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MODELING AND ANALYSIS OF A REVERSE SUPPLY CHAIN NETWORK FOR LEAD-ACID BATTERY MANUFACTURING

By

Hailun (Helen) Zhang

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through the Department of Industrial and Manufacturing Systems Engineering
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ABSTRACT

The North American lead-acid battery industry gains its environmental edge from its employment of closed-loop life cycle production. Nowadays, the typical new lead-acid battery contains 60 to 80 percent recycled lead and plastics.

In this thesis, the closed-loop supply chain of a lead-acid battery manufacturing process has been investigated which extends the traditional supply chain to the entire product life cycle. A new tactical planning model has been developed for the entire closed-loop manufacturing process including purchasing, production, and end-of-life product return and recycling. The model is a multi-objective, multi-echelon mixed integer linear programming model, which minimizes the total costs and the total transportation pollution emissions, subject to structural and functional constraints. Decisions are made regarding material procurement, production, recycling and inventory levels, and the transportation modes between the echelons. Sensitivity analysis has been performed to evaluate the integration with third party outsourcing, changes in parameters and design options.

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This master's study afforded me the opportunity to broaden and improve my skill and knowledge of industrial engineering. I appreciate this experience and I am grateful for those people who gave me this chance.

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CHAPTER 1 – INTRODUCTION

In 1982, two management consultants, Keith R. Oliver and Michael D. Webber, coined the term Supply Chain Management (SCM). As they noted: "conflicting functional objectives along the supply chain are reconciled and balanced ... and finally, that an integrated systems strategy that reduces the vulnerability is developed and implemented" (Oliver and Webber, 1982). According to them, forming a supply chain out of a group of individual companies which acts like a single entity is a challenging and rewarding task.

In the short history of supply chain management research, many authors have tried to define SCM concisely and accurately. The simplest definition by far has been given by Customer Relationship Management (CRM) Primer*. "This is the process of optimizing the delivery of goods, services, and information from the supplier to the customer."

During the pasted years, SCM concept has been worldwidely accepted, and thousands of the models and case studies have been done approached to traditional supply chain design and modeling. Today reverse logistics/close-loop supply chain attracts the attention of both academic and industrial world. In this research work, a model for reverse supply chain network has been developed within a close-loop domain based on operations research point of view. This main achievement of the model is that it addressed both the environmental and the economic objective on a tactical planning level base, which can provided a decision making tool for the management.

1.1. Forward supply chains

The forward supply chain, also known as the forward logistics network (Figure 1.1), consists of suppliers, plants, distribution centers, and retail outlets, as well as raw

---

* Customer Relationship Management (CRM) Primer, Available at http://www.crmguru.com/members/primer/index.html

materials, work in process (WIP) and finished products that flow between the nodes along the chain (Simchi-levi, et al., 2004). With advance planning, a decision maker can:

- Minimize inventory, transportation and manufacturing costs
- Match supply and demand under uncertainty by adjusting inventories

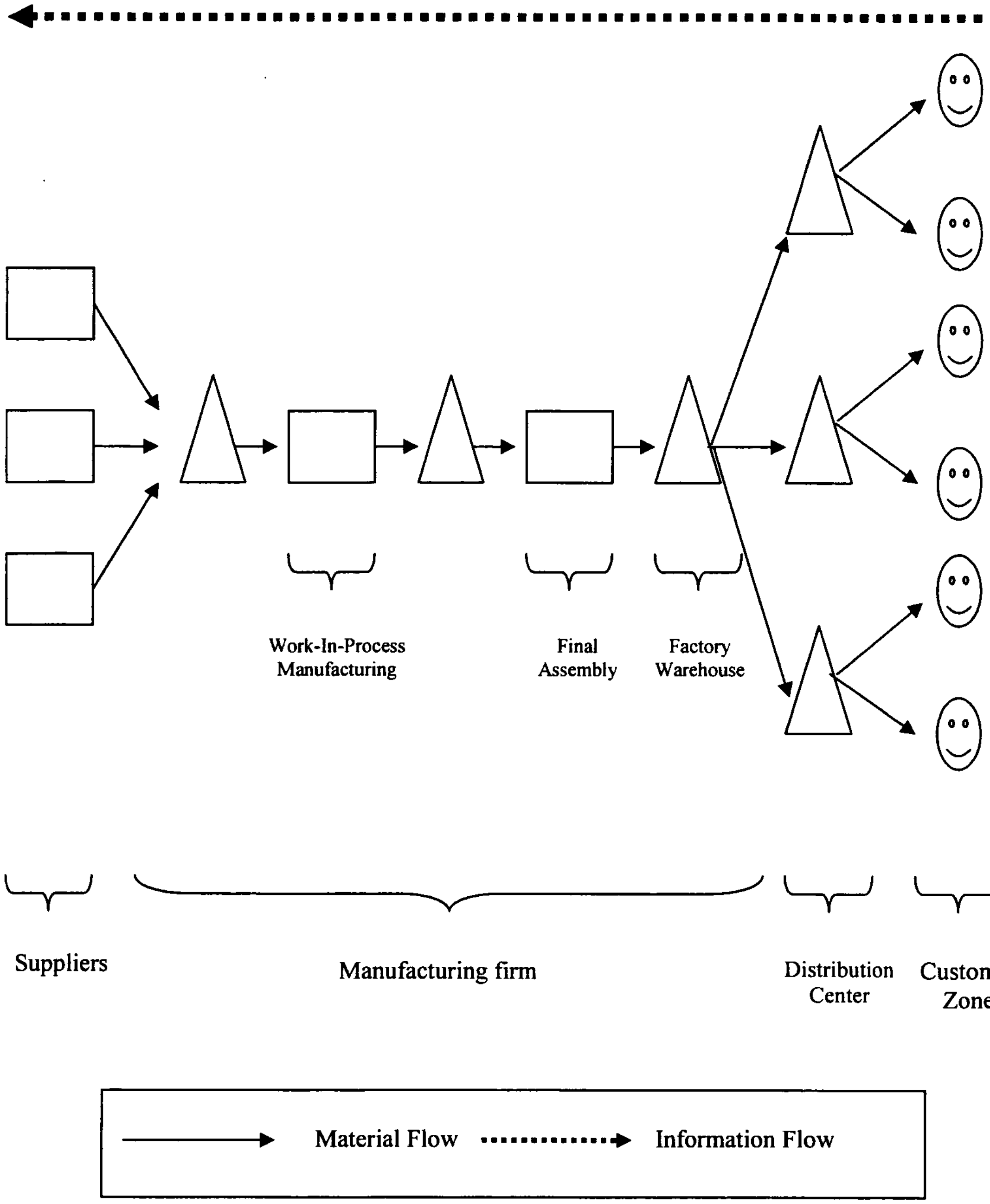


Figure 1.1: Typical forward supply chain network flow (Revised from Stadtler and Kilger, 2000)

Optimizing supply chain networks in the real world business environment is a very difficult task because that the supply chain leader, usually refer to the manufacturer along the supply chain, has to deal with inherent uncertainties in supply and demand along with conflicting objectives and tradeoffs along the different elements along the chain.

1.2. Reverse supply chains

The Council of Logistics Management (CLM) has defined the reverse supply chain as "...the term often used to refer to the role of logistics in recycling, waste disposal, and management of hazardous materials."*

Tibben-Lembke and Rogers (2002) more accurately and in-detail defined reverse logistics as "...the process of planning, implementing and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods, and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal."

Reverse supply chain networks may be classified into several categories based on the source of the reverse flow, destination, in-transit position and transportation mode.

With respect to the source of the reverse flow, the returned items can come from:

- End-of-use returns
- Commercial returns
- Warranty returns
- Production scrap and by-products
- Packaging

With respect to product destinations, the items may be:

- Returned to the vender
- Repackaged and sold as new
- Sold via outlet

---

* Council of Logistics Management (CLM): reorganized as Council of Supply Chain Management Professionals (CSCMP). Information available at http://www.cscmp.org/

- Sold to the broker
- Remanufactured/refurbished
- Donated to charity
- Recycled
- Sent to landfill

Fleischmann et al. (1997) pointed out that reverse logistics is "not necessarily a symmetric picture of forward distribution". Compared to the forward logistics flow, a reverse logistics flow is much more reactive and much less visible.

In a reverse supply chain, the most important position is the returned items collection center. When a consumer returns an item to a retail store, the store collects the items to be sent to a centralized return center (CRCs) which processes all returned products (Tibben-Lembke and Rogers, 2002). Theoretically, the forward distribution center (DC) could be used as the place to process the returned products. When the products arrive at the CRC/DC, the employees assess the condition of each incoming item and decide on its destination. A typical reverse supply chain network framework is shown in Figure 1.2.

1.3. Differences and relations between forward and reverse supply chains

Three important characteristics differentiate a reverse logistics system from a traditional supply chain system:

- Most logistics systems are not equipped to handle product movement in a reverse channel
- Reverse distribution costs may be higher than moving the original product from the manufacturing site to the consumer
- Returned goods often cannot be transported, stored, or handled in the same manner as in the regular channel

Table 1.1 shows a comparison of how various features of logistics systems differ in forward and reverse supply chain networks, and a comparison of the costs in the two networks is provided in Table 1.2.

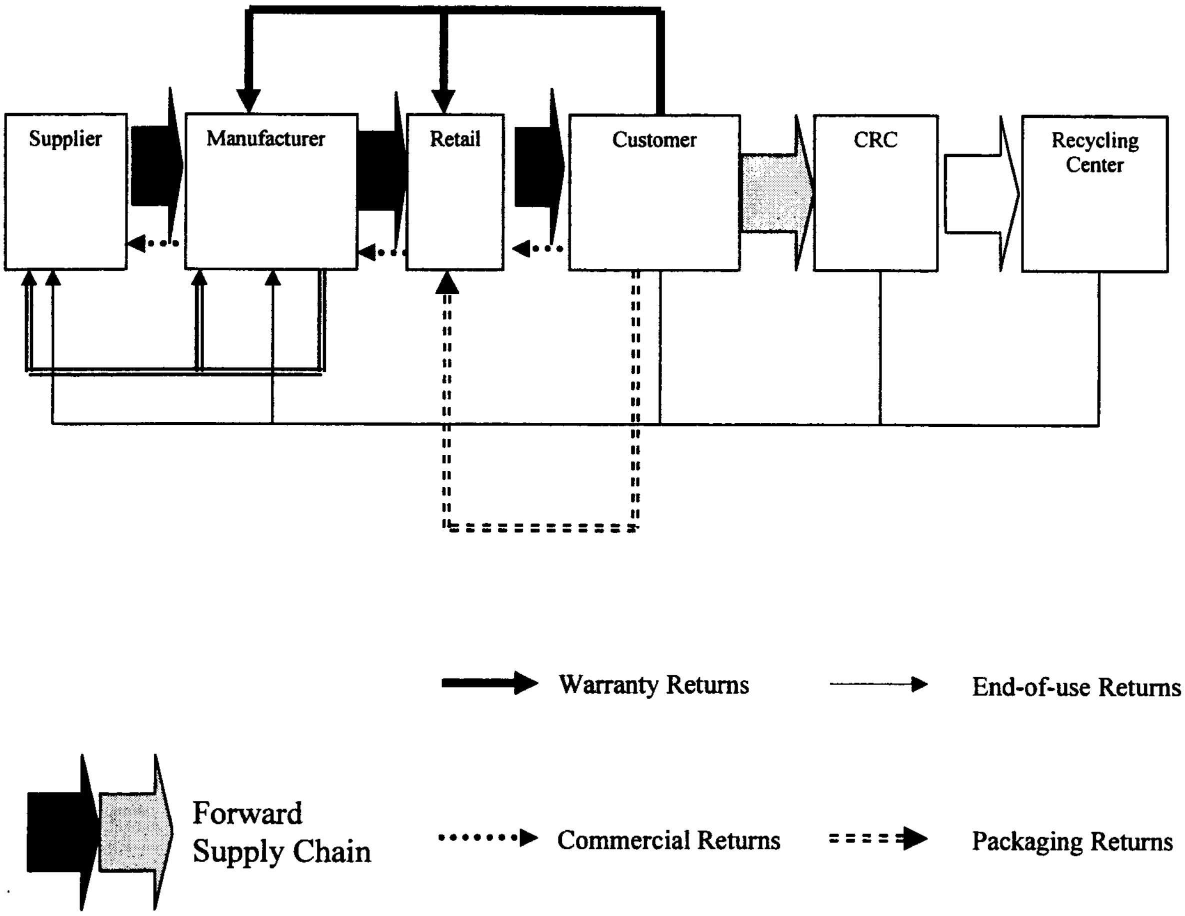


Figure1.2: Reserve logistics flows in a supply chain (revised from Fleischmann, 2001)

Table 1.1: Differences in forward and reverse logistics (modified from Tibben-Lembke and Rogers, 2002)

Category	**Forward Supply Chain**	**Reverse Supply Chain**
Forecasting	Straightforward	Difficult
Product arrival	Uncertain demand	Random
Transportation	One to many	Many to one
Quality	Product quality uniform	Product quality not uniform
Packaging	Product packaging uniform	Product packaging often damaged
Routing	Decided and clear	Unclear
Channel	Standardized channel	Exception driven
Disposition	Disposition options clear	Not clear
Pricing	Uniform	Depend on many factors
On-time	Important	Not considered as priority
Inventory management	Consistent	More affected by seasonal accounting deadlines
Tracking Information	Real-time information available	Less visible
Handling	Uniform	More complex
Marketing	Regular marketing method	More restrictions

Table 1.2: Comparison of the costs in forward and reverse logistics

Cost	**Forward Logistics**	**Reverse Logistics**
Ordering	Important	Less important
Handling	Lower	Much higher
Transportation	Lower	Higher, more shipping required
Holding	Higher	Lower
Collecting	Does not exist	Important
Sorting, Quality diagnosis	Lower	Much higher
Refurbishment	Does not exist	Significant in reverse logistics

The importance of information use in the supply chain is to link the point of production seamlessly with the point of delivery or purchase. The idea is to have an information trail that follows the product's physical trail.

Figure 1.3 shows the information and physical material flows at the retailer point in the forward logistics system. The forward logistics forecast is used to help predict the demand, and the shipments are sent in response to the need at each level of the network. At each level, advanced shipping notices (ASN) provide visibility for the product coming in.

Compared to the forward logistics network, the reverse logistics flow is much different. There is almost no planning and decision making on the part of the firms (Figure 1.4.). When a customer returns an item to a retailer, the store collects the items to be sent to a centralized return center (CRC), and meanwhile, the information about the item and the condition of the end-of-life (EOL) dead product is recorded and entered into the system.

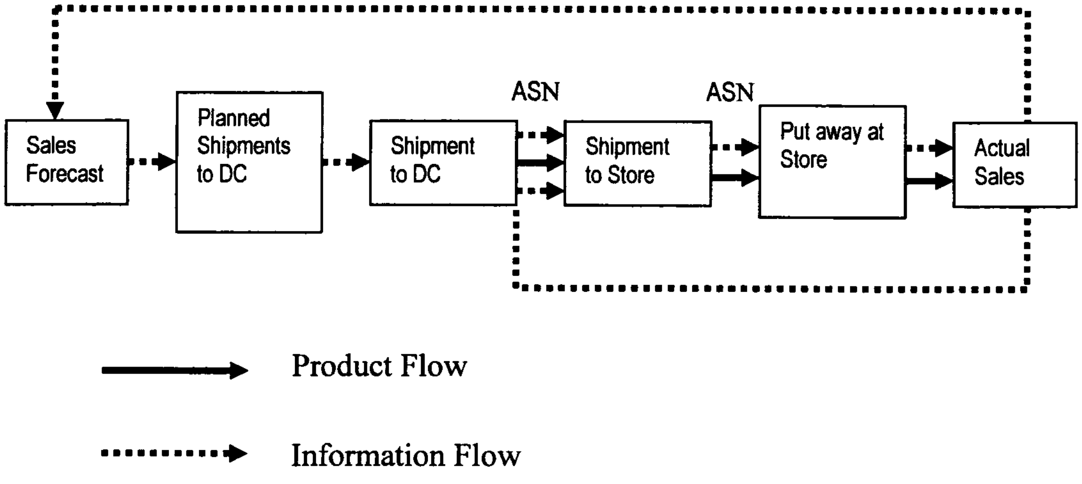
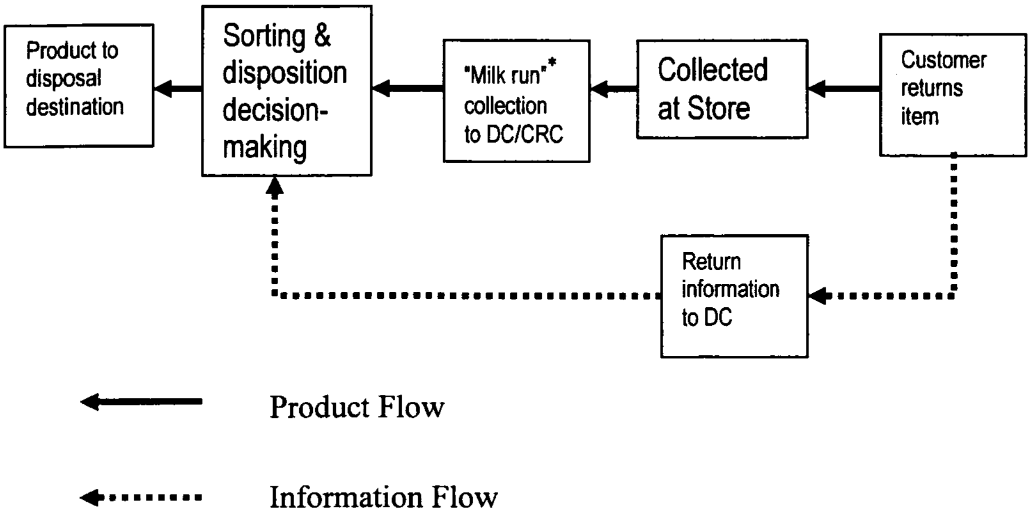


Figure 1.3: Forward logistics information flow for retail (Tibben-Lembke and Rogers, 2002)



* Milk run is a routing method which involves stops at many places.

Figure 1.4: Reverse logistics information flow retail (Tibben-Lembke and Rogers, 2002)

There are mainly four reasons that lead companies to strategize their reverse supply chains. First, substantial long term economic benefits can be derived from maintaining beneficial contacts with customers through customer service in addition to value added production recycling (Reddy, 2002).

Second, companies can reduce the "bullwhip effect" by using a reverse supply chain to get slow-moving products off distribution networks and into recycling channels. In the traditional supply chain, companies assume that consumers will buy all the products put in the distribution channel. When products are not moving, sales strategies such as markdowns and closeout sales are employed to entice customers. These sales practices send false demand signals up the supply chain. The reverse supply chain would have isolated the traditional supply chain system from receiving false demand signals. The reverse supply chain could then move the products to other channels for profitable disposal.

The third reason is the concept of industrial ecology (Seuring, 2004). With the reverse supply chain, the business can exist within an extended supply chain of environmental and ecological resources, and waste and inefficiency in this eco-supply chain will be eliminated, just as economic waste must be eliminated in the narrower supply chain of business activities.

The last and the most important reason is that a growing concern for the environment has led to a range of new environmental policies for various industries in which the recovery of waste is an essential element.

Policy and trade of waste management are increasingly influenced worldwide by the European Union. As part of this, EU member states have to follow guidelines for implementation of European environmental policies. A number of so-called priority waste streams have been defined. Special directives are in force, e.g., the directive on Waste of Electrical and Electronics Equipment (WEEE) (submitted 2001), the directive on Restriction on Hazardous Substances (RoHS) and the one on Eco-design of End-use Equipment (EEE). Once the directives are in force, EU member states must implement them into legislation on "producer responsibility" within 18 months*.

