
@FOR(PLANT(p):
    @FOR(PRODUCT(i):
        xp(p,i)= @SUM(DISTRIBUTION_CENTER(d): xpd(p,d,i))
));
@FOR(DISTRIBUTION_CENTER(d):
    @FOR(PRODUCT(i):
        @SUM(PLANT(p):xpd(p,d,i))= @SUM(RETAIL_OUTLET(v): xdv(d,v,i))
));
@FOR(COLLECTION_CENTER(c):
    @FOR(PRODUCT(i):
        @SUM(PREPROCESS_CENTER(b):xcb(c,b,i))<=
RV(c,i)*@SUM(DISTRIBUTION_CENTER(d): xdv(d,c,i))
));
@FOR(PREPROCESS_CENTER(b):
    @FOR(PRODUCT(i):
        @SUM(DISASSEMBLY_PLANT(r):xbr(b,r,i))= RB(b,i)*
@SUM(COLLECTION_CENTER(c): xcb(c,b,i))
));
! Logical Constraints for decision variables;
```

```
@FOR(PLANT(p):
   @SUM(DISTRIBUTION_CENTER(d): @SUM(PRODUCT(i): xpd(p,d,i)))<=BIG*
yp(p)
);
@FOR(SUPPLIER(s):
   @SUM(PLANT(p): @SUM(MATERIAL(m): xsp(s,p,m)))<=BIG* ys(s)
);
@FOR(DISTRIBUTION_CENTER(d):
   @SUM(RETAIL_OUTLET(v): @SUM(PRODUCT(i): xdv(d,v,i)))<=BIG* yd(d)
);
@FOR(RETAIL_OUTLET(v):
   @SUM(DISTRIBUTION_CENTER(d): @SUM(PRODUCT(i): xdv(d,v,i)))<=BIG*
yv(v)
);
@FOR(COLLECTION_CENTER(c):
   @SUM(PREPROCESS_CENTER(b): @SUM(PRODUCT(i): xcb(c,b,i)))<=BIG*
yc(c)
);
@FOR(PREPROCESS_CENTER(b):
```

```
    @SUM(DISASSEMBLY_PLANT(r): @SUM(PRODUCT(i): xbr(b,r,i)))<=BIG*
yb(b)
);
@FOR(DISASSEMBLY_PLANT(r):
    @SUM(PLANT(p): @SUM(MATERIAL(m): xrp(r,p,m)))<=BIG* yr(r)
);
! Bounds on decision variables;
@FOR(COUNTRY(k): @FREE(nibtd(k)));
@FOR(COUNTRY(k): @FREE(nibtp(k)));
@FOR(COUNTRY(k): @FREE(nibtv(k)));
@FOR(COUNTRY(k): @FREE(nibtc(k)));
@FOR(COUNTRY(k): @FREE(nibtb(k)));
@FOR(COUNTRY(k): @FREE(nibtr(k)));
@FOR(PLANT(p): @BIN(yp(p)));
@FOR(DISTRIBUTION_CENTER(d): @BIN(yd(d)));
@FOR(RETAIL_OUTLET(v): @BIN(yv(v)));
@FOR(COLLECTION_CENTER(c): @BIN(yc(c)));
@FOR(PREPROCESS_CENTER(b): @BIN(yb(b)));
@FOR(DISASSEMBLY_PLANT(r): @BIN(yr(r)));
@FOR(SUPPLIER: @BIN(ys));
```

```
! Integer variables;

!@FOR(PLANT_PRODUCT: @GIN(xp));

!@FOR(COLLECT_PREPRO_PRODUCT: @GIN(xcb));

!@FOR(PREPRO_DISA_PRODUCT: @GIN(xbr));

!@FOR(DISTR_RETAIL_PRODUCT: @GIN(xdv));

!@FOR(PLANT_DISTR_PRODUCT: @GIN(xpd));

!@FOR(DISA_PLANT_MATERIAL: @GIN(xrp));

!@FOR(SUPPLY_PLANT_MATERIAL: @GIN(xsp));

END
```