In June 2001, the EU environmental ministers agreed in principle to bring the above directive in force. It boils down to the following targets for member states:

- Minimize the use of dangerous substances and phase out a number of plastics and some materials (e.g. Mercury) (RoHS)
- Promote design for recycling (EEE)
- Producers should take responsibility for end-of-life phases of their products, encode new products for identification, and provide information to the processors for accurate recycling (WEEE)
- Appropriate systems for separate collection of WEEE should be put in place and private households are entitled to return for free
- Producers have to set up and finance appropriate systems in order to ensure accurate processing and reuse/recycling of WEEE and the producers are responsible for all these processing activities from the beginning of the collection
- A collection target of 4 kg WEEE per head of populations has been set per year. Collection services must be offered by retailers (trade-ins) and municipalities.

---

* EUROPA-Environmental, available at: http://www.europa.eu.int/comm/environmental and US Environmental Protection Agency, available at: http://www.epa.gov

Goods must be collected separately and pre-processed such that optimal recovery is possible (WEEE)

- Recovery quotas are set between 70% and 90% for the goods collected depending on the product category. Hazardous contents must be removed at all times and processed according to strict prescriptions. Reuse in the original supply chain is encouraged, however, only plastics are the targets (5% of weight of newly produced consumer electronics) (WEEE)

Producers will be responsible for collecting, sorting and recycling of discarded products at the end of their service life, a process knows as extended product responsibility (EPR). Most of the North American manufacturers, especially the automobile OEMs (Original Equipment Manufacturers) and their part suppliers, are willing to take this EPR in order to enter the European automobile market.

With remanufacturing and recycling through outsourcing, the companies have to pay extra costs which lead to higher lifecycle costs for their products. Therefore, an integrated network planning system of closed-loop supply chain, which connects the forward supply chain network and the reverse supply chain network, has been introduced.

1.4. Closed loop supply chains

Closed Loop Supply Chains (CLSC) are designed to consider the acquisition and return flows of products, reuse activities, and the distribution of the recovered products (Guide et al., 2003). It links the reverse logistics to the forward supply chain since in many cases the original suppliers or the manufacturers are in the best position to control all the returns. The CLSC is defined as a full process of shipment out and back by the same organization, found particularly in high-tech service and support roles (Blumberg, 2005).

Figure 1.5 shows the high tech closed loop supply chain pipeline established by Blumberg (2005). It involves the continuing flow of parts, sub assemblies, and the whole units. At the central warehouse facility, material flows in form the organization's manufacturer or vendor (to the extent they exist), as well as through a return loop from the field for failed subassemblies return operations. The parts (stock keeping units, SKU), subassemblies, and whole units then flow downward to the regional warehouses or part depots, and ultimately to test service engineers, installers in the field, or both. This material is then used in the installation, maintenance, and repair tasks associated with servicing the installed customer base.

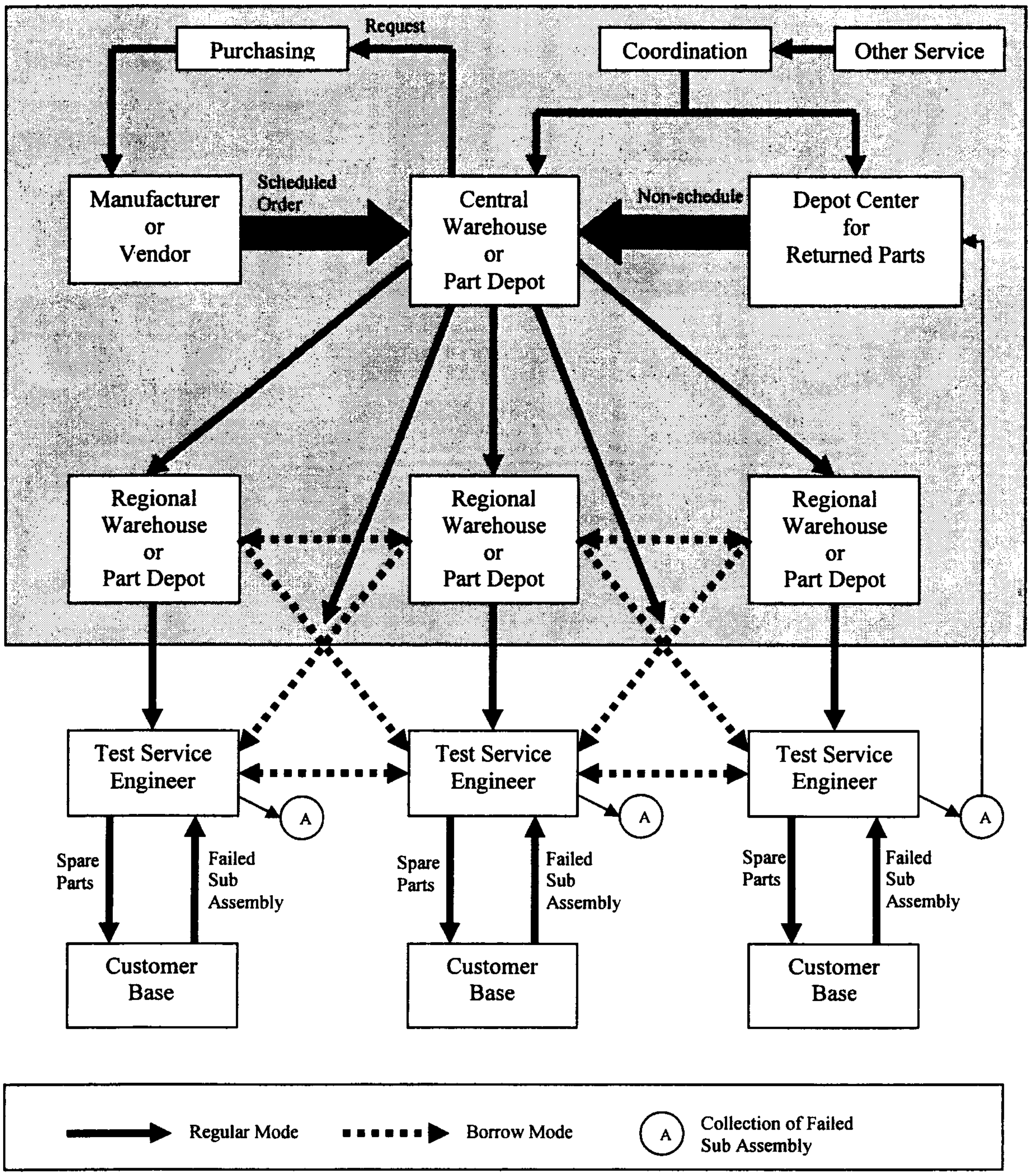


Figure 1.5: High tech closed loop supply chain pipeline (modified from Blumberg, 2005)

1.5. Scope of study

In this research, the purpose is to develop an integrated closed-loop supply chain network model connecting the forward supply chain network with the reverse network. The boundary in this case will be set at the collection center (theoretically at the same location as the distribution center) and the manufacturing plant, as shown in Figure 1.6.

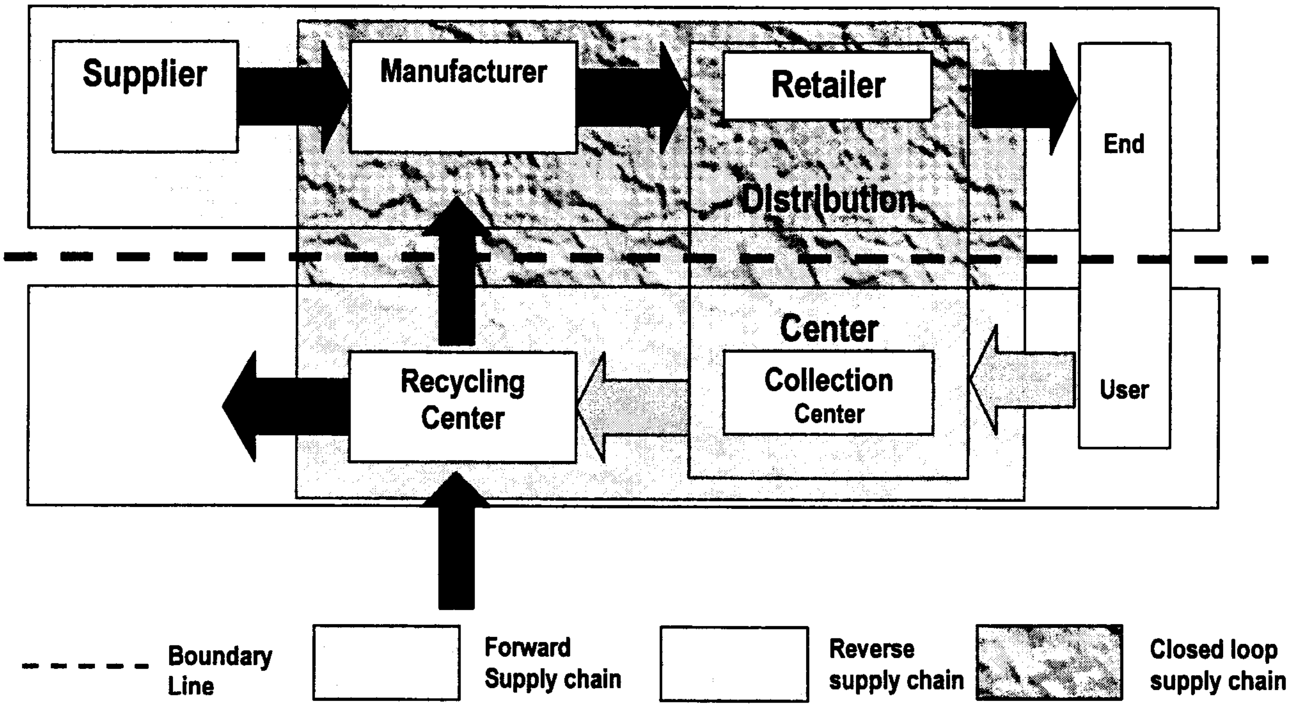


Figure 1.6: The boundary of forward supply chain and reverse supply chain

The proposed model is based on the operations of a battery manufacturer located in North America. The company is a leading manufacturer of lead-acid batteries like SLI (Starting, Lighting & Ignition) batteries, industrial batteries and stationary batteries. The company operates five manufacturing plants, one large on-site centralized warehouse, one recycling center and one plastics molding plant on its two-million-square-foot plant site. In addition to these facilities, the company also has five regional distribution centers distributing more than 4,000 different kinds of batteries to both the OEM and the aftermarket (AM). The company has approximately 4,500 employees and net sales of $2.5 billion USD in the 2004 fiscal year.[*]

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[*] Information is available at http://www.eastpenn-deka.com/

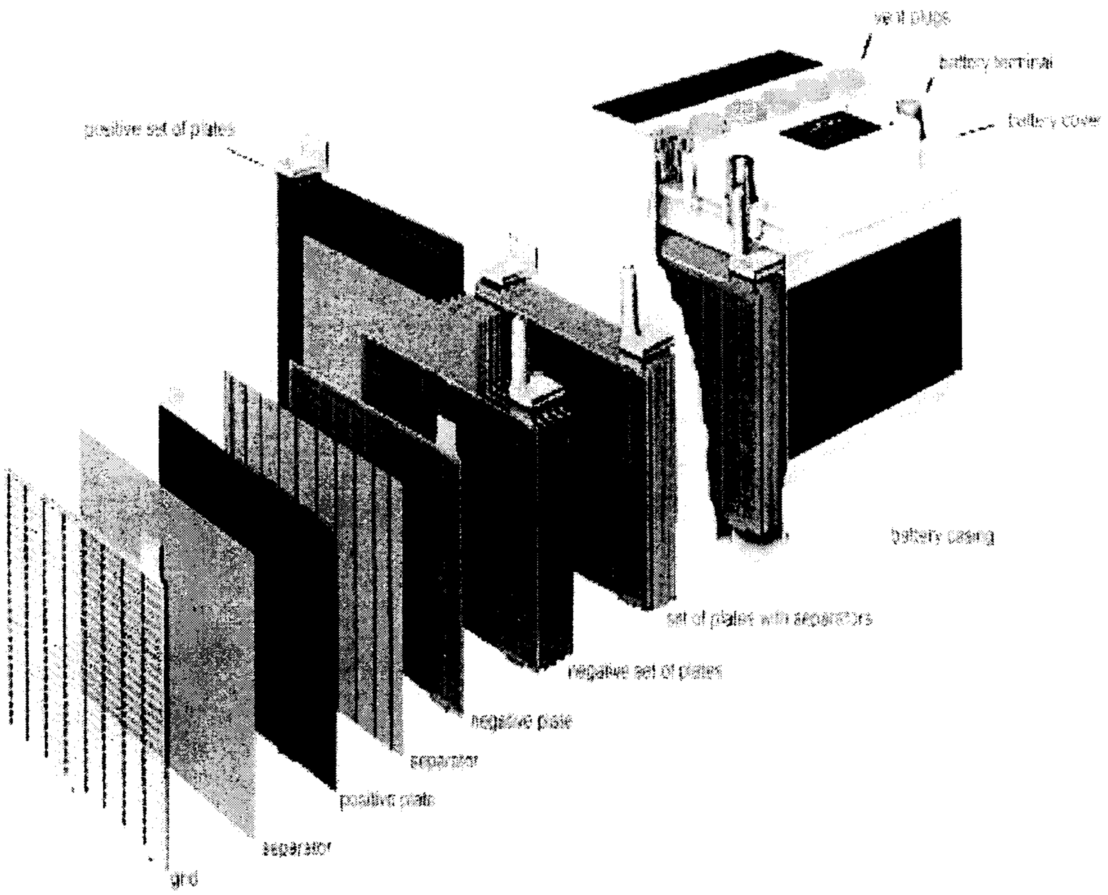

Figure 1.7: Product components of a basic lead-acid battery (Battery Council International)

This industry has been chosen for this study because in the lead-acid battery manufacturing, roughly 96 percent of all battery lead is recycled. A typical lead battery contains 18-20 pounds of lead, 11 pounds of sulfuric acid, and three pounds of plastic – all reclaimable, recyclable and reusable. Product components are shown in Figure 1.7. Almost 20 percent of all U.S. homes store at least one old automotive-type battery, amounting to 30-40 million used lead batteries in storage.*

---

* Survey from Battery Council International, available at www.batterycouncil.org/

The main characteristics of the proposed model are:

- seasonal and downward trend demand for finished goods
- long lead time for manufacturing process
- manufacturing and recycling are parts of the same decision making system with separate inventory systems
- integration of forward and reverse distribution systems
- closed loop supply chain network consideration
- centralized safety stock policy for the raw materials inventory. Both the virgin raw materials and the recycled materials will be considered as incoming material flow simultaneously
- based on the fact that the company has a large on-site warehouse, centralized safety stock policy for finished goods will be used at the manufacturing facility

The material flow diagram in Figure 1.8 shows the proposed model of the lead-acid battery manufacturer. In this specific system, the manufacturer produces the batteries based on customer demand. It keeps the finished goods at the centralized warehouses to a safety stock level, and delivers them to the regional distribution center through its distribution network. The customers pick up the batteries by themselves so that the batteries flow out of the system for their service life. After their service life, some portion (50%~70%) of the end-of-life dead products will be returned to distribution centers through the channel of dead product recall and bad product return. These dead products enter the system again as the source of recycled raw materials. The on-site recycling center obtains these dead products and processes them into recycled raw materials; these recycled raw materials combined with the virgin raw materials enter the manufacturing operations to make new batteries.

As a tactical level model, the planning horizon has been decided as five weeks (week is the length of the period for planning), because in the presence of seasonal and non-uniform demand patterns, the forecast loses its accuracy over longer periods. Also, when the transportation lead time is small compared to the length of the planning period, the effects of in-transit inventory tends to be ignored or neglected.

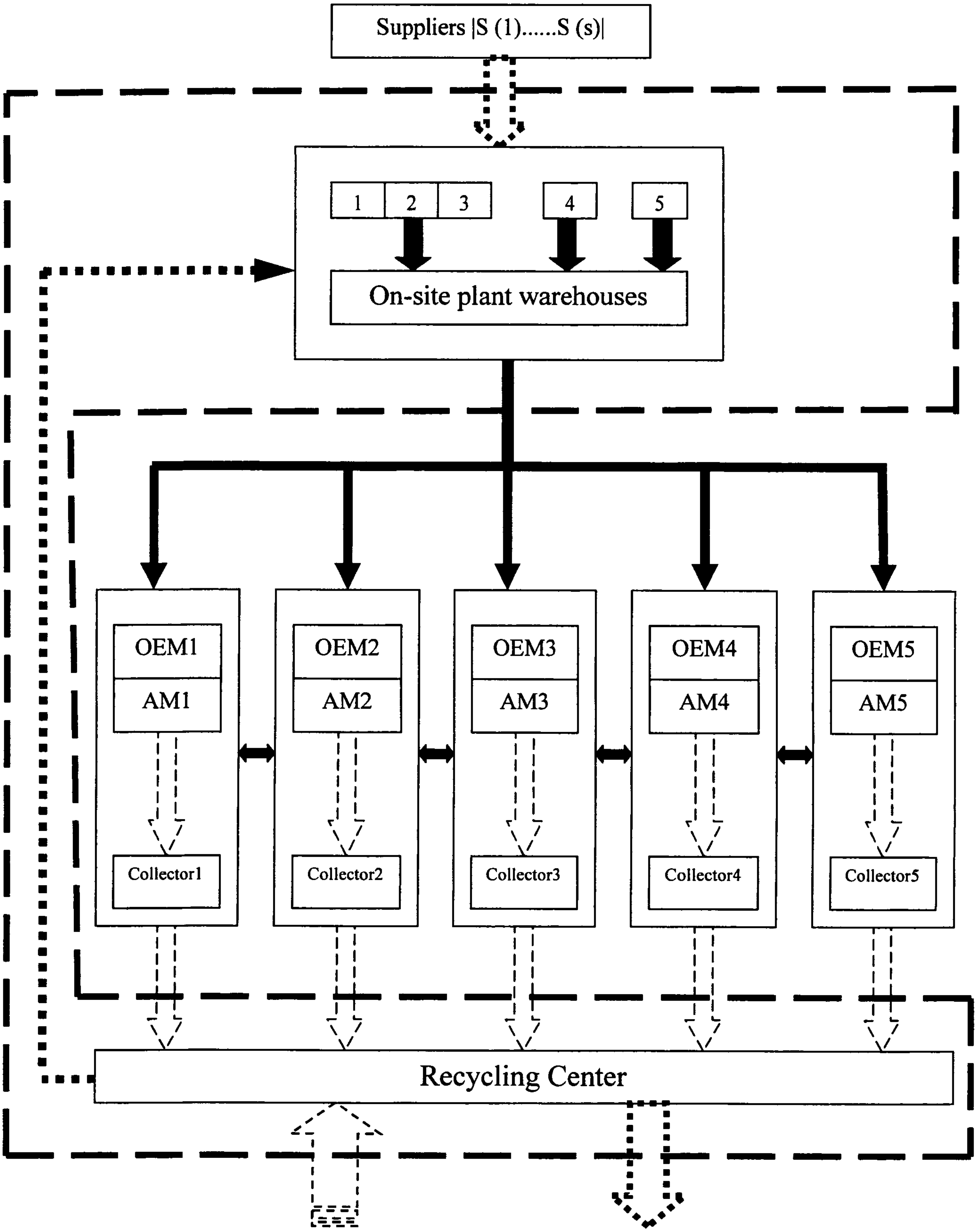

Figure 1.8: Material flow diagram of the case study

1.6. Outline of the thesis

The materials presented in this thesis have been organized into the following chapters:

1. **Introduction:** A brief background of the definitions and the decisions in reverse supply chain is provided. The research work undertaken has been explained, and the scope of the current research has been discussed briefly.
2. **Literature review**: A detailed review of literature in the area of mathematical modeling in reversed supply chain network design, and planning for integrated closed-loop supply chain management is presented. The main characteristics of the selected models or case studies have been summarized and compared.
3. **Mathematical model**: A detail overview of the model has been presented. The parameters and the decision variables have been established, the underlying assumptions of the model have been explained, and the mathematical model has been developed.
4. **Numerical examples and computational experiment:** An example has been presented to demonstrate how the mathematical model works. Some of the computational experiences of the model have been reported.
5. **Sensitivity analysis:** The sensitivity of the model to changes in some key parameters have been studied; the consequences of outsourcing services have been analyzed; and the changes in network design options and their impact on the primary objective function have been investigated to examine the model robustness.
6. **Summary and future direction:** A summary of this work has been presented. Analysis and discussion of the implementation of the model, some concluding remarks about the current work and the scope for future research have been presented as well.

CHAPTER 2 - LITERATURE REVIEW

The recent work on the development of models for strategic, tactical or even operational planning in supply chain management is indicative of a trend toward modeling the reverse logistics network along with the forward network. Few models consider the forward and reverse networks as interrelated transportation vehicle routing problems. Although several authors have considered supply chain network with either forward or reverse direction, no author has considered both directions in the same financial and production planning framework. In this study, a generalized model has been developed to consider the network in both directions within the same system with multiple objectives (both economics and environmental) which are given the same priority.

Stock (1998) pointed out that from a business logistics perspective, reverse logistics refers to the role of logistics in material allocation flow; from an engineering logistics perspective, reverse logistics is referred to as reverse logistics management and is a systematic business model that applies the best logistics engineering and management methodologies across the enterprise in order to profitably close the loop on the supply chain. This chapter will focus on the planning and controlling tasks arising in this context, addressed from an operations research point of view.

First of all, the reverse logistics network involves the physical transportation of used products from the end user back to a producer, thus the *distribution planning* aspect. Then the producer transforms the returned products into usable products again, thus the *closed-loop supply chain network* domain. And within the reverse supply chain planning, there is a very important module, *inventory management.*

2.1. Reverse distribution planning:

The corresponding decision models include location-allocation models (strategic level), vehicle routing models (tactical level) and scheduling models (production level).

Barros et al. (1998) reported a case study on the design of a logistics network for recycling sand resulting from the processing of construction waste in the Netherlands. The authors proposed a two-level capacitated facility location model, formulated as a mixed integer linear program. As in the other capacitated facility location problems (CFLP), the proposed model is NP-hard, and a heuristic method is proposed to solve it. The quality of the feasible solutions obtained was assessed by means of linear relaxation.

Louwers et al. (1999) have considered the design of a recycling network for carpet waste with applications in both Europe and USA. The goal of the study was to determine appropriate facility locations and capacities for the regional recovery centers with the objective of minimizing investment, processing and transportation cost. The model differs from other facility location allocation models developed for supporting the design of reuse networks, because of the completely free choice for the locations of the preprocessing centers and the explicit inclusion of depreciation costs. The resulting nonlinear model solved to its optimum using Fortran 90 programming with the MS Excel interface.

Angelelli et al. (2001) considered a dynamic vehicle routing problem (VRP) faced by a courier company where pick-up and delivery requests arrive on-line to a call center. The authors solved the real life problem using a three-stage algorithm with different objectives. At stage one, a static optimization problem with the objective of maximizing the total value of the served requests was solved; while at stages two and three, the algorithm required decisions coordination over time with the objective of minimizing the operational cost.

Dethloff (2001) developed a VRP considering simultaneous delivery and pick-up activities. The author presented a MIP model in which the objective function minimizes the total distance instead of the transportation cost. A heuristic algorithm was developed using the Fortune 77 programming.

Shih (2001) employed a MIP model to design an optimal collection and recycling system plan for End-of-Life computers and home appliances. Integer variables are incorporated for the site selection for storage and treatment facilities. The physical flow of dead products going through the collection points, storage sites, recycling plants, and the final disposition sites was optimized while the cost included the revenue from selling reclaimed material. Scenarios for different take-back rates and operating conditions are simulated via the model.

Krumwiede and Sheu (2002) developed a strategic decision-making model to guide the process of examining the feasibility of implementing reverse logistics in third-party (3PL) providers such as transportation companies. The model provided structure, and the guidance needed, for the decision to expand the reverse logistics business. The authors tested the model using a field study of a large United States 3PL transportation firm.

Archetti and Speranza (2003) presented a case study of waste collection in the county of Brescia, located in the North of Italy, which they call the 1-Skip Collection Problem (1-SCP). The case study considered the different kinds of waste, time windows for the customers and the plants, shift-times, different kinds of skips (units of collection of different kinds of waste), the number of drivers available to serve, and the priority assigned to the customers. The objective of this application was to minimize the total cost including regular and overtime labor cost and the penalty cost paid if a customer was not served. This case was solved by a heuristic method, which first constructed a feasible solution by means of the nearest neighbor algorithm, and then improved it.

Jayaraman et al. (2003) have analyzed a reverse distribution network of an electronic equipment remanufacturing company in USA. The authors developed an analytical model that minimizes reverse distribution costs. The model addressed a single-source plant with a restricted number of collection sites and refurbishing sites that could be open. The paper used AMPL as a front-end interface to CPLEX, which was the MIP solver for the sub-problems, and used the random selection and heuristic concentration algorithm to solve the problem.

Lim et al. (2005) designed a reverse supply chain network that can facilitate the reverse flow of used products in an efficient way. The authors addressed a reverse network for product refurbishment using a multi-period and multi-objective MIP model, and applied spanning-tree based genetic algorithms to find non-dominated solutions. Then the non-dominated solutions were simulated under several scenarios of uncertainties to determine the best-preferred solution.

Fleischmann et al. (1997) surveyed a review of quantitative models for reverse logistics from an operations research perspective. Fleischmann et al. (2000) identified the general characterization of logistics networks for product recovery based on a review of case studies in different industries and compared this characterization with traditional logistics structure. In the book "Quantitative models for reverse logistics", Lecture Notes in Economics and Mathematical Systems, Fleischmann (2001) presented all his works as a PhD student at the Erasmus University including the quantitative models, case studies and reviews.

2.2. Closed loop supply chain networks:

Spengler (2003) has developed an integrated daily operation level decision support system for electronic scrap recycling companies in Germany. The MILP model was multi-stage model based on the linear activity analysis. It maximized the total achievable marginal income subject to mass balance equations and capacity restriction for the recycling process of dismantling and bulk recycling from the discard products. This research analysis combined modeling of material flows throughout the disassembly and multi-stage bulk recycling units, and the integration of the acquisition, disassembly and bulk recycling planning into one MILP. The problem was solved by the commercial solver LINGO, using a branch-and-bound technique.

Geyer and Van Wassenhove (2003) explored the impact of constraints on the performance of a closed-loop supply chain based on component reuse. They developed a mathematical model which maximizes the remanufacturing yield rate with constraints on limited component durability and finite product life cycles. They showed that these constraints introduce a non-linearity into the flow rates of the production system, and have significant impact on the performance of the supply chain. However, the authors didn't introduce an efficient model to solve the real life problem.

Schultmann et al. (2003) developed a hybrid method to establish a closed-loop supply chain for spent batteries. The model included a two-stage (collection point-sorting –recycling or disposal) facility-location optimization problem. The authors found the optimal sorting centers to open to serve the recycling facilities through a MILP model which minimizes the total cost, and implemented the model in GAMS (General Algebraic Modeling System) and solved it using a branch-and-bound algorithm. As a hybrid method, it also approached to a simulation under different scenarios for a steel making process.

Beamon and Fernandes (2004) addressed a closed loop supply chain in which the plants produced new products and remanufactured used products. A multi-period integer programming model was introduced to determine which warehouses and collection centers should be open, and which should have the sorting capabilities and how much was shipped between the sites. The authors did not propose to sort materials early in the supply chain which results in a centralized network. Unlike the other papers using fixed cost depreciation, the authors used the present worth method, so that the investment costs were considered one-time cost while per-cycle operational costs were considered over a horizon length.

Sheu et al. (2005) presented an optimization model to deal with integrated logistics operational problems of Green-Supply Chain Management (G-SCM) according to the regulation of the Taiwan EPA for 2003. The authors developed a linear multi-objective programming model to optimize the operations of both the integrated logistics and the corresponding used-product reverse logistics in a given chain of five layers. The authors also proposed a real world case study for a Taiwan based notebook computer manufacturer.

2.3. Inventory management issues in reverse logistics:

Similar to conversional supply chain management, reducing inventory levels plays an important role in a reverse logistics context. Just-In-Time (JIT) philosophies and Vendor-Management-Inventories (VMI) are some of the concepts pointing in this direction. From a mathematical inventory theory perspective, deterministic and stochastic models can be distinguished, and further subdivided into periodic and continuous review models.

The deterministic models correspond to the classical economic order quantity

(EOQ) seeking an optimal tradeoff between fixed setup and variable holding costs. Teunter (2001) considered an EOQ model for a modified disposal policy. In his model, rather than assuming a constant disposal rate, all returns occurring during a certain time span were disposed without a certain rate.

Kim et al. (2005) generated a recycling system where recycled material was used as raw material for an economic production quantity (EPQ)-type of production system. The authors developed mathematical expressions of the inventory level of recycled material under Last-In-First-Out (LIFO) issuing policy and studied exponential and Weibull distribution for the time of the deterioration of the item.

Stochastic models of reversed logistics system are more complicated than those of the forward logistics. In most of the contributions cited in the literature, an optimal policy is sought for procurement, recovery and disposal decisions, and the models differed mainly in terms of the assumptions concerning the relation between demand and returns.

Inderfurth et al. (2001) presented a model for assigning returned products to alternative recovery options or disposal, which gave rise to a two-level divergent inventory system. In the model, the demand and returns were assumed to be independent, and the optimal policy was shown to have a complicated structure.

Beltran and Krass (2002) considered dynamic lot sizing for an inventory point facing both demand and returns. In the model, the authors assumed that there was a period of zero inventories between any two actions (procurement or disposal) in an optimal policy. The authors proposed a dynamic programming algorithm which was of complexity $\sigma(N^3)$ in the general case.

In the case study of IBM spare part management; Fleischmann et al. (2003) developed an analytic inventory control model and a simulation model to address the choice of recovery opportunities to use, the channel design, and the coordination of alternative supply sources. Their result showed that procurement cost savings largely outweigh reverse logistics costs and that information management is the key to an efficient solution.

2.4. Scope of the current work:

Table 2.1 shows the proposed model in relation to selected models reviewed in this section. The research presented in this thesis is a step forward in the modeling of integrated closed loop supply chain systems.

This thesis research attempts to develop an integrated, multi-echelon, multi-product, multi-period, multi-objective MILP model linking a reverse supply chain network to a forward network to form a closed-loop supply chain network. The thesis presents a tactical level optimization model based on a systemic approach to the material flow in both directions of the supply chain, which specializes in end-of-life material recovery of used product.

The modeling of this closed-loop supply chain network is done in the context of a lead acid battery operation involved in the production, distribution and recycling of automobile, industrial and stationary batteries. All products are manufactured on-site and shipped to the distribution centers. Finished products leave the system for retail points. Used products go back to the system through end-of-life product return. In the model, pollution emission or energy consumption during the service life of the products are not considered.

Table 2.1: Companion of the features of the proposed model in relation to other chosen models

Model Name*	**Reverse /integral**	**Open/close loop**	**Supply-driver**	**Reuse-driver**	**Multi-stage #**	**Investment**	**Potential Location**	**Capacities**	**Multi-period**	**Commodities**	**Mathematical programming**	**Planning level**	**Solver**	**method**
1	Integral	Open	Push	Pull	2	Fixed cost	Discrete	Capacitated	1	1	MILP	Strategic	NA	Linear relax
2	Reverse	Open	Pull/ push	Push/ Pull	N	Fixed cost	Continuous	Select	1	1	Non-linear	Strategic	Fortran	E04UCF routing
3	Integral	Close	Push	Pull	N	Fixed cost	Discrete	Capacitated	N	N	MILP	Operational	LINGO	Branch & Bound
4	Integral	Close	Push	Pull	2	NA	Fixed	Capacitated	N	N	MILP	Strategic	GAMS	Branch & Bound
5	Integral	Close	Push	Pull	2	Present Worth	Discrete	Select	N	N	IP	Strategic	NA	NA
6	Reverse	Open	Push	Pull	2	NA	Fixed	Capacitated	N	N	IP	Operational	N/A	Heuristics
7	Reverse	Open	Push	Pull	2	NA	Fixed	Capacitated	N	N	MILP	Tactical	Fortran	Heuristics
8	Integral	Close	Push	Pull	N	Performance	Fixed	Capacitated	N	1	Non-linear	Operational	N/A	N/A
9	Integral	Close	Push	Pull	5	NA	Fixed	Capacitated	1	1	Linear	Operational	N/A	Linear
10	Integral	close	push	Pull	3 + 2	NA	Fixed	Capacitated	N	N	MILP	Tactical	LINGO	Branch & Bound

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* 1: Barros et al. (1998); 2: Louwerst et al. (1999); 3: Spengler (2003); 4: Schultmann et al. (2003); 5: Beamon and Fernandes (2004) ; 6 : Angelelli et al. (2001); 7: Dethloff (2001); 8: Geyer and Van Wassenhove (2003); 9: Sheu et al. (2005) 10 : proposed model

CHAPTER 3 – MATHEMATICAL MODEL

A tactical model has been developed in this section to determine the material flow and transportation routing for an existing manufacturing facility, and it is applied to an integrated multi-product, multi-echelon, multi-period, multi-objective function systems planning network.

3.1. Mathematical modeling

The model optimizes two objectives:

Objective function 1: minimize the total costs

Objective function 2: minimize the pollution emissions

Total costs =

Cost at first stage: from suppliers to manufacturing plants

|virgin raw material cost | + |virgin raw material inventory holding cot at manufacturing plants|

+Cost at second stage: from manufacturing plants to distribution centers

|cost of regular and overtime labor hours | + |cost of increasing labor hours to adjust the labor capacity |+ |finished goods inventory holding cost at manufacturing plants| + |cost of transporting finished goods from manufacturing plants to distribution centers| + |cost of in-transit transportation of finished goods from manufacturing plants to distribution centers|

+Cost at third stage: transshipment between distribution centers

|finished goods inventory holding cost at distribution centers| + |handling cost of finished goods at distribution centers| + |cost of transshipments between distribution centers| + |cost of in-transit inventory of transshipments between distribution centers|

+Cost at fourth stage: from distribution centers to the recycling center

|cost of collecting end-of-life dead products| + |dead products inventory holding cost at

distribution centers|+ |handling cost of dead products at distribution centers| + |cost of pretreatment of dead products| + |cost of transporting pretreated and non-pretreated dead products from distribution centers to the recycling center| + |cost of in-transit inventory of dead products between distribution centers and the recycling center|

+Cost at fifth stage: from the recycling center to manufacturing plants

|the processing cost of recycling| + |dead products inventory holding cost at the recycling center| + |handling cost of dead products at the recycling center| + |cost of purchasing dead products sludge| - |revenue from selling surplus recycled raw materials|

Pollution emissions =

|pollution emission index during the transportation from manufacturing plants to distribution centers| + |pollution emission index during the transportation from the collection centers to the recycling center|

Subject to the following classes of constraints:

1. customer demand satisfaction
2. suppliers capacity restriction
3. production labor hours capacity restriction
4. inventory storage capacity restriction
5. recycling process restriction
6. transport carriers' capacity restriction

3.2. Mathematical formulations

3.2.1. Assumptions

In the formulation of the model, the following assumptions have been considered:

1. Demand for finished goods is stochastic and assumed to follow a normal distribution
2. Floor space is the only constrained inventory resource at the manufacturing plants, the distribution centers and the recycling center
3. All in-transit transportation inventory costs are accounted for at the source (for example, the cost of all the in-transit shipments from manufacturing plants

distribution centers are charged to manufacturing plants)

4. Safety stocks of raw materials (both virgin raw materials and recycled raw materials) and finished goods are included in the model, using a centralized safety stock policy
5. Assume that the manufacturing plants operate 8 hours a day, 5 days a week. Adjustment to the labour hours can be made by hiring new labour, or using overtime
6. At distribution centers where dead products are collected, they can choose either to pre-treat the product or leave them untreated
7. When the dead products are pretreated, they will be separated into parts and the un-recyclable parts will be sent to landfill at the same location. It is assumed that the volume of the dead products decreases by 50% after pre-treatment
8. The number of returned end-of-life products are calculated based on the historical sales data multiplied by the take-back rate
9. In addition to the end-of-life products collected from the distribution centers, the recycling center purchases dead product sludge[*] from the secondary material market, which has already been pre-treated. These two sources of dead products are combined to provide input into the raw material recycling process
10. The outgoing materials from the recovery process are assumed to be of the same grade as the virgin raw material bought from the suppliers
11. Logically and economically, a manufacturing plant chooses the raw material from the recycling centers first, then the raw material from other suppliers; any surplus is sold to other industries
12. During the recycling process, the materials which can not be recycled are disposed of, and the disposal costs are included in the recycling costs
13. The lead time of recycled raw material equals the lead time of producing recycled material plus the lead time for transporting the recycled raw material from the recycling center to the manufacturing plant

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[*] Battery sludge is originally collected from the replacement market, where the collectors drain the batteries and shred them. The sludge includes the following components: Plastics chips, lead sulfate ($PbSO_4$), lead Oxide (PbO) and lead metallic.

3.2.2. Notations

Indices and sets

$d \in D$	Index for regional distribution centers
$i \in I$	Index for raw materials
$k \in K$	Index for transportation modes
$p \in P$	Index for manufacturing plants
$q \in \mathrm{Q}$	Index for product families
$r \in \mathrm{R}$	Index for recycling center
$s \in S$	Index for suppliers/vendors
$t \in T$	Index for time periods (weekly)

3.2.3. Mathematical equations

The multi-echelon mathematical model is divided into five stages: 1). from the suppliers to the manufacturing plants; 2). from the manufacturing plants to the distribution centers; 3). from the distribution centers to the distribution centers; 4). from the distribution centers (the collection center) to the recycling center; 5). from the recycling center to the manufacturing plants. In each stage we consider the corresponding costs and the constraints.

3.2.3.1. First Stage: from the suppliers to the manufacturing plants

3.2.3.1.1. Parameters

CSM_{sit}	Purchasing cost of one unit of raw material *i* from supplier *s* during time period *t*
$CSICP_p$	Rate of inventory carrying cost (raw materials) at manufacturing plant *p* for one period
$CSIV_i$	Inventory value of raw material *i* ($/unit)
$ISVM_i$	Volume of one unit of raw material *i*
$ISWM_i$	Unit weight of raw material *i*
$LRLT_{rip}$	Average transportation lead-time for sending recycled raw material *i* from recycling center *r* to manufacturing plant *p*

$LSCV_{spk}$	Coefficient of variation of the probability distribution of transportation lead-time from supplier s to manufacturing plant p using transportation mode k
$LSLT_{sip}$	Average transportation lead-time for sending virgin raw material i from supplier s to manufacturing plant p
$LSLTM_{spk}$	Transportation lead-time from supplier s to manufacturing plant p using transportation mode k
SC_{sit}	Capacity of supplier s to provide virgin raw material i during time period t
TR_{ir}	Time required to recycle one unit of raw material i at recycling center r
$ZBOM_{qi}$	Bill of material rate (BOM): utilization rate for each raw material i per item of product family q
$ZCSF$	Cycle stock factor (expressed as the percentage of total inventory during one replenishment cycle)
$ZCSL(ip)$	Cycle service level of raw material i at manufacturing plant p, the fraction of the periods in which no stock-out occurs for raw material i at manufacturing plant t
$ZSSF_{ZCSL(ip)}$	Safety stock factor of raw material i at manufacturing plant p, equal to the value of the standard normal variable at which the cumulative probability is $ZCSL(ip)$
$\sigma_{DE_{pq}}$	Standard deviation of the demand for product family q at manufacturing plant p

3.2.3.1.2. Decision variables

SS_{ip}	Safety stock inventory of raw material i at manufacturing plant p
$XSITM_{sipkt}$	In-transit inventory of virgin raw material i on transportation mode k from supplier s to manufacturing plant p held at the end of period t
XRM_{ipt}	Amount of raw material i used in manufacturing process at the manufacturing plant p at the end of period t
XSM_{ipt}	Inventory of raw material i at manufacturing plant p at the end of period t
$XSTRM_{sipkt}$	Amount of raw material i purchased from supplier s to manufacturing plant p using transportation mode k during time period t

XP_{pqt}	Number of product family q produced at manufacturing plant p in time period t
$XRTP_{irpt}$	The unit of raw material i recycled from recycling center r used at manufacturing plant p in time period t
YRM_{spt}	The raw material indicator, $YRM_{spt} = 1$ if $\sum_{i=1}^{I}\sum_{k=1}^{K} XSTRM_{sipkt} \neq 0$, that is, if there is any virgin raw material purchased from supplier s and shipped to manufacturing plant p using transportation mode k at time period t; 0 otherwise

3.2.3.1.3. Objective function

Minimize the summation of the following costs:

[OS1] Virgin raw material cost, i.e., the purchasing cost of the virgin raw material from various suppliers

$$\sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{k=1}^{K}\sum_{t=1}^{T} CSM_{sit} XSTRM_{sipkt} \qquad \text{...(ob1)}$$

[OS2] Virgin raw material inventory holding costs at the manufacturing plants

$$\sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{t=1}^{T} CSICP_{p} CSIV_{i} XSM_{ipt} \qquad \text{...(ob2)}$$

3.2.3.1.4. Constraints

[CS1] Constraint on supplier's capacity, i.e., the amount of virgin raw materials procured from a supplier in any time period should be within the supplier's capacity:

$$\sum_{p=1}^{P}\sum_{k=1}^{K} XSTRM_{sipkt} \leq 1000 \times SC_{sit} \qquad \forall s,\, i,\, t \qquad \text{...(1)}$$

[CS2] Inventory balance of raw material at the manufacturing plants (adjusted for the recycled raw material from the recycling centers), i.e., the raw material inventory at time period t is equal to the previous time period inventory plus the virgin raw material received from the suppliers plus the recycled raw material from the recycling centers minus the virgin raw material used for production:

$$XSM_{ipt} = XSM_{ip(t-1)} + \sum_{s=1}^{S}\sum_{k=1}^{K} XSTRM_{sipk(t-LSLTM_{spk})} + \sum_{r=1}^{R} XRTP_{irp(t-LRLT_{rip})} - XRM_{ipt} \qquad \forall\ i, p, t \qquad \ldots(2)$$

Here, $XSTRM_{sipk(t-LSLTM_{spk})}$ represents the units of virgin raw material i shipped from supplier s using transportation mode k at time period $t\text{-}LSLTM_{spk}$ and received at manufacturing plant p at time period t, and $XRTP_{irp(t-LRLT_{rip})}$ represents the units of recycled raw material i shipped from recycling center r and received at manufacturing plant p at time period t.

[CS3] In-transit inventory balance of virgin raw material between suppliers and manufacturing plants, i.e., in any time period, the in-transit inventory is equal to the previous period's in-transit inventory plus the shipments of raw material made in that period minus the shipments of raw material received in the same period.

$$XSITM_{sipkt} = XSITM_{sipk(t-1)} + XSTRM_{sipkt} - XSTRM_{sipk(t-LSLTM_{spk})} \qquad \forall\ s, i, p, k, t \qquad \ldots(3)$$

Here, $XSTRM_{sipk(t-LSLTM_{spk})}$ is the unit of raw material i shipped from supplier s at time period $t\text{-}LSLTM_{spk}$ and received at manufacturing plant p using transportation mode k at time period t.

[CS4] Raw material inventory safety stock at the manufacturing plants: Safety stock of raw materials is the minimal level of inventory kept on hand, at the manufacturing plant, in order to protect the manufacturing plant against short term variations in demand and transportation lead time between suppliers and manufacturing plants.

$$SS_{ip} = ZSSF_{ZCSL(ip)}\left(\sqrt{MAX\left(\frac{\sum_{t=1}^{T}\sum_{s=1}^{S} LSLT_{sip}YRM_{spt}}{S \times T}, \frac{\sum_{r=1}^{R} TR_{ir} + \sum_{r=1}^{R} LRLT_{rip}}{R}\right)}\left(\sum_{q=1}^{Q} ZBOM_{qi}\sigma_{DE_{pq}}\right)\right) \qquad \forall\ i, p \qquad \ldots(4)$$

$$XSM_{ipt} \geq SS_{ip} \qquad \forall\ i, p, t \qquad \ldots(5)$$

Here, the term $\sum_{q=1}^{Q} ZBOM_{qi}\sigma_{DE_{pq}}$ refers to the standard deviation of raw materials demand forecast error at manufacturing plants for all product families, the term $\frac{\sum_{t=1}^{T}\sum_{s=1}^{S} LSLT_{sip}YRM_{spt}}{S \times T}$ refers to the average transportation lead time of virgin raw material i from the suppliers to manufacturing plant p, and the term $\frac{\sum_{r=1}^{R} TR_{ir} + \sum_{r=1}^{R} LRLT_{rip}}{R}$ refers to the average lead time (including recycling lead time and transportation lead time) of recycled raw material i from recycling centers to manufacturing plant p.

The equation can be simplified as follows. We consider the factor

$$\left(\sqrt{MAX\left(\frac{\sum_{t=1}^{T}\sum_{s=1}^{S} LSLT_{sip}YRM_{spt}}{S \times T}, \frac{\sum_{r=1}^{R} TR_{ir} + \sum_{r=1}^{R} LRLT_{rip}}{R}\right)}\right)$$

as a set by dropping the 0-1 binary decision variable YRM_{spt}. This prescribes us with $ROOT1_{ip}$ and $ROOT11_{ip}$, where

$$\text{ROOT1}_{\text{ip}} = \sqrt{\frac{\sum_{r=1}^{R} TR_{ir} + \sum_{r=1}^{R} LRLT_{rip}}{R}} \quad \text{and}$$

$$\text{ROOT11}_{\text{ip}} = \sqrt{\left(\frac{\sum_{s=1}^{S} LSLT_{sip}}{S} - \frac{\sum_{r=1}^{R} TR_{ir} + \sum_{r=1}^{R} LRLT_{rip}}{R}\right)},$$

so that equation (4) can be replaced by:

$$SS_{ip} = \frac{ZSSF_{ZCSL(ip)} \times \sum_{q=1}^{Q} ZBOM_{qi}\sigma_{DE_{pq}} \times \sum_{s=1}^{S}\sum_{t=1}^{T}\left(ROOT1_{ip} + ROOT11_{ip} \times YRM_{spt}\right)}{S \times T} \qquad \text{... (4a)}$$

[CS5] binary variable linkage between $XSTRM_{sipkt}$ and YRM_{spt}

$$\sum_{i=1}^{I}\sum_{k=1}^{K} XSTRM_{sipkt} \le (M)YRM_{spt} \qquad \forall\ s, p, t \qquad \text{...(6)}$$

Here, M is a large positive number and the binary variable YRM_{spt} indicate whether there are any virgin raw material purchased from the suppliers in each time period

[CS6] Raw material consumption in the manufacturing plants: The amount of raw material used in a manufacturing plant should be sufficient to meet the production level at the manufacturing plant, while it should stay within the 6-sigma quality control limits. Given the statistical process control policy of 6-sigma (99.73% acceptance rate, 0.27% scrap rate)

$$XRM_{ipt} \ge \sum_{q=1}^{Q} ZBOM_{qi} XP_{pqt} \qquad \forall\ i, p, t \qquad \text{...(7)}$$

$$XRM_{ipt} \le (1.0027)\sum_{q=1}^{Q} ZBOM_{qi} XP_{pqt} \qquad \forall\ i, p, t \qquad \text{...(8)}$$

We assume that the bill-of-materials remains the same for a product family that is produced at more than one manufacturing plant.

3.2.3.2. Second Stage: from the manufacturing plants to the distribution centers

3.2.3.2.1. Parameters:

$CPIL_{pt}$	Per unit cost of increasing labor-hours by hiring new staff at manufacturing plant p in time period t
$CPRL_{pt}$	Per unit cost of regular time labor-hours at manufacturing plant p at time period t
$CPOL_{pt}$	Per unit cost of overtime labor-hours at manufacturing plant p at time period t
$CPTP_{pdk}$	Cost of transporting one shipment from manufacturing plant p to distribution center d using transportation mode k
$CPIV_q$	Inventory value of product family q
$CPICP_p$	Inventory carrying cost rate at manufacturing plant p for one period
$IPFS_q$	Floor space (sq. unit) required for holding a unit of product family q in

	inventory
$IPFC_{pt}$	Floor space capacity (sq. unit) available at manufacturing plant p at time period t
$IPVT_{pdk}$	Volume capacity of one full transportation consignment used for shipping from manufacturing plant p to distribution center d using transportation mode k
$IPWT_{pdk}$	Weight capacity of one full transportation consignment used for shipping from manufacturing plant p to distribution center d using transportation mode k
$IPWP_q$	Unit weight of product family q
$IPVP_q$	Unit volume of product family q
$LPCV_{pdk}$	Coefficient of variation of the probability distribution of transportation lead-time from manufacturing plant p to distribution center d using transportation mode k
$LPLT_{pd}$	Average transportation lead-time from manufacturing plant p to distribution center d
$LPLTP_{pdk}$	Transportation lead-time from manufacturing plant p to distribution center d using transportation mode k
$LPTP_{pq}$	Average lead-time to produce an item of product family q at manufacturing plant p
LHC_{pt}	Labor hour capacity at manufacturing plant p in time period t
RLH_{pq}	Required labor hours to produce a unit of product family q at manufacturing plant p
$RIPD_{pdk}$	Replenishment interval/shipment inter-arrival time between manufacturing plant p and distribution center d using transportation mode k
f_p	Ratio of overtime labor hours to regular time labor hours at manufacturing plant p
$ZCSF$	Cycle stock factor (expressed as the percentage of total inventory during one replenishment cycle)
$ZPSL(pq)$	Cycle service level of product q at manufacturing plant p, the fraction of replenishment cycles that end with all the customer demand being met

$ZPSF_{ZPSL(pq)}$	Pooled safety stock factor of product family q at manufacturing plant p, equal to the value of the standard normal variable at which the cumulative probability is $ZPSL(pq)$
ϕ	Cycle length of the periodic review policy at each manufacturing plant

3.2.3.2.2. Decision variables

XP_{pqt}	Number of units of product family q produced at manufacturing plant p in time period t
$XPIL_{pqt}$	Inventory of product family q at manufacturing plant p at the end of period t
$XPITP_{pqdkt}$	In-transit inventory of product family q on transportation mode k from manufacturing plant p to distribution center d held at the end of period t
$XPTP_{pdkt}$	Number of shipments from manufacturing plant p to distribution center d on transportation mode k in time period t
PS_{pq}	Pooled safety stock for product family q at manufacturing plant p
$XPOL_{pt}$	Number of overtime labor hours required at manufacturing plant p at time period t
$XPRL_{pt}$	Number of regular time labor hours required at manufacturing plant p in time period t
$XPHL_{pt}$	Increase in labor hours by hiring new staff at manufacturing plant p in time period t
$XPTPD_{pqdkt}$	Units of product family q shipped from manufacturing plant p to distribution center d on transportation mode k in time period t

3.2.3.2.3. Objective function:

[OP1] Cost of regular and overtime labor hours:

$$\sum_{p=1}^{P}\sum_{t=1}^{T}\left(CPRL_{pt}XPRL_{pt} + CPOL_{pt}XPOL_{pt}\right) \qquad \ldots\text{(ob3)}$$

[OP2] Cost of increasing labor hours to adjust the labor capacity:

$$\sum_{p=1}^{P}\sum_{t=1}^{T}CPIL_{pt}XPHL_{pt} \qquad \ldots\text{(ob4)}$$

[OP3] Finished goods inventory holding cost at manufacturing plants:

$$\sum_{p=1}^{P}\sum_{q=1}^{Q}\sum_{t=1}^{T} CPICP_p CPIV_q XPIL_{pqt} \qquad \ldots(ob5)$$

[OP4] Cost of transporting finished goods from manufacturing plants to distribution centers: the variable cost is proportional to the number of transportation shipment.

$$\sum_{p=1}^{P}\sum_{d=1}^{D}\sum_{k=1}^{K}\sum_{t=1}^{T} CPTP_{pdk} XPTP_{pdkt} \qquad \ldots(ob6)$$

[OP5] Cost of in-transit transportation of finished goods from manufacturing plants to distribution centers: variable shipping cost between manufacturing plants and distribution centers.

$$\sum_{p=1}^{P}\sum_{q=1}^{Q}\sum_{d=1}^{D}\sum_{k=1}^{K}\sum_{t=1}^{T} CPICP_p CPIV_q [LPLTP_{pdk} + ZPSF_{ZPSL(pq)} LPCV_{pdk} LPLTP_{pdk} + RIPD_{pdk} ZCSF] XPTPD_{pqdkt} \qquad \ldots(ob7)$$

In order to account for the uncertainties in lead time, we include two time components (Vidyarthi, 2003):

- **Adjustment for time corresponding to cycle inventories:** Cycle stock factor (expressed as a percentage of total inventories during one replenishment cycle) determines the amount of inventory that is to be carried on hand, and depends on the shipment inter-arrival time or replenishment interval. The higher the replenishment frequency, the lower the cycle stock factor would be. For example, for all shipments from manufacturing plant *p* to distribution center *d*, this adjustment factor is given by $RIPD_{pdk} \times ZCSF$
- **Adjustment for time corresponding to safety stock inventories:** This depends on the safety stock factor and the length of transportation lead time. The higher the uncertainties in lead time, the higher the amount of safety stock that has to be held. For example, for manufacturing plant *p* to the distribution center *d*, this adjustment factor is given by $ZPSF_{ZPSL(pq)} LPCV_{pdk} LPLTP_{pdk}$.

3.2.3.2.4. Constraints

[CP1] Balance equation of work force: The available work force level at the beginning of every period is equal to the previous period's workforce level plus any increase in workforce level:

$$XPRL_{pt} = XPRL_{p(t-1)} + XPHL_{pt} \qquad \forall\ p, t \qquad ...(9)$$

[CP2] Limit on regular time labor hours: The workforce level at manufacturing plant p in any time period should not be more than the maximum allowable limit:

$$XPRL_{pt} \le LHC_{pt} \qquad \forall\ p, t \qquad ...(10)$$

[CP3] Limit on over time labor hours: Labor hours on overtime at manufacturing plant p in any period are normally restricted as a percentage of the regular time hours:

$$XPOL_{pt} \le f_p XPRL_{pt} \qquad \forall\ p, t \qquad ...(11)$$

[CP4] Labor hours on regular time and on overtime together should meet the production requirement:

$$XPRL_{pt} + XPOL_{pt} \ge \sum_{q=1}^{Q} RLH_{pq} XP_{pqt} \qquad \forall\ p, q, t \qquad ...(12)$$

[CP5] Inventory balance of finished goods at manufacturing plants: in any time period, the inventory of a product is equal to previous period's inventory plus the production in that period minus shipments to the distribution centers:

$$XPIL_{pqt} = XPIL_{pq(t-1)} + XP_{pqt} - \sum_{d=1}^{D}\sum_{k=1}^{K} XPTPD_{pqdkt} \qquad \forall\ p, q, t \qquad ...(13)$$

[CP6] Inventory capacity at manufacturing plants: The inventory level at the end of the time period that would be carried over should be within the manufacturing plant's inventory capacity. Manufacturing plant inventory capacity generally refers to storage space (floor space).

$$\sum_{q=1}^{Q} IPFS_q XPIL_{pqt} \le IPFC_{pt} \qquad \forall\ p, t \qquad ...(14)$$

We assume that the available storage space at a manufacturing plant may vary over different time periods.

[CP7] Provision of applied centralized safety stock policy: the safety stocks are pooled at manufacturing plants in order to protect the manufacturing plant against short term variations in demand and manufacturing lead time:

$$PS_{pq} = ZPSF_{ZPSL(pq)}\sqrt{\phi + LPTP_{pq}}\,(\sigma_{DE_{pq}}) \qquad \forall\ p, q \qquad \ldots(15)$$

At the end of any given time period t, the inventory level of product family q at manufacturing plant p, should be at least equal to the pooled safety stock PS_{pq}

$$\mathrm{XPIL}_{pqt} \geq PS_{pq} \qquad \forall\ p, q, t \qquad \ldots(16)$$

[CP8] In-transit inventory balance between manufacturing plants and distribution centers: In any time period, the in-transit inventory is equal to the previous period's in-transit inventory plus the shipments sent out in that period minus the shipments received at distribution centers:

$$XPITP_{pqdkt} = XPITP_{pqdk(t-1)} + XPTPD_{pqdkt} - XPTPD_{pqdk(t-LPLTP_{pdk})}$$

$$\forall\ p, q, d, k, t \qquad \ldots(17)$$

Here $XPTPD_{pqdk(t-LPLTP_{pdk})}$ represents the units of product family q shipped from manufacturing plant p in time period $t\text{-}LPLTP_{pdk}$ and received at distribution center d using transportation mode k in time period t.

[CP9] Constraints on transport carrier weight capacity from manufacturing plants to distribution centers: The weight of finished products transported should be within the transport carriers' weight capacity:

$$\sum_{q=1}^{Q} IPWP_q XPTPD_{pqdkt} \leq IPWT_{pdk} XPTP_{pdkt} \qquad \forall\ p, d, k, t \qquad \ldots(18)$$

$$\text{or } XPTP_{pdkt} \geq \frac{\sum_{q=1}^{Q} IPWP_q XPTPD_{pqdkt}}{IPWT_{pdk}} \qquad \forall\ p, d, k, t \qquad \ldots(18a)$$

[CP10] Constraints on transport carrier volume capacity from manufacturing plants to distribution centers: The volume of finished products transported from a manufacturing plant to a distribution center should be within the transport carriers' volume capacity:

$$\sum_{q=1}^{Q} IPVP_q XPTPD_{pqdkt} \leq IPVT_{pdk} XPTP_{pdkt} \qquad \forall\ p,\ d,\ k,\ t \qquad \text{...(19)}$$

$$\text{or } XPTP_{pdkt} \geq \frac{\sum_{q=1}^{Q} IPVP_q XPTPD_{pqdkt}}{IPVT_{pdk}} \qquad \forall\ p,\ d,\ k,\ t \qquad \text{...(19a)}$$

The number of transportation consignments required between manufacturing plants and distribution centers is now, therefore, the larger of the two numbers computed in equations (20a) and (21a):

$$XPTP_{pdkt} \geq \left[max\left(\frac{\sum_{q=1}^{Q} IPWP_q XPTPD_{pqdkt}}{IPWT_{pdk}}, \frac{\sum_{q=1}^{Q} IPVP_q XPTPD_{pqdkt}}{IPVT_{pdk}} \right) \right] \qquad \forall\ p,\ d,\ k,\ t \qquad \text{...(19b)}$$

3.2.3.3. Third stage: transshipments between the distribution centers

3.2.3.3.1. Parameters:

CDH_{qd}	Cost of handling a unit of product family *q* at distribution center *d* (including the cost of packaging material, labor cost, and overhead cost)
$CDTS_{dd'k}$	Transportation cost of a transshipment consignment between distribution centers *d* and *d'* using transportation mode *k*
$CDIC_d$	Inventory carrying cost rate of finished goods at distribution center *d* for one period
IDC_{dt}	Inventory capacity at distribution center *d* in time period *t* in terms of floor space (sq.ft)
$LDTD_{dd'k}$	Transportation lead time between distribution centers *d* and *d'* using transportation mode *k*
$IDVBD_{dd'k}$	Volume capacity of a full transportation consignment used for shipments between distribution centers *d* and *d'* using transportation mode *k*
$IDWBD_{dd'k}$	Weight capacity of one full transportation consignment used for shipments between distribution centers *d* and *d'* using transportation mode *k*

3.2.3.3.2. Decision variables

$XDPD_{pqdt}$	Inventory of product family q produced at manufacturing plant p stored at distribution center d at the end of period t
$XDITBD_{pqdd'kt}$	In-transit inventory of product family q produced at manufacturing plant p, on transportation mode k between distribution centers d and d', at the end of period t
$XDTS_{dd'kt}$	Number of full transportation mode k consignments needed for transshipment of products between distribution centers d and d' in time period t
$XDNTS_{pqdd'kt}$	Number of units of product family q produced at manufacturing plant p and transshipped between distribution centers d and d' in time period t

3.2.3.3.3. Objective function:

[OD1] Finished goods inventory holding cost at distribution centers: the inventory holding cost is proportional to the inventory level of products stored at the distribution centers:

$$\sum_{p=1}^{P}\sum_{q=1}^{Q}\sum_{d=1}^{D}\sum_{t=1}^{T} CDIC_d CPIV_q XDPD_{pqdt} \qquad \ldots\text{(ob8)}$$

[OD2] Handling cost of finished goods at distribution centers:

$$\sum_{p=1}^{P}\sum_{q=1}^{Q}\sum_{d=1}^{D}\sum_{d'=1,d\neq d'}^{D}\sum_{k=1}^{K}\sum_{t=1}^{T} CDH_{qd} XDNTS_{pqdd'kt} \qquad \ldots\text{(ob9)}$$

[OD3] Cost of transshipments between distribution centers: the transshipment cost is proportional to the number of transport carriers

$$\sum_{d=1}^{D}\sum_{d'=1,d'\neq d}^{D}\sum_{k=1}^{K}\sum_{t=1}^{T} CDTS_{dd'k} XDTS_{dd'kt} \qquad \ldots\text{(ob10)}$$

[OD4] Cost of in-transit inventory of transshipments between distribution centers:

$$\sum_{p=1}^{P}\sum_{q=1}^{Q}\sum_{d=1}^{D}\sum_{d'=1,d\neq d'}^{D}\sum_{k=1}^{K}\sum_{t=1}^{T} CDIC_d CPIV_q LDTD_{dd'k} XDNTS_{pqdd'kt} \qquad \ldots\text{(ob11)}$$

3.2.3.3.4. Constraints

[CD1] Constraint on distribution center inventory capacity: The net inventory carried over at the end of a time period should be within the distribution center's inventory capacity (floor space)

$$\sum_{p=1}^{P}\sum_{q=1}^{Q} IPFS_q XDPD_{pqdt} \le IDC_{dt} \qquad \forall\ d, t \qquad \ldots(20)$$

[CD2] Constraints on distribution center inventory balance: the net inventory in any time period is equal to the previous period's net inventory plus shipments received in that period (from manufacturing plants and other distribution centers) minus shipments sent out (to other distribution center) in the same period:

$$XDPD_{pqdt} = XDPD_{pqd(t-1)} + \sum_{k=1}^{K} XPTPD_{pqdk(t-LPLTP_{pdk})} + \sum_{d=1}^{D}\sum_{d'=1}^{D}\sum_{k=1}^{K} XDNTS_{pqdd'k(t-LDTD_{dd'k})} - \sum_{d=1}^{D}\sum_{d'=1}^{D}\sum_{k}^{K} XDNTS_{pqdd'kt}$$

$$\forall\ p, q, d, d', t \qquad \ldots(21)$$

Here, $XPTPD_{pqdk(t-LPLTP_{pdk})}$ is the number of units of product family q shipped from manufacturing plant p at time period $t\text{-}LTLTP_{pdk}$ using transportation mode k, and received at distribution center d in time period t, and $XDNTS_{pqdd'k(t-LDTD_{dd'k})}$ is the number of units of product family q, produced at manufacturing plant p, shipped from distribution center d, using transportation mode k, in time period $t\text{-}LDTD_{dd'k}$, and received at distribution center d' at time period t.

[CD4] Constraints on the in-transit inventory of transshipments between distribution centers: in any time period, the in-transit inventory is equal to the previous period's in-transit inventory plus the shipments sent out in that time period, minus the shipments received at the distribution centers:

$$XDITBD_{pqdd'kt} = XDITBD_{pqdd'k(t-1)} + XDNTS_{pqdd'kt} - XDNTS_{pqdd'k(t-LDTD_{dd'k})}$$

$$\forall\ p, q, d, d', k, t \qquad \ldots(22)$$

Here, $XDNTS_{pqdd'k(t-LDTD_{dd'k})}$ is the number of units of product family q, produced at manufacturing plant p, shipped from distribution center d, and received at distribution center d' using transportation mode k at time period t.

[CD5] Constraints on transport carrier weight capacity between distribution centers: The weight of finished products should be within the transport carriers' weight capacity:

$$\sum_{p=1}^{P}\sum_{q=1}^{Q} IPWP_q XDNTS_{pqdd'kt} \leq IDWBD_{dd'k} XDTS_{dd'kt} \qquad \forall d,\ d',\ k,\ t \qquad \ldots(23)$$

or

$$XDTS_{dd'kt} \geq \frac{\sum_{p=1}^{P}\sum_{q=1}^{Q} IPWP_q XDNTS_{pqdd'kt}}{IDWBD_{dd'k}} \qquad \forall d,\ d',\ k,\ t \qquad \ldots(23a)$$

[CD6] Constraints on transport carrier volume capacity between distribution centers: The volume of finished products transported should be within the transport carriers' volume capacity:

$$\sum_{p=1}^{P}\sum_{q=1}^{Q} IPVP_q XDNTS_{pqdd'kt} \leq IDVBD_{dd'k} XDTS_{dd'kt} \qquad \forall\ d,\ d',\ k,\ t \qquad \ldots(24)$$

or

$$XDTS_{dd'kt} \geq \frac{\sum_{p=1}^{P}\sum_{q=1}^{Q} IPVP_q XDNTS_{pqdd'kt}}{IDVBD_{dd'k}} \qquad \forall\ d,\ d',\ k,\ t \qquad \ldots(24a)$$

The number of transportation consignments required between distribution centers is now the larger of two numbers computed in equations (26a) and (27a):

$$XDTS_{dd'kt} \geq \left\lceil max\left(\frac{\sum_{p=1}^{P}\sum_{q=1}^{Q} IPVP_q XDNTS_{pqdd'kt}}{IDVBD_{dd'k}}, \frac{\sum_{p=1}^{P}\sum_{q=1}^{Q} IPWP_q XDNTS_{pqdd'kt}}{IDWBD_{dd'k}}\right)\right\rceil$$

$$\forall\ d,\ d',\ k,\ t \qquad \ldots(24b)$$

3.2.3.4. Fourth stage: from distribution center to recycling center

3.2.3.4.1. Parameters:

$CCCP_{qdt}$	Cost of collecting one unit of dead product q at distribution center d in time period t
$CCIC_d$	Inventory carrying cost rate for dead products at distribution center d
$CCIV_q$	Inventory value of dead product family q
$CCPT_{qd}$	Cost of pre-treatment for one unit of dead product family q at distribution

	center *d*
CCH_{qd}	Cost of handling a unit of dead product family *q* at distribution center *d*
$CCCR_{drk}$	Transportation cost of one shipment from distribution center *d* to recycling center *r* using transportation mode *k* (for un-pretreated products)
$CCACR_{qdrk}$	per unit transportation cost of dead product *q* shipped from distribution center d to recycling center *r* using transportation mode *k* (for pretreated product)
FC_{qdt}	Forecast collection of the dead product family *q* in distribution center *d* in time period t (equal to historical sales × take-back rate)
ICC_{dt}	Inventory capacity (in terms of floor space) at collection center *d* in time period t, for the end-of-life dead products
$ICWT_{drk}$	Volume capacity of one full transportation consignment used for shipments from distribution center *d* to recycling center *r* using transportation mode *k*
$ICVT_{drk}$	Weight capacity of one full transportation consignment used for shipments from distribution center *d* to recycling center *r* using transportation mode *k*
$LCPT_{qd}$	Labor hour required per unit of dead product *q* to be pretreated at collection center *d*
$LCTPT_{dt}$	Total labor hour capacity at collecting center *d* for pretreatment in time period *t*
$LCCR_{drk}$	Lead time from distribution center *d* to recycling center *r* on transportation mode *k* (non-pretreated product)
$LCCR'_{drk}$	Lead time from distribution center *d* to recycling center *r* on transportation mode *k* (pretreated product)
REC_i	Recycling parameter indicating whether a raw material can be reused (REC_i=1) in the production process or not (REC_i=0)

3.2.3.4.2. Decision variable:

$XCIL_{qdt}$	Inventory level of dead product family *q* stored at distribution center *d* in time period *t*

$XCITC_{qdrkt}$	In-transit Inventory of non-pretreated dead product family q using transportation mode k from distribution center d to recycling center r in time period t
$XCITC'_{qdrkt}$	In-transit Inventory of pretreated dead product family q using transportation mode k from distribution center d to recycling center r in time period t
$XCCR_{drkt}$	Number of transportation consignments (of non-pretreated products) from distribution center d to recycling center r using transportation mode k in time period t
$XCCR'_{drkt}$	Number of transportation consignments (of pretreated products) from distribution center d to recycling center r using transportation mode k in time period t
$XCNCR_{qdrkt}$	Number of units of non-pretreated dead product family q sent from distribution center d to recycling center r using transportation mode k in time period t
$XCNCR'_{qdrkt}$	Number of units of pretreated dead product family q sent from distribution center d to recycling center r using transportation mode k in time period t

3.2.3.4.3. Objective function:

[OC1] Cost of collecting end-of-life dead products: the cost is proportional to the number of end-of-life dead products collected in each time period

$$\sum_{q=1}^{Q}\sum_{d=1}^{D}\sum_{t=1}^{T} CCCP_{qdt} FC_{qdt} \qquad \ldots(ob12)$$

[OC2] Dead products inventory holding cost at distribution centers: the inventory holding cost is proportional to the inventory level of products stored at collection centers:

$$\sum_{q=1}^{Q}\sum_{d=1}^{D}\sum_{t=1}^{T} CCIC_{d} CCIV_{q} XCIL_{qdt} \qquad \ldots(ob13)$$

[OC3] Handling cost of dead products at distribution centers:

$$\sum_{q=1}^{Q}\sum_{d=1}^{D}\sum_{t=1}^{T} CCH_{qd} FC_{qdt} \qquad \ldots(ob14)$$

[OC4] The cost of pretreatment of dead products: the cost is proportional to the number of dead products to be sorted, tested and dismantled.

$$\sum_{q=1}^{Q}\sum_{d=1}^{D}\sum_{r=1}^{R}\sum_{k=1}^{K}\sum_{t=1}^{T} CCPT_{qd} XCNCR'_{qdrkt} \qquad \text{...(ob15)}$$

[OC5] The cost of transporting pretreated and non-pretreated dead products from distribution centers to the recycling center (assuming a 10% weight reduction)

$$\sum_{q=1}^{Q}\sum_{d=1}^{D}\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{r=1}^{R} (0.9 \times CCACR_{qdrk} IPWP_{q} XCNCR'_{qdrkt} + CCCR_{drk} XCCR_{drkt}) \qquad \text{...(ob16)}$$

[OC6] The cost of in-transit inventory of dead products between distribution centers and the recycling center: the cost of in-transit is proportional to the number of the dead products in transit during the transportation lead time.

$$\sum_{q=1}^{Q}\sum_{d=1}^{D}\sum_{r=1}^{R}\sum_{k=1}^{K}\sum_{t=1}^{T} CCIC_{d} CCIV_{q} (LCCR_{drk} XCNCR_{qdrkt} + LCCR'_{drk} XCNCR'_{qdrkt}) \qquad \text{...(ob17)}$$

3.2.3.4.4. Constraints

[CC1] The inventory floor space capacity at collection centers (distribution center): The inventory of dead products stored at a collection center at the end of a time period should not exceed the storage capacity of the warehouse in distribution center:

$$\sum_{q=1}^{Q} IPFS_{q} XCIL_{qdt} \le ICC_{dt} \qquad \forall \ d, t \qquad \text{...(25)}$$

[CC2] Inventory balance equation at collection centers (distribution centers): the inventory level at the end of a time period is equal to the previous period's inventory plus the collected dead products minus the dead products shipped to the recycling centers:

$$XCIL_{qdt} = XCIL_{qd(t-1)} + FC_{qdt} - \sum_{r=1}^{R}\sum_{k=1}^{K} XCNCR_{qdrkt} - \sum_{r=1}^{R}\sum_{k=1}^{K} XCNCR'_{qdrkt}$$

$$\forall \ q, d, t, \qquad \text{...(26)}$$

[CC3] In-transit inventory balance equation (for non-pretreated products) between recycling centers and distribution centers: the in-transit inventory at the end of a time period should be equal to the last period's inventory plus any dead products shipped out minus any dead products received

$$XCITC_{qdrkt} = XCITC_{qdrk(t-1)} + XCNCR_{qdrkt} - XCNCR_{qdrk(t-LCCR_{drk})}$$

$\forall\ q, d, r, k, t$ ...(27)

Here, $XCNCR_{qdrk(t-LCCR_{drk})}$ is the number of non-pretreated dead products q sent from distribution center d and received at recycling center r using transportation mode k in time period t.

[CC4] In-transit inventory balance equation (for pretreated products) between recycling centers and distribution centers:

$$XCITC'_{qdrkt} = XCITC'_{qdrk(t-1)} + XCNCR'_{qdrkt} - XCNCR'_{qdrk(t-LCCR'_{drk})}$$

$\forall\ q, d, r, k, t$ ...(28)

Here, $XCNCR'_{qdrk(t-LCCR'_{drk})}$ is the number of pretreated dead product q sent from distribution center d and received at recycling center r using transportation mode k in time period t.

[CC5] Constraints on transport carrier weight capacity from distribution centers to recycling centers (non-pretreated products):

$$\sum_{q=1}^{Q} IPWP_q XCNCR_{qdrkt} \leq ICWT_{drk} XCCR_{drkt} \qquad \forall\ d, r, k, t \qquad ...(29)$$

or

$$XCCR_{drkt} \geq \frac{\sum_{q=1}^{Q} IPWP_q XCNCR_{qdrkt}}{ICWT_{drk}} \qquad \forall\ d, r, k, t \qquad ...(29a)$$

[CC6] Constraints on transport carrier volume capacity from distribution centers to recycling centers (non-pretreated products):

$$\sum_{q=1}^{Q} IPVP_q XCNCR_{qdrkt} \leq ICVT_{drk} XCCR_{drkt} \qquad \forall\ d, r, k, t \qquad ...(30)$$

or

$$XCCR_{drkt} \geq \frac{\sum_{q=1}^{Q} IPVP_q XCNCR_{drkt}}{ICVT_{drk}} \qquad \forall\ d, r, k, t \qquad ...(30a)$$

The number of transportation consignments required between distribution centers and recycling centers is now, therefore, the larger of the two numbers compared in equations (32a) and (33a):

$$XCCR_{drkt} \geq \left[max \left(\frac{\sum_{q=1}^{Q} IPWP_q XCNCR_{qdrkt}}{ICWT_{drk}}, \frac{\sum_{q=1}^{Q} IPVP_q XCNCR_{qdrkt}}{ICVT_{drk}} \right) \right] \quad \forall \; d, r, k, t \qquad \ldots(30b)$$

[CC7] Constraints on transport carrier weight capacity from distribution centers to recycling centers (pretreated products):

$$\sum_{q=1}^{Q} \sum_{i=1}^{I} 0.9 \times IPWP_q ZBOM_{qi} REC_i XCNCR'_{qdrkt} \leq ICWT_{drk} XCCR'_{drkt}$$

$$\forall \; d, r, k, t \qquad \ldots(31)$$

or

$$XCCR'_{drkt} \geq \frac{\sum_{q=1}^{Q} \sum_{i=1}^{I} 0.9 \times IPWP_q ZBOM_{qi} REC_i XCNCR'_{qdrkt}}{ICWT_{drk}} \quad \forall \; d, r, k, t \qquad \ldots(31a)$$

[CC8] Constraints on transport carrier volume capacity from distribution centers to recycling centers (pretreated product):

$$\sum_{q=1}^{Q} \sum_{i=1}^{I} (0.5 \times IPVP_q) ZBOM_{qi} REC_i XCNCR'_{qdrkt} \leq ICVT_{drk} XCCR'_{drkt}$$

$$\forall \; d, r, k, t \qquad \ldots(32)$$

or

$$XCCR'_{drkt} \geq \frac{\sum_{q=1}^{Q} \sum_{i=1}^{I} (0.5 \times IPVP_q) ZBOM_{qi} REC_i XCNCR'_{qdrkt}}{ICVT_{drk}} \quad \forall \; d, r, k, t \qquad \ldots(32a)$$

Here, it is assumed that after pretreatment, the volume of the dead products decreases by 50%.

The number of transportation consignments required between distribution centers and recycling centers is now, therefore, the larger of the two numbers computed in equations (34a) and (35a).

$$XCCR'_{drkt} \geq \left[max \left(\begin{array}{c} \frac{\sum_{q=1}^{Q} \sum_{i=1}^{I} 0.9 \times IPWP_q ZBOM_{qi} REC_i XCNCR'_{qdrkt}}{ICWT_{drk}}, \\ \frac{\sum_{q=1}^{Q} \sum_{i=1}^{I} (0.5 \times IPVP_q) ZBOM_{qi} REC_i XCNCR'_{qdrkt}}{ICVT_{drk}} \end{array} \right) \right] \quad \forall \; d, r, k, t \qquad \ldots(32b)$$

[CC9] Pretreatment capacity at collection centers (distribution centers): the total labor hours required to pre-treat the dead products should not exceed the labor hour capacity in any time period

$$\sum_{q=1}^{Q}\sum_{r=1}^{R}\sum_{k=1}^{K} LCPT_{qd}XCNCR'_{qdrkt} \le LCTPT_{dt} \qquad \forall\ d, t \qquad \ldots(33)$$

3.2.3.5. Fifth stage: from recycling center to the manufacturing plants

3.2.3.5.1. Parameters:

$CRRM_{qrt}$	Cost of recycling for one unit of dead product family q at recycling center r in time period t
$CRIC_r$	Inventory carrying cost rate for dead products at recycling center r
CRH_{ir}	Cost of handling a unit of recycled material i at recycling center r
$CROS_{qrt}$	Cost of buying one unit of dead product family q sludge by recycling center r from the secondary material market in time period t
ECR_{drk}	The pollution emission index corresponding to one transportation consignment when transported from a distribution center d to a recycling center r using transportation mode k
$EDD_{dd'k}$	The pollution emission index corresponding to one transportation consignment when transshipped from a distribution center d to another distribution center d using transportation mode k
EPD_{pdk}	The emission index corresponding to a unit of raw material i (before recycling process) when transported from a distribution center d to a recycling center r using transportation mode k
IRC_{rt}	The floor space capacity at recycling center r to store recycled raw material in time period t
IRP_{rt}	Time capacity of recycling process at recycling center r in time period t
PR_i	Per unit price of recycled raw material i
TR_{ir}	Time required to recycle one unit of raw material i at recycling center r

3.2.3.5.2. Decision variables:

$XRRM_{qrt}$	Number of units of dead product family q recycled at recycling center r in time period t
$XRIL_{qrt}$	The inventory level of dead product family q at recycling center r in time period t
$XROS_{qrt}$	The amount of dead product q sludge purchased by recycling center r in time period t
$XRTP_{irpt}$	The amount of recycled raw material i processed at recycling center r and used at manufacturing plant p in time period t
XR_{it}	The amount of recycled raw material i sold in time period t

3.2.3.5.3. Objective function:

[OR1] The processing cost of recycling: The cost is proportional to the number of dead products recycled at each recycling center in each time period

$$\sum_{q=1}^{Q}\sum_{r=1}^{R}\sum_{t=1}^{T} CRRM_{qrt} XRRM_{qrt} \qquad \ldots(\text{ob18})$$

[OR2] Dead products inventory holding cost: the cost is proportional to the inventory level in each time period

$$\sum_{q=1}^{Q}\sum_{r=1}^{R}\sum_{t=1}^{T} CRIC_{r} CCIV_{q} XRIL_{qrt} \qquad \ldots(\text{ob19})$$

[OR3] Handling cost of dead products at the recycling center

$$\sum_{q=1}^{Q}\sum_{r=1}^{R}\sum_{t=1}^{T} CRH_{ir} XRTP_{irpt} \qquad \ldots(\text{ob20})$$

[OR4] The cost of purchasing dead products sludge: the recycling center can buy the dead product sludge from the secondary material market

$$\sum_{q=1}^{Q}\sum_{r=1}^{R}\sum_{t=1}^{T} CROS_{qrt} XROS_{qrt} \qquad \ldots(\text{ob21})$$

[OR5] Revenue from selling recycled raw materials: the recycled raw materials can be sold to other industries

$$\sum_{i=1}^{I}\sum_{t=1}^{T} PR_i XR_{it} \qquad \ldots\text{(ob22)}$$

[MOR1] The index of pollution emission during transportation between manufacturing plants and distribution centers: the pollution emission into the environment is measured by the amount of carbon dioxide released into the air through the fuel consumption

$$\sum_{p=1}^{P}\sum_{d=1}^{D}\sum_{k=1}^{K}\sum_{t=1}^{T} EPD_{pdk} \times XPTP_{pdkt} \qquad \ldots\text{(ob23)}$$

[MOR2] The index of pollution emission during transshipments between distribution centers: the pollution emission into the environment is measured by the amount of carbon dioxide released into the air through the fuel consumption

$$\sum_{d=1}^{D}\sum_{d'=1}^{D}\sum_{k=1}^{K}\sum_{t=1}^{T} EDD_{dd'k} \times XDTS_{dd'kt} \qquad \ldots\text{(ob24)}$$

[MOR3] The index of pollution emission during transportation between collection centers and the recycling center: the pollution emission into the environment is measured by the amount of carbon dioxide released into the air through the fuel consumption

$$\sum_{d=1}^{D}\sum_{r=1}^{R}\sum_{k=1}^{K}\sum_{t=1}^{T} ECR_{drk} \times \left(XCCR_{drk} + XCCR'_{drk}\right) \qquad \ldots\text{(ob25)}$$

3.2.3.5.4. Constraints

[CR1] The inventory floor space capacity at recycling centers for the incoming dead products: the inventory of dead products kept at recycling centers waiting to be processed can not exceed the storage capacity of the recycling center

$$\sum_{q=1}^{Q} IPFS_q XRIL_{qrt} \le IRC_{rt} \qquad \forall\ r, t \qquad \ldots(34)$$

[CR2] The processing capacity at recycling centers for the incoming dead products: the total processing time of recycling raw material *i* can not exceed the time capacity at recycling center *r*

$$\sum_{i=1}^{I} REC_i TR_{ir} ZBOM_{qi} XRRM_{qrt} \le IRP_{rt} \qquad \forall\ r, t \qquad \ldots(35)$$

[CR3] Inventory balance equation at recycling centers: the inventory level of dead products at the end of a time period is equal to the last period's inventory plus the dead products received from the collection center plus the sludge purchased from the secondary material market minus the number of units used in the recovery process

$$XRIL_{qrt} = XRIL_{qr(t-1)} + \sum_{d=1}^{D}\sum_{k=1}^{K} XCNCR_{qdrk(t-LCCR_{drk})} + \left(\frac{XROS_{qrt}}{IPWP_{q}}\right) - XRRM_{qrt}$$

$$+ \sum_{d=1}^{D}\sum_{k=1}^{K} XCNCR'_{qdrk(t-LCCR'_{drk})}$$

$$\forall \quad q, r, t, \qquad \ldots(36)$$

Here, $\sum_{d=1}^{D}\sum_{k=1}^{K} XCNCR_{qdrk(t-LCCR_{drk})}$ represents the units of non-pretreated dead product q shipped from distribution center d using transportation mode k in time period $t\text{-}LCCR_{drk}$ and received at recycling center r in time period t, and $\sum_{d=1}^{D}\sum_{k=1}^{K} XCNCR'_{qdrk(t-LCCR'_{drk})}$ represents the units of pretreated dead product q shipped from distribution center d using transportation mode k in time period $t\text{-}LCCR'_{drk}$ and received at recycling center r in time period t

[CR4] Recycled raw material balance equation: the recycled raw material i can be sent to manufacturing plants as raw material or sold to other industries

$$XR_{it} \leq \sum_{r=1}^{R} REC_{i} ZBOM_{qi} XRRM_{qrt} - \sum_{r=1}^{R}\sum_{p=1}^{P} XRTP_{irpt} \qquad \forall \quad i, t \qquad \ldots (37)$$

Binary Constraints:

$YRM_{spt,} = \{0, 1\},$

Integer Constraints:

$SS_{ip}, XRM_{ipt}, XSM_{ipt}, XSITM_{sipkt}, XSTM_{spkt}, XSTRM_{sipkt}, XP_{pqt}, XPIL_{pqt}, XPITP_{pqdkt}, XPTP_{pdkt}, PS_{pq}, XPTPD_{pqdkt}, XDPD_{pqdt}, XDITBD_{pqdd'k}, XDTS_{dd'kt}, XDNTS_{pqdd'kt}, XCIL_{qdt}, XCITC_{qdrkt}, XCITC'_{qdrkt}, XCCR_{drkt}, XCCR'_{drkt}, XCNCR_{dqrkt}, XCNCR'_{dqrkt}, XRRM_{qrt}, XRIL_{qrt}, XRTP_{irpt}, XR_{it} = integer$

Non-negativity Constraints:

$SS_{ip}, XRM_{ipt}, XSM_{ipt}, XSITM_{sipkt}, XSTM_{spkt}, XSTRM_{sipkt}, XP_{pqjt}, XPIL_{pqt}, XPITP_{pqdkt}, XPTP_{pdkt},$

$PS_{pq},\ XPTPD_{pqdkt},\ XDPD_{pqdt},\ XDITBD_{pqdd'k},\ XDTS_{dd'kt},\ XDNTS_{pqdd'kt},\ XCIL_{qdt},\ \mathrm{XCITC}_{\mathrm{qdrkt}},$
$\mathrm{XCITC'}_{\mathrm{qdrkt}},\ XCCR_{drkt},\ XCCR'_{drkt},\ XCNCR_{dqrkt},\ XCNCR'_{dqrkt},\ XRRM_{qrt},\ XRIL_{qrt},\ XRTP_{irpt},$
$XR_{it}, XPOL_{pt}, XPRL_{pt}, XPHL_{pt}, XROS_{qrt},\ \geq 0$

3.3. Summary of the mathematical model

The mathematical model is now summarized as follows.

3.3.1. Objective function 1: minimize the total costs

$$\sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{k=1}^{K}\sum_{t=1}^{T} CSM_{sit}XSTRM_{sipkt} + \sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{t=1}^{T} CSICP_{p}CSIV_{i}XSM_{ipt}$$
$$+\sum_{p=1}^{P}\sum_{t=1}^{T}\left(CPRL_{pt}XPRL_{pt} + CPOL'_{pt}XPOL_{pt}\right) + \sum_{p=1}^{P}\sum_{t=1}^{T} CPIL_{pt}XPHL_{pt}$$
$$+\sum_{p=1}^{P}\sum_{q=1}^{Q}\sum_{t=1}^{T} CPICP_{p}CPIV_{q}XPIL_{pqt} + \sum_{p=1}^{P}\sum_{d=1}^{D}\sum_{k=1}^{K}\sum_{t=1}^{T} CPTP_{pdk}XPTP_{pdkt}$$
$$+\sum_{p=1}^{P}\sum_{q=1}^{Q}\sum_{d=1}^{D}\sum_{k=1}^{K}\sum_{t=1}^{T} CPICP_{p}CPIV_{q}[LPLTP_{pdk} + ZPSF_{ZPSL(pq)}\, LPCV_{pdk}LPLTP_{pdk}$$
$$+ RIPD_{pdk}ZCSF]XPTPD_{pqdkt}$$
$$+\sum_{p=1}^{P}\sum_{q=1}^{Q}\sum_{d=1}^{D}\sum_{t=1}^{T} CDIC_{d}CPIV_{q}XDPD_{pqdt} + \sum_{p=1}^{P}\sum_{q=1}^{Q}\sum_{d=1}^{D}\ \sum_{d'=1,d\neq d'}^{D}\ \sum_{k=1}^{K}\sum_{t=1}^{T} CDH_{qd}XDNTS_{pqdd'kt}$$
$$+\sum_{d=1}^{D}\ \sum_{d'=1,d'\neq d}^{D}\ \sum_{k=1}^{K}\sum_{t=1}^{T} CDTS_{dd'k}XDTS_{dd'kt} + \sum_{q=1}^{Q}\sum_{d=1}^{D}\sum_{t=1}^{T} CCCP_{qdt}FC_{qdt}$$
$$+\sum_{p=1}^{P}\sum_{q=1}^{Q}\sum_{d=1}^{D}\ \sum_{d'=1,d\neq d'}^{D}\ \sum_{k=1}^{K}\sum_{t=1}^{T} CDIC_{d}CPIV_{q}LDTD_{dd'k}XDNTS_{pqdd'kt}$$
$$+\sum_{d=1}^{D}\sum_{q=1}^{Q}\sum_{t=1}^{T} CCIC_{d}CCIV_{q}XCIL_{qdt} + \sum_{q=1}^{Q}\sum_{d=1}^{D}\sum_{t=1}^{T} CCH_{qd}FC_{qdt} + \sum_{q=1}^{Q}\sum_{d=1}^{D}\sum_{t=1}^{T} CCPT_{qd}XCNCR'_{qdt}$$
$$+\sum_{q=1}^{Q}\sum_{d=1}^{D}\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{r=1}^{R}(CCACR_{drk}IPWP_{q}XCNCR'_{dqrkt} + CCCR_{drk}XCCR_{drkt})$$
$$+\sum_{q=1}^{Q}\sum_{d=1}^{D}\sum_{r=1}^{R}\sum_{k=1}^{K}\sum_{t=1}^{T} CCIC_{r}CCIV_{q}(LCCR_{drk}XCNCR_{qdrkt} + LCCR'_{drk}\, XCNCR'_{qdrkt})$$
$$+\sum_{q=1}^{Q}\sum_{r=1}^{R}\sum_{t=1}^{T} CRRM_{qrt}XRRM_{qrt} + \sum_{q=1}^{Q}\sum_{r=1}^{R}\sum_{t=1}^{T} CRIC_{r}CCIV_{q}XRIL_{qrt} + \sum_{q=1}^{Q}\sum_{r=1}^{R}\sum_{t=1}^{T} CRH_{ir}XRTP_{irpt}$$
$$+\sum_{q=1}^{Q}\sum_{r=1}^{R}\sum_{t=1}^{T} CROS_{qrt}XROS_{qrt}\ -\ \sum_{i=1}^{I}\sum_{t=1}^{T} PR_{i}XR_{it}$$

3.3.2. Objective function 2: minimize the pollution emissions

$$\sum_{p=1}^{P}\sum_{d=1}^{D}\sum_{k=1}^{K}\sum_{t=1}^{T} EPD_{pdk} \times XPTP_{pdkt} + \sum_{d=1}^{D}\sum_{d'=1}^{D}\sum_{k=1}^{K}\sum_{t=1}^{T} EDD_{dd'k} \times XDTS_{dd'kt}$$

$$+\sum_{d=1}^{D}\sum_{r=1}^{R}\sum_{k=1}^{K}\sum_{t=1}^{T} ECR_{drk} \times \left(XCCR_{drk} + XCCR'_{drk}\right)$$

3.3.3. Constraints

$$\sum_{p=1}^{P}\sum_{k=1}^{K} XSTRM_{sipkt} \leq 1000 \times SC_{sit} \tag{1}$$

$$XSM_{ipt} = XSM_{ip(t-1)} + \sum_{s=1}^{S}\sum_{k=1}^{K} XSTRM_{sipk(t-LSLTM_{spk})} + \sum_{r=1}^{R} XRTP_{irp(t-LRLT_{rip})} - XRM_{ipt} \tag{2}$$

$$XSITM_{sipkt} = XSITM_{sipk(t-1)} + XSTRM_{sipkt} - XSTRM_{sipk(t-LSLTM_{spk})} \tag{3}$$

$$SS_{ip} = ZSSF_{ZCSL(ip)}\left(\sqrt{MAX\left(\frac{\sum_{t=1}^{T}\sum_{s=1}^{S} LSLT_{sip}YRM_{spt}}{S \times T}, \frac{\sum_{r=1}^{R} TR_{ir} + \sum_{r=1}^{R} LRLT_{rip}}{R}\right)}\left(\sum_{q=1}^{Q} ZBOM_{qi}\sigma_{DE_{pq}}\right)\right) \tag{4}$$

$$XSM_{ipt} \geq SS_{ip} \tag{5}$$

$$\sum_{i=1}^{I}\sum_{k=1}^{K} XSTRM_{sipkt} \leq (M)YRM_{spt} \tag{6}$$

$$XRM_{ipt} \geq \sum_{q=1}^{Q} ZBOM_{qi}XP_{pqt} \tag{7}$$

$$XRM_{ipt} \leq (1.027)\sum_{q=1}^{Q} ZBOM_{qi}XP_{pqt} \tag{8}$$

$$XPRL_{pt} = XPRL_{p(t-1)} + XPHL_{pt} \tag{9}$$

$$XPRL_{pt} \leq LHC_{pt} \tag{10}$$

$$XPOL_{pt} \leq f_{p}XPRL_{pt} \tag{11}$$

$$XPRL_{pt} + XPOL_{pt} \geq \sum_{q=1}^{Q} RLH_{pq}XP_{pqt} \tag{12}$$

$$XPIL_{pqt} = XPIL_{pq(t-1)} + XP_{pqt} - \sum_{d=1}^{D}\sum_{k=1}^{K} XPTPD_{pqdkt} \tag{13}$$

$$\sum_{q=1}^{Q} IPFS_{q}XPIL_{pqt} \leq IPFC_{pt} \tag{14}$$

$$PS_{pq} = ZPSF_{ZPSL(pq)}\sqrt{\phi + LPLT_{pq}}(\sigma_{DE_{pq}}) \tag{15}$$

$$XPIL_{pqt} \geq PS_{pq} \tag{16}$$

$$XPITP_{pqdkt} = XPITP_{pqdk(t-1)} + XPTPD_{pqdkt} - XPTPD_{pqdk(t-LPLTP_{pdk})} \tag{17}$$

$$\sum_{q=1}^{Q} IPWP_q XPTPD_{qpdkt} \le IPWT_{pdk} XPTP_{pdkt} \tag{18}$$

$$\sum_{q=1}^{Q} IPVP_q XPTPD_{pqdkt} \le IPVT_{pdk} XPTP_{pdkt} \tag{19}$$

$$\sum_{p=1}^{P} \sum_{q=1}^{Q} IPFS_q XDPD_{pqdt} \le IDC_{dt} \tag{20}$$

$$\begin{aligned} XDPD_{pqdt} = {} & XDPD_{pqd(t-1)} + \sum_{k=1}^{K} XPTPD_{pqdk(t-LPLTP_{pdk})} + \sum_{d'=1}^{D} \sum_{k=1}^{K} XDNTS_{pqdd'k(t-LDTD_{dd'k})} \\ & - \sum_{d'=1}^{D} \sum_{k}^{K} XDNTS_{pqdd'kt} \end{aligned} \tag{21}$$

$$XDITBD_{pqdd'kt} = XDITBD_{pqdd'k(t-1)} + XDNTS_{pqdd'kt} - XDNTS_{pqdd'k(t-LDTD_{dd'k})} \tag{22}$$

$$\sum_{p=1}^{P} \sum_{q=1}^{Q} IPWP_q XDNTS_{pqdd'kt} \le IDWBD_{dd'k} XDTS_{dd'kt} \tag{23}$$

$$\sum_{p=1}^{P} \sum_{q=1}^{Q} IPVP_q XDNTS_{pqdd'kt} \le IDVBD_{dd'k} XDTS_{dd'kt} \tag{24}$$

$$\sum_{q=1}^{Q} IPFS_q XCIL_{qdt} \le ICC_{dt} \tag{25}$$

$$XCIL_{qdt} = XCIL_{qd(t-1)} + FC_{qdt} - \sum_{r=1}^{R} \sum_{k=1}^{K} XCNCR_{qdrkt} - \sum_{r=1}^{R} \sum_{k=1}^{K} XCNCR'_{qdrkt} \tag{26}$$

$$XCITC_{qdrkt} = XCITC_{qdrk(t-1)} + XCNCR_{qdrkt} - XCNCR_{qdrk(t-LCCR_{drk})} \tag{27}$$

$$XCITC'_{qdrkt} = XCITC'_{qdrk(t-1)} + XCNCR'_{qdrkt} - XCNCR'_{qdrk(t-LCCR'_{drk})} \tag{28}$$

$$\sum_{q=1}^{Q} IPWP_q XCNCR_{qdrkt} \le ICWT_{drk} XCCR_{drkt} \tag{29}$$

$$\sum_{q=1}^{Q} IPVP_q XCNCR_{qdrkt} \le ICVT_{drk} XCCR_{dqrkt} \tag{30}$$

$$\sum_{q=1}^{Q} \sum_{i=1}^{I} \left(0.9 \times IPWP_q\right) ZBOM_{qi} REC_i XCNCR'_{qdrkt} \le ICWT_{drk} XCCR'_{drkt} \tag{31}$$

$$\sum_{q=1}^{Q} \sum_{i=1}^{I} \left(0.5 \times IPVP_q\right) ZBOM_{qi} REC_i XCNCR'_{qdrkt} \le ICVT_{drk} XCCR'_{dqrkt} \tag{32}$$

$$\sum_{q=1}^{Q} \sum_{r=1}^{R} \sum_{k=1}^{K} LCPT_{qd} XCNCR'_{qdrkt} \le LCTPT_{dt} \tag{33}$$

$$\sum_{q=1}^{Q} IPFS_q XRIL_{qrt} \le IRC_{rt} \tag{34}$$

$$\sum_{i=1}^{I} REC_i TR_{ir} ZBOM_{qi} XRRM_{qrt} \le IRP_{rt} \tag{35}$$

$$XRIL_{qrt} = XRIL_{qr(t-1)} + \sum_{d=1}^{D}\sum_{k=1}^{K} XCNCR_{qdrk(t-LCCR_{drk})} + \left(\frac{XROS_{qrt}}{IPWP_{q}}\right) - XRRM_{qrt} + \sum_{d=1}^{D}\sum_{k=1}^{K} XCNCR'_{qdrk(t-LCCR'_{drk})} \tag{36}$$

$$XR_{it} \leq \sum_{r=1}^{R} REC_{i} ZBOM_{qi} XRRM_{qrt} - \sum_{r=1}^{R}\sum_{p=1}^{P} XRTP_{irpt} \tag{37}$$

$SS_{ip}, XRM_{ipt}, XSM_{ipt}, XSITM_{sipkt}, XSTM_{spkt}, XSTRM_{sipkt}, XP_{pqjt}, XPIL_{pqt}, XPITP_{pqdkt}, XPTP_{pdkt},$

$PS_{pq}, XPTPD_{pqdkt}, XDPD_{pqdt}, , XDITBD_{pqdd'k}, XDTS_{dd'kt}, XDNTS_{pqdd'kt}, XCIL_{qdt}, XCITC_{qdrkt},$

$XCITC'_{qdrkt}, XCCR_{drkt}, XCCR'_{drkt}, XCNCR_{qdrkt}, XCNCR'_{qdrkt}, XRRM_{qrt}, XRIL_{qrt}, XRTP_{irpt},$

$XR_{it}, = integer$

$SS_{ip}, XRM_{ipt}, XSM_{ipt}, XSITM_{sipkt}, XSTM_{spkt}, XSTRM_{sipkt}, XP_{pqjt}, XPIL_{pqt}, XPITP_{pqdkt}, XPTP_{pdkt},$

$PS_{pq}, XPTPD_{pqdkt}, XDPD_{pqdt}, , XDITBD_{pqdd'k}, XDTS_{dd'kt}, XDNTS_{pqdd'kt}, XCIL_{qdt}, XCITC_{qdrkt},$

$XCITC'_{qdrkt}, XCCR_{drkt}, XCCR'_{drkt}, XCNCR_{qdrkt}, XCNCR'_{qdrkt}, XRRM_{qrt}, XRIL_{qrt}, XRTP_{irpt},$

$XR_{it}, XPOL_{pt}, XPRL_{pt}, XPIL_{pt}, XPDL_{pt}, XROS_{qrt}, \lambda_{pt} \geq 0$

$YRM_{spt}, = \{0, 1\}$

CHAPTER 4 -
NUMERICAL EXAMPLE AND COMPUTATIONAL EXPERIENCE

The main objectives of this chapter are two fold:

1. To test the model with a realistic-sized problem in order to validate its calculations and the outcome
2. To measure and evaluate the impact of decision making in an integrated supply chain management environment

In the following section, the input parameters and the data used in the case study will be presented and explained.

4.1. Introduction of the battery manufacturer

This research presents information for creating a model specifically for a battery manufacturer named ABC. The model is generalized so that it can be adopted by any real world manufacturer. Some of the key reasons for modeling this specific case are as follows:

1) The company produces more than 4000 different kinds of products that are grouped into three product families based on their similarities in terms of their BOM (bill of material), manufacturing process, production capacity requirements, etc. A product family may be produced at more than one manufacturing plant.
2) Suppliers provide manufacturing plants with the virgin raw materials needed to produce the products.
3) Processing technology differs from plant to plant, prompting differences in unit processing times as well as unit production costs.
4) The storage capacities of the warehouses vary due to periodic review policies.
5) The recycling centers are usually situated in a different location from the manufacturing plants. The material recovery process lead time includes the lead times for both the recycling process and the transportation between the recycling centers and the manufacturing plants.

ABC operates five manufacturing plants which produce three product families (Table 4.1), one large size centralized warehouse, one recycling center and one plastics molding plant—which are grouped into one recycling processing center (Table 4.2). In addition to these on-site facilities, the company has five regional distribution centers which function as retailer and collection centers (Table 4.3).

Table 4.1: Product families produced at manufacturing plants

Plant, p	**Product Family, q**	**Product Detail Description**
1 2 3	1	1: Automotive – LTV 2: Recreation Vehicle 3: Farm Equipment 4: Small Engine – Lawn & Garden 5: Military Ordnance
4	2	1: Motive Power – lift truck 2: Railroad
5	3	1: Telecommunication –UPS 2: Solar 3:Marine 4: Small Engine – Power sports 5: Golf Car –EV – Floor Scrubber 6: Commercial Service 7: Wheelchair – Cable TV

Table 4.2: On-site facility descriptions of battery manufacturer ABC

Plant, p	**Facility Category**	**Product Detail**
1 2 3	**SLI Battery Plant 1** **SLI Battery Plant 2** **SLI Battery Plant 3**	automotive, small engine and commercial batteries
4	**Industrial Battery Plant**	large motive power batteries for material handling equipment, airport support vehicles and locomotives
5	**Stationary Battery Plant**	Batteries for telecommunications, UPS, solar, wheelchair and other types of equipment
other	**Recycling Center**	Recycles spent lead-acid batteries into lead, sulfuric acid, plastic, and liquid fertilizer.

Table 4.4 presents the factor values of the bill of material (BOM). Since this is a process-oriented industry, the bill of material refers to the units of raw material that go into one product family unit. This table gives the percentage of content based on product weight.

Table 4.3: Regional distribution center description

Regional Distribution Center, *d*	**Service Area**
1	Western coastal area
2	Central American
3	Eastern coastal area
4	Western Canada: BC, AB, MB, SK
5	Central and southeast of Canada: ON, QB, NB, NS

Table 4.4: Bill of material information for product families, $ZBOM_{qi}$,

Product Family, *q*	**Raw material, i^***						
	1	**2**	**3**	**4**	**5**	**6**	**7**
1	0.58	0.36	0.01	0	0.04	0.01	0
2	0.65	0.25	0.01	0	0.08	0.01	0
3	0.75	0.15	0.01	0.01	0.06	0.01	0.01

Table 4.5 shows the parameter values for raw materials. The inventory value of the virgin raw materials is used for calculating inventory holding costs, whereas the volume and weight of raw materials are used for calculating the number of transportation consignments. REC_i indicates whether material i can be recycled and used again (REC_i =1), or not ($REC_i = 0$).

Table 4.5: Input data for raw materials

Raw material, *i*	**Inventory Value, $CSIV_i$ ($/unit)**	**Volume, $ISVM_i$ (cu.ft/unit)****	**Weight, $ISWM_i$ (lbs/unit)**	**Recycle Indicator REC_i**
1	0.46	0.0014	1	1
2	1.22	0.0089	1	0
3	2.80	0.0024	1	0
4	0.92	0.0028	1	0
5	0.50	0.0097	1	1
6	2.00	0.013	1	0
7	3.65	0.0022	1	0

Table 4.6 shows the inventory carrying cost rate at various suppliers, the virgin raw material costs from various suppliers and the supply capacities. It is assumed that the capacities and the virgin raw material costs remain the same from period to period.

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[*] The raw material indices stand for:
1: lead; 2: Sulfuric Acid; 3: Antimony; 4: Arsenic; 5: Polypropylene; 6: Calcium; 7: Tin

[**] The weights of metal and acid are listed at the following website:
http://www.ugr.es/~azzaro/pesospec.htm

Table 4.6: Suppliers' inventory carrying cost rate, $CSIC_s$; virgin raw material costs (US$), CSM_{sit} and supplier capacities, SC_{sit} (× 1000 units)

Supplier, s	**Carrying cost rate, $CSIC_s$**	**Raw material, i CSM_{sit}, SC_{sit}**						
		1	**2**	**3**	**4**	**5**	**6**	**7**
1	0.002	27.6, 4000	73.2, 2000	5.6, 60	1.84, 20	30, 400	4, 70	7.3, 20
2	0.003	28.2, 5000	72.6, 2100	5.4, 59	1.8, 22	29.4, 400	3.8, 70	7.16, 18
3	0.005	30, 5500	72, 1800	5.2, 60	1.78, 20	31.8, 480	3.6, 70	7.1, 24
4	0.006	26.4, 4500	74.4, 1900	5.8, 65	1.88, 25	27.6, 450	4.2, 78	7.4, 25
5	0.004	28.8, 4800	75, 2300	6.0, 62	1.9, 25	30.6, 500	4.0, 75	7.54, 25

Table 4.7 illustrates the safety stock factor of the raw materials used by the manufacturing plants. Safety stocks of raw materials are maintained in order to protect the manufacturing plants from coming up short of the necessary raw material in the face of variations in transportation lead times and demand from distribution centers. The value of safety stock factors is kept relatively high for critical raw materials. In this case, the safety stock factor of lead should be higher than that the others. In each cell, the first entry refers to *ZCSL(ip)*, probability of having enough stock, and the second entry is $ZSSF_{ZCSL(ip)}$, the standard normal variable at this probability.

Table 4.7: Safety stock factor $ZSSF_{ZCSL(ip)}$ of raw materials at manufacturing plants

Raw material, i	**Plant, P**				
	1	**2**	**3**	**4**	**5**
1,2,5	97.5%, 1.96	99.5%, 2.58	97.5%, 1.96	97.5%, 1.96	95%, 1.64
3,4,6,7	95%, 1.64	95%, 1.64	95%, 1.64	95%, 1.64	90%, 1.28

Table 4.8 displays the various parameter values related to the transportation activities, between the suppliers and the manufacturing plants. Here a lead time of zero means that shipments generally made during the week are also received in the same week. The lead times are rounded up to the nearest integer value.

Table 4.8: Input data for transportation modes between suppliers and plants

Supplier, s	**plant p**	**Mode k**	**Coefficient $LSCV_{spk}$**	**Transportation Cost, $CSTM_{spk}$ ($/consignment)**	**Lead time $LSLTM_{spk}$ (week)**	**Replenish Interval, $RISP_{spk}$ (weeks)**	**Volume capacity $ISVT_{spk}$ (cuft)**	**Weight capacity $ISWT_{spk}$ (units)**
1	1	1	0.42	$99.50	1	1	3605	5000
		2	0.32	$175.75	0	1	3605	5000
		3	0.25	$150.00	1	1	5010	8500
	2	1	0.42	$219.25	1	1	3605	5000
		2	0.32	$386.75	0	1	3605	5000
		3	0.25	$330.00	1	1	5010	8500
	3	1	0.43	$179.25	2	1	3605	5000
		2	0.37	$316.50	1	1	3605	5000
		3	0.29	$270.00	0	1	5010	8500
	4	1	0.42	$338.75	1	1	3605	5000
		2	0.32	$597.75	0	1	3605	5000
		3	0.25	$510.00	0	1	5010	8500
	5	1	0.43	$350.00	1	1	3605	5000
		2	0.37	$625.00	0	1	3605	5000
		3	0.29	$621.25	0	1	5010	8500
2	1	1	0.39	$348.75	0	1	3605	5000
		2	0.32	$615.25	0	1	3605	5000
		3	0.29	$525.00	0	1	5010	8500
	2	1	0.42	$129.50	2	1	3605	5000
		2	0.32	$228.50	1	1	3605	5000
		3	0.25	$195.00	1	1	5010	8500
	3	1	0.42	$89.75	2	1	3605	5000
		2	0.32	$158.25	1	1	3605	5000
		3	0.25	$135.00	2	1	5010	8500
	4	1	0.40	$199.25	1	1	3605	5000
		2	0.37	$351.50	0	1	3605	5000
		3	0.23	$300.00	0	1	5010	8500
	5	1	0.39	$212.25	1	1	3605	5000
		2	0.37	$331.75	0	1	3605	5000
		3	0.23	$335.00	0	1	5010	8500
3	1	1	0.40	$99.50	2	1	3605	5000
		2	0.32	$175.75	2	1	3605	5000
		3	0.25	$150.00	2	1	5010	8500
	2	1	0.36	$219.25	1	1	3605	5000
		2	0.32	$386.75	0	1	3605	5000
		3	0.29	$330.00	0	1	5010	8500
	3	1	0.46	$179.25	1	1	3605	5000
		2	0.32	$316.50	0	1	3605	5000
		3	0.29	$270.00	0	1	5010	8500
	4	1	0.42	$338.75	0	1	3605	5000
		2	0.32	$597.75	0	1	3605	5000
		3	0.25	$510.00	0	1	5010	8500

* Mode 1=Regular Truck, Mode 2=Expedited Truck, Mode 3=Rail

Table 4.8: (continued...)

Supplier, s	**plant p**	**Mode k**	**Coefficient $LSCV_{spk}$**	**Transportation Cost, $CSTM_{spk}$ ($/consignment)**	**Lead time $LSLTM_{spk}$ (week)**	**Replenish Interval, $RISP_{spk}$ (weeks)**	**Volume capacity $ISVT_{spk}$ (cuft)**	**Weight capacity $ISWT_{spk}$ (units)**
3	5	1	0.41	$59.75	1	1	3605	5000
		2	0.29	$105.50	0	1	3605	5000
		3	0.23	$90.00	0	1	5010	8500
4	1	1	0.42	$259.00	2	1	3605	5000
		2	0.32	$457.00	2	1	3605	5000
		3	0.25	$390.00	2	1	5010	8500
	2	1	0.42	$209.25	1	1	3605	5000
		2	0.32	$369.25	1	1	3605	5000
		3	0.25	$315.00	1	1	5010	8500
	3	1	0.43	$239.00	0	1	3605	5000
		2	0.37	$422.00	0	1	3605	5000
		3	0.29	$360.00	0	1	5010	8500
	4	1	0.42	$242.50	0	1	3605	5000
		2	0.32	$397.00	0	1	3605	5000
		3	0.25	$339.25	0	1	5010	8500
	5	1	0.42	$59.75	1	1	3605	5000
		2	0.32	$105.50	0	1	3605	5000
		3	0.25	$90.00	0	1	5010	8500
5	1	1	0.22	$179.25	1	1	3605	5000
		2	0.32	$316.50	1	1	3605	5000
		3	0.26	$270.00	1	1	5010	8500
	2	1	0.40	$119.50	1	1	3605	5000
		2	0.38	$211.00	0	1	3605	5000
		3	0.35	$180.00	0	1	5010	8500
	3	1	0.43	$179.25	1	1	3605	5000
		2	0.37	$316.50	1	1	3605	5000
		3	0.39	$270.00	1	1	5010	8500
	4	1	0.40	$86.75	1	1	3605	5000
		2	0.32	$116.75	0	1	3605	5000
		3	0.29	$89.50	0	1	5010	8500
	5	1	0.42	$59.75	2	1	3605	5000
		2	0.32	$105.50	2	1	3605	5000
		3	0.25	$90.00	2	1	5010	8500

Table 4.9 displays the input data related to the manufacturing of each product family. The term *manufacturing lead time* refers to the time span stretching from the time the raw materials are available, until the finished goods are ready in the warehouses to be shipped out. The expected demand of product family q at plant p is extracted from the demand forecast data.

Table 4.9: Input data for product families by manufacturing plants

Plant, p	**Product family, q**	**Required Labor Hours, RLH_{pq}**	**Safety Stock Factor $ZPSF_{ZCSL(pq)}$, (95.00%)**	**Expected Manufacturing Lead Time $LPTP_{pq}$ (in weeks)**	**Expected Demand DE_{pq}**	**Standard Deviation of Forecasted Demand $\sigma_{DE_{pq}}$**
1	1	2.2	1.64	0.1	67589	13289
	3	204.6	1.64	2	105	24
2	1	2.2	1.64	0.1	48278	9492
	2	17.6	1.64	0.8	11903	2795
3	1	2.5	1.64	0.12	57934	11391
	2	17.5	1.64	0.8	7935	1863
4	1	2.5	1.64	0.12	19311	3797
	2	17.6	1.64	0.8	15870	3726
5	2	17.8	1.64	0.82	3968	932
	3	204.9	1.64	2.1	418	96

Table 4.10 provides the information about labor costs, the labor hours allowed, the overtime factor, and the inventory capacity at the inventory carrying cost rate at each plant.

Table 4.10: Input data for labor hour, inventory cost and storage capacity for the manufacturing plants

Plant, p	**Regular Time Cost, $CPRL_{pt}$ ($/hour)**	**Overtime Cost, $CPOL_{pt}$ ($/hour)**	**Cost of Increasing Labor, $CPIL_{pt}$ ($/hour)**	**Max. Allowable workforce LHC_{pt} (hours/ week)**	**Overtime factor, f_p**	**Inventory Carrying Cost Rate, $CPICP_p$**	**Inventory Capacity*, in each period $IPFC_{pt}$ (sq. ft)**
1	$15.00	$23.00	$18.00	180179	0.2	$0.0040	35330
2	$15.00	$23.00	$18.00	305704	0.2	$0.0050	41862
3	$15.00	$23.00	$18.00	263698	0.2	$0.0045	40993
4	$10.00	$15.00	$12.00	317590	0.5	$0.0055	32741
5	$10.00	$15.00	$12.00	176279	0.5	$0.0055	8539

Table 4.11 shows the transportation related data for the shipments between manufacturing plants and distribution centers, while Table 4.12 displays the similar data for the trans-shipments between different distribution centers.

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[*] Inventory (storage) capacities are assumed to be independent of time periods in this study

Table 4.11: Transportation related data for shipments between manufacturing plants and distribution centers

plant p	**DC,** d	**Mode** k*	**Coefficient** $LPCV_{pdk}$	**Transportation Cost,** $CPTP_{pdk}$ **(/consignment)**	**Lead time** $LPLTP_{pdk}$ **(week)**	**Replenish Interval,** $RIPD_{pdk}$ **(weeks)**	**Volume capacity** $IPVT_{pdk}$ **(cuft)**	**Weight capacity** $IPWT_{pdk}$ **(units)**	**Pollution emission index**** EPD_{pdk}
1	**1**	**1**	0.42	$239.00	1	2	3605	5000	932
		2	0.32	$422.00	0	1	3605	5000	932
		3	0.25	$360.00	2	2	5010	8500	1572
	2	**1**	0.42	$332.00	1	2	3605	5000	1294
		2	0.32	$586.00	0	2	3605	5000	1294
		3	0.25	$500.00	2	3	5010	8500	2183
	3	**1**	0.43	$398.50	2	1	3605	5000	1553
		2	0.37	$703.25	1	2	3605	5000	1553
		3	0.29	$600.00	2	3	5010	8500	2620
	4	**1**	0.42	$478.25	2	2	3605	5000	1863
		2	0.32	$843.75	1	1	3605	5000	1863
		3	0.25	$720.00	3	1	5010	8500	3144
	5	**1**	0.42	$428.25	3	2	3605	5000	2070
		2	0.32	$793.75	1	1	3605	5000	2070
		3	0.25	$670.00	3	1	5010	8500	3493
2	**1**	**1**	0.42	$239.00	1	2	3605	5000	932
		2	0.32	$422.00	0	1	3605	5000	932
		3	0.25	$360.00	2	2	5010	8500	1572
	2	**1**	0.42	$332.00	1	2	3605	5000	1294
		2	0.32	$586.00	0	2	3605	5000	1294
		3	0.25	$500.00	2	3	5010	8500	2183
	3	**1**	0.43	$398.50	2	1	3605	5000	1553
		2	0.37	$703.25	1	2	3605	5000	1553
		3	0.29	$600.00	2	3	5010	8500	2620
	4	**1**	0.42	$478.25	2	2	3605	5000	1863
		2	0.32	$843.75	1	1	3605	5000	1863
		3	0.25	$720.00	3	1	5010	8500	3144
	5	**1**	0.42	$428.25	3	2	3605	5000	2070
		2	0.32	$793.75	1	1	3605	5000	2070
		3	0.25	$670.00	3	1	5010	8500	3493

* Mode 1=Regular Truck, Mode 2=Expedited Truck, Mode 3=Rail

** Pollution emission index is related to the distance between two nodes in the network, given the equation: EPD_{pdk}= amount of CO_2 released using transportation mode k (gram/mile) * distance between nodes (miles)

Table 4.11: continued

plant p	DC, d	Mode k	Coefficient $LPCV_{pdk}$	Transportation Cost, $CPTP_{pdk}$ (/consignment)	Lead time $LPLTP_{pdk}$ (week)	Replenish Interval, $RIPD_{pdk}$ (weeks)	Volume capacity $IPVT_{pdk}$ (cuft)	Weight capacity $IPWT_{pdk}$ (units)	Pollution emission index EPD_{pdk}
3	1	1	0.42	$239.00	1	2	3605	5000	932
		2	0.32	$422.00	0	1	3605	5000	932
		3	0.25	$360.00	2	2	5010	8500	1572
	2	1	0.42	$332.00	1	2	3605	5000	1294
		2	0.32	$586.00	0	2	3605	5000	1294
		3	0.25	$500.00	2	3	5010	8500	2183
	3	1	0.43	$398.50	2	1	3605	5000	1553
		2	0.37	$703.25	1	2	3605	5000	1553
		3	0.29	$600.00	2	3	5010	8500	2620
	4	1	0.42	$478.25	2	2	3605	5000	1863
		2	0.32	$843.75	1	1	3605	5000	1863
		3	0.25	$720.00	3	1	5010	8500	3144
	5	1	0.42	$428.25	3	2	3605	5000	2070
		2	0.32	$793.75	1	1	3605	5000	2070
		3	0.25	$670.00	3	1	5010	8500	3493
4	1	1	0.42	$239.00	1	2	3605	5000	932
		2	0.32	$422.00	0	1	3605	5000	932
		3	0.25	$360.00	2	2	5010	8500	1572
	2	1	0.42	$332.00	1	2	3605	5000	1294
		2	0.32	$586.00	0	2	3605	5000	1294
		3	0.25	$500.00	2	3	5010	8500	2183
	3	1	0.43	$398.50	2	1	3605	5000	1553
		2	0.37	$703.25	1	2	3605	5000	1553
		3	0.29	$600.00	2	3	5010	8500	2620
	4	1	0.42	$478.25	2	2	3605	5000	1863
		2	0.32	$843.75	1	1	3605	5000	1863
		3	0.25	$720.00	3	1	5010	8500	3144
	5	1	0.42	$428.25	3	2	3605	5000	2070
		2	0.32	$793.75	1	1	3605	5000	2070
		3	0.25	$670.00	3	1	5010	8500	3493
5	1	1	0.42	$239.00	1	2	3605	5000	932
		2	0.32	$422.00	0	1	3605	5000	932
		3	0.25	$360.00	2	2	5010	8500	1572
	2	1	0.42	$332.00	1	2	3605	5000	1294
		2	0.32	$586.00	0	2	3605	5000	1294
		3	0.25	$500.00	2	3	5010	8500	2183
	3	1	0.43	$398.50	2	1	3605	5000	1553
		2	0.37	$703.25	1	2	3605	5000	1553
		3	0.29	$600.00	2	3	5010	8500	2620
	4	1	0.42	$478.25	2	2	3605	5000	1863
		2	0.32	$843.75	1	1	3605	5000	1863
		3	0.25	$720.00	3	1	5010	8500	3144
	5	1	0.42	$428.25	3	2	3605	5000	2070
		2	0.32	$793.75	1	1	3605	5000	2070
		3	0.25	$670.00	3	1	5010	8500	3493

Table 4.12: Transportation related data for shipments between the distribution centers*

DC, d	DC, d	Mode** k	Transportation Cost, $CDTS_{dd'k}$ ($/consignment)	Lead time $LDTD_{dd'k}$ (in weeks)	Volume capacity $IDVBD_{dd'k}$ (cuft)	Weight capacity $IDWBD_{dd'k}$ (units)	Pollution emission index*** $EDD_{dd'k}$
1	2	1	$162.50	1	3605	5000	460
		2	$287.50	0	3605	5000	460
		3	$237.50	1	5010	8500	776
	3	1	$162.50	1	3605	5000	1012
		2	$287.50	0	3605	5000	1012
		3	$237.50	1	5010	8500	1708
	4	1	$162.50	1	3605	5000	828
		2	$287.50	0	3605	5000	828
		3	$237.50	1	5010	8500	1397
	5	1	$157.50	2	3605	5000	1564
		2	$237.50	0	3605	5000	1564
		3	$187.50	1	5010	8500	2639
2	3	1	$162.50	1	3605	5000	414
		2	$290.00	0	3605	5000	414
		3	$247.50	1	5010	8500	699
	4	1	$187.50	1	3605	5000	920
		2	$337.50	0	3605	5000	920
		3	$287.50	1	5010	8500	1553
	5	1	$137.50	2	3605	5000	1012
		2	$287.50	0	3605	5000	1012
		3	$262.50	1	5010	8500	1708
3	4	1	$175.00	1	3605	5000	276
		2	$312.50	0	3605	5000	276
		3	$270.00	1	5010	8500	466
	5	1	$100.00	3	3605	5000	1196
		2	$262.50	0	3605	5000	1196
		3	$245.00	1	5010	8500	2018
4	5	1	$200.00	3	3605	5000	552
		2	$437.50	1	3605	5000	552
		3	$295.00	1	5010	8500	932

Table 4.13: Distribution center storage capacity and inventory carrying cost rate

Distribution Centers, d	Inventory Carrying Cost Rate at DC, $CDIC_d$	Inventory Carrying Cost Rate at CDC (dead product) $CCIC_d$	Inventory Capacity, ICC_{dt} (sq.unit)	Inventory Capacity, IDC_{dt} (sq. unit)
1	$0.006	$0.008	42630	41505
2	$0.0073	$0.0085	62080	65031
3	$0.01	$0.02	23252	26305
4	$0.008	$0.012	13400	15308
5	0.009	0.015	67645	68275

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[*] One-way transportation costs are assumed to be the same in either direction.

[**] Mode 1=Regular Truck, Mode 2=Expedited Truck, Mode 3=Rail

[***] Pollution emission index is related to the distance between two nodes in the network, given the equation: $EDD_{dd'k}$=amount of CO_2 released using transportation mode k (gram/mile) * distance between nodes (miles)

Table 4.13 shows the inventory related costs and capacities at the distribution centers (DCs). The DC inventory capacity refers to the effective storage space available for holding products in inventory. In this case, the cost rate does not vary throughout the planning period.

The disaggregated forecast demands by product families are recorded in Table 4.14, and are calculated using Winters' method (Winters, 1960)* based on the historical data from previous years. We can generally assume that the historical data has been accurately recorded and is easily obtained from the management system.

Table 4.14: Forecasted demand of product family q at the regional distribution center d in time period *t*, D_{qdt} (in Stock-keeping Unit, SKU)

product family, *q*	**DC, *d***	**Planning period, *t***				
		1	**2**	**3**	**4**	**5**
1	1	35922	41897	30302	28567	23595
	2	66867	77989	56406	53176	43920
	3	31161	36345	26286	24781	20468
	4	18177	21201	15334	14456	11940
	5	64270	74961	54216	51111	42215
2	1	13370	8084	8858	7412	8102
	2	16496	9973	10929	9144	9996
	3	4978	3010	3298	2759	3016
	4	3010	1820	1994	1668	1824
	5	20027	12108	13268	11102	12135
3	1	141	129	98	82	81
	2	239	219	166	140	137
	3	96	88	66	56	55
	4	26	23	18	15	15
	5	192	176	133	112	110

Table 4.15 provides the inventory related input data for product families. In this case, we consider the floor space as the primary inventory resource required for holding and storing products at each plant warehouse and distribution centers.

Table 4.16 shows the input data for the end-of-life dead products. The cost of collecting the dead products in this case is assumed to remain independent of the time period (although in the model it is dependent on the time period *t*). The carrying cost rates for both inventory holding and dead product families are used to calculate the

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* Calculation details are shown in Appendix III.

inventory cost. The cost of pre-treatment and the cost of handling are used to calculate the sorting, testing and handling of the dead products.

Table 4.15: Input data for product families

Product family, *q*	**Storage Space Required, $IPFS_q$ (sq.ft/unit)**	**Inventory Value, $CPIV_q$ (\$/unit)**	**Volume, $IPVP_q$ (cu.ft/unit)**	**Weight, $IPWP_q$ (lbs/unit)**
1	0.51	150	0.34	42
2	1.44	260	2.95	350
3	6.28	12130	31.62	3290

Table 4.16: Input data for end-of-life dead product: inventory value of dead product $CCIV_q$, collection cost $CCCP_{qdt,}$ and pre-treatment cost $CCPT_{qd}$:

Product Family, *q*	**Inventory Value, $CCIV_q$**	**$CCCP_{qdt}$, $CCPT_{qd}$ Collection Center (DC), *d***				
		1	**2**	**3**	**4**	**5**
1	45	5, 15	5, 15	10, 15	5, 15	5, 15
2	78	10, 25	10, 25	12, 25	10, 25	12, 25
3	3639	0, 1200	0, 1200	0, 1200	0, 1200	0, 1200

Table 4.17 displays the cost of handling and packaging products at the distribution centers, while Table 4.18 shows the cost of handling end-of-life dead products at the DC (which functions as a CRC in this example).

Table 4.17: Handling cost of product families, CDH_{qd}

Product family, *q*	**CDH_{qd} Distribution Center, *d***				
	1	**2**	**3**	**4**	**5**
1	\$0.28	\$0.42	\$0.35	\$0.46	\$0.53
2	\$0.35	\$0.42	\$0.42	\$0.60	\$0.60
3	\$0.42	\$0.53	\$0.63	\$0.56	\$0.70

Table 4.18: Handling cost of end-of-life product families, CCH_{qd}

Product family, *q*	**CCH_{qd}* Distribution Center, *d***				
	1	**2**	**3**	**4**	**5**
1	\$0.42	\$0.63	\$0.53	\$0.69	\$0.80
2	\$0.53	\$0.63	\$0.63	\$0.90	\$0.90
3	\$0.63	\$0.80	\$0.95	\$0.84	\$1.05

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* Assume that the handling cost CCH_{qd} is 1.5 times the regular handling cost CDH_{qd}

Table 4.19 shows the number of the end-of-life dead products forecasted to be collected, with Appendix 2 providing the details of the calculation.

Table 4.19: Forecasted collection of the dead products, FC_{qd}

Product Family, q	DC, d	Period, t				
		1	2	3	4	5
1	1	20530	21165	21424	27061	21282
	2	38216	39397	39879	50372	39615
	3	17809	18360	18584	23474	18461
	4	10389	10710	10841	13693	10769
	5	36732	37867	38330	48416	38077
2	1	11933	14463	13572	18798	12499
	2	14722	17845	16745	23193	15421
	3	4443	5385	5053	6998	4653
	4	2686	3256	3055	4232	2814
	5	17874	21664	20329	28157	18722
3	1	266	229	220	277	280
	2	452	389	374	471	476
	3	181	156	150	188	191
	4	49	42	40	50	51
	5	363	313	300	378	383

Table 4.20: Input data for transportation between the DCs and the recycling center

DC, d	Mode, k^*	Transportation Cost, $CCCR_{drk}$ (/consignment)	Lead time $LCCR_{drk}$ (weeks)	Lead time (Dead prod.) $LCCR'_{drk}$ (weeks)	Volume capacity $ICVT_{drk}$ ** (cuft)	Weight capacity $ICWT_{drk}$ (units)	Pollution emission index*** ECR_{drk}
1	1	\$119.50	1	2	3605	5000	932
	2	\$211.00	0	1	3605	5000	932
	3	\$180.00	2	2	5010	8500	1572
2	1	\$166.00	1	2	3605	5000	1294
	2	\$293.00	0	2	3605	5000	1294
	3	\$250.00	2	3	5010	8500	2183
3	1	\$199.25	2	1	3605	5000	1553
	2	\$351.63	1	2	3605	5000	1553
	3	\$300.00	2	3	5010	8500	2620
4	1	\$239.13	2	2	3605	5000	1863
	2	\$421.88	1	1	3605	5000	1863
	3	\$360.00	3	3	5010	8500	3144
5	1	\$214.13	3	3	3605	5000	2070
	2	\$396.88	1	1	3605	5000	2070
	3	\$335.00	3	3	5010	8500	3493

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* Mode 1=Regular Truck, Mode 2=Expedited Truck, Mode 3=Rail

** The volume capacities for dead product transportation are assume to be the same as the regular capacity for the same transportation mode

*** Pollution emission index is related to the distance between two nodes in the network, given the equation: ECR_{drk} =amount of CO_2 released using transportation mode k (gram/mile) * distance between nodes (miles)

Table 4.20 shows the input data used to calculate the cost of transportation between the distribution centers and the recycling centers. In this specific case, there is only one recycling center located on-site at the manufacturing facility.

Table 4.21 records the input data for pretreatment capacity and labor requirements at the distribution center for dead products. This data is used to calculate the amount of the dead products that may be pre-treated before the dead products are sent to the recycling center.

Table 4.22 shows the costs associated with the recycling process. In this specific case, it is unlikely that the cost will vary over the planning horizon from week to week. However, in the formulation, the variables include an index of time "*t*" to account for any variations in cost over time.

Table 4.21: Input data for pretreatment capacity at distribution centers

Distribution Center d	**Labor Capacity, $LCTPT_{dt}$[*]**	**$LCPT_{qd}$ Product family, q**		
		1	**2**	**3**
1	703958	4.4	35.2	409
2	978595	4.5	35.4	410
3	342678	4.4	35.1	408
4	181559	4.6	35.4	408.2
5	2297537	4.4	35.2	406

Table 4.22: Input data for cost of recycling process, $CRRM_{qrt}$; cost of secondary material sludge, $CROS_{qrt}$

Recycling Center, r	**Cost of recycling process $CRRM_{qrt}$ (\$/unit)**			**Cost of secondary material purchase $CROS_{qrt}$ (\$/lbs)**		
	Product family, q			**Product family, q**		
	1	**2**	**3**	**1**	**2**	**3**
1	5	9.75	455	0.15	0.05	0.18

Table 4.23 shows the transportation cost—per unit weight—of each pre-treated dead product from the distribution center (functioning as the collection center) to the recycling center.

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[*] It is assumed that the labor capacity at each DC remains the same from week to week

Table 4.23: Transportation cost of dead product from DCs to recycling center

Product family, q	**DC, d**	**Mode, K**	**Transportation Cost, $CCACR_{qdrk}$ ($/unit)**
1	1	1	$2.00
		2	$17.00
		3	$237.50
	2	1	$3.50
		2	$29.75
		3	$420.00
	3	1	$1.50
		2	$12.50
		3	$177.50
	4	1	$2.50
		2	$22.50
		3	$325.00
	5	1	$5.00
		2	$40.00
		3	$325.00
2	1	1	$2.50
		2	$20.00
		3	$250.00
	2	1	$3.25
		2	$28.25
		3	$397.50
	3	1	$6.00
		2	$50.00
		3	$700.00
	4	1	$3.00
		2	$25.00
		3	$495.00
	5	1	$4.00
		2	$34.25
		3	$477.00
3	1	1	$7.00
		2	$57.50
		3	$842.50
	2	1	$3.50
		2	$29.50
		3	$357.50
	3	1	$3.50
		2	$30.50
		3	$427.50
	4	1	$6.75
		2	$56.50
		3	$792.50
	5	1	$3.25
		2	$27.50
		3	$334.25

Table 4.24 shows the input data for the recycling process at the recycling center and includes the cost of handling recycled raw material (CRH_{ir}), the labor hours required for the recycling process (TR_{ir}) and the labor hour capacity at the recycling center (IRP_{rt}).

These parameters are used to calculate the cost of the recycling process and the constraints on the recycling capacity. In our model formulation, we assume that the labor hour capacity at the recycling center does not vary from week to week.

Table 4.24: Data related to the recycling process

Recycling Center r	**Raw Material** i	**Labor Hour Capacity,** IRP_{rt}	**Handling Cost,** CRH_{irt}	**Labor Hour Required,** TR_{ir}
1	1	22,768,050	0.14	84
	2		0.37	120
	3		0.84	-
	4		0.28	-
	5		0.15	60
	6		0.60	-
	7		1.10	-

Table 4.25 shows the inventory related data at the recycling center which includes the inventory carrying cost rate ($CRIC_r$), and the floor space capacity (IRC_r).

Table 4.25: Inventory cost and capacity at recycling center

Recycling center r	**carrying cost rate,** $CRIC_r$	**Floor space capacity,** IRC_{rt}
1	0.005	209,998

Table 4.26 shows the price information for the recycled raw materials leaving the recycling center (PR_i), and the recycling parameter (REC_i). This data is used to calculate the profits from selling recycled raw material.

Table 4.26: Input data for recycled raw material

Raw material i	**Price of recycled raw material***, PR_i	**Recyclable index** REC_i
1	0.32	1
2	0.85	0
3	1.96	0
4	0.64	0
5	0.35	1
6	1.40	0
7	2.56	0

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* The data in this section are extracted from London Metal Exchange, Information available at http://www.lme.co.uk

4.2. Solution methodology

The planning model was solved using Lingo 9.0 (LINGO Systems Inc., 2005). The Lingo program scripts have been provided in Appendix 1. Given the concerns regarding the large number of general integer variables, it is reasonable to treat these variables as continuous, and round up the continuous variable solution in order to maintain the integrality and reduce the computational complexity of the large-scale integer programming model.

In so far as the model is a multi-objective one, the definition of "optimal solution" becomes uncertain (Rardin, 2000). The objective functions are sometimes contradictory to each other, which leads to the difficulty in achieving the optimum value of each objective function individually. In this section we obtain the ***efficient points*** and the ***efficient frontier***—which help to characterize the "best" feasible solution in multi-objective models.

We use the constraint-oriented transformation (or, the ε-constraint method) to convert the multi-objective problem into a single-objective optimization problem. In this model, we choose the total cost function (OBJ1) as the primary objective, then turn the pollution emission function (OBJ2) into a constraint with the right-hand side specified as ε, as shown below:

$$\sum_{p=1}^{P}\sum_{d=1}^{D}\sum_{k=1}^{K}\sum_{t=1}^{T} EPD_{pdk} \times XPTP_{pdkt} + \sum_{d=1}^{D}\sum_{d'=1}^{D}\sum_{k=1}^{K}\sum_{t=1}^{T} EDD_{dd'k} \times XDTS_{dd'kt}$$
$$+ \sum_{d=1}^{D}\sum_{r=1}^{R}\sum_{k=1}^{K}\sum_{t=1}^{T} ECR_{drk} \times \left(XCCR_{drk} + XCCR'_{drk}\right) \leq \left(\varepsilon \pm \lambda\right) \qquad \ldots (38)$$

As the value of ε varies, we generate different efficient solutions for the problem. The solution approach can be summarized as follows:

(1) Solve the model with OBJ1 as the single objective function. The optimum solution provides a lower bound on the value of objective function 1, while OBJ2 evaluated at the current solution, provides an upper bound on the value of objective function 2

(2) Now, solve the model with OBJ2 as the single objective function. The optimum solution provides a lower bound on the value of objective function 2,

while OBJ1 evaluated at the current solution, provides an upper bound on the value of objective function 1

(3) Select an appropriate step size λ for ε and add it to the previous bound

(4) If the problem is infeasible, adjust ε accordingly

(5) Go to step 3 unless the ε is at the limit

In Table 4.27, we present some scenarios used to determine the efficient frontier to the multi-objective model. The model was run under 20 different scenarios in order to calculate the corresponding minimum total cost subject to various upper bounds on the total pollution emissions.

Table 4.27: Solution from various scenarios for the model

Scenario	**OBJ2 (Pollution Index)**	**OBJ1 (Total cost, US$)**	**Scenario**	**OBJ2 (Pollution Index)**	**OBJ1 (Total cost, US$)**
1	20,396,610	3,382,317,000	11	21,000,000	86,801,490
2	20,400,000	3,243,198,000	12	22,000,000	80,372,560
3	20,460,000	1,686,189,000	13	23,000,000	74,674,460
4	20,470,000	1,477,445,000	14	24,000,000	70,208,610
5	20,500,000	904,697,900	15	25,000,000	66,298,370
6	20,540,000	199,670,100	16	26,000,000	62,636,720
7	20,570,000	89,824,520	17	27,000,000	59,534,850
8	20,575,000	89,717,980	18	28,000,000	56,654,150
9	20,576,000	89,696,670	19	29,000,000	53,844,970
10	20,579,000	89,646,440	20	29,326,830	53,430,940

The efficient solutions given in Table 4.27 are plotted as the efficient frontier in Figure 4.1. It is evident from the figure that the second objective function (OBJ2: pollution emissions) cannot be improved without deteriorating the first objective function (OBJ1: total cost). When the pollution emission index decreases from 29,326,830 to 20,579,000, the result is a relatively small increase in total cost (from $53.43 million to $89.64 million). This indicates that in this range, the pollution emission index can be decreased at a fairly low marginal cost. When the pollution emission index decreases further—from 20,579,000 to 20,396,610—the total cost increases dramatically (from $89.64 million to $3,382 million). It follows that, in this range, further decreases in the pollution emission index are possible only at very high marginal costs.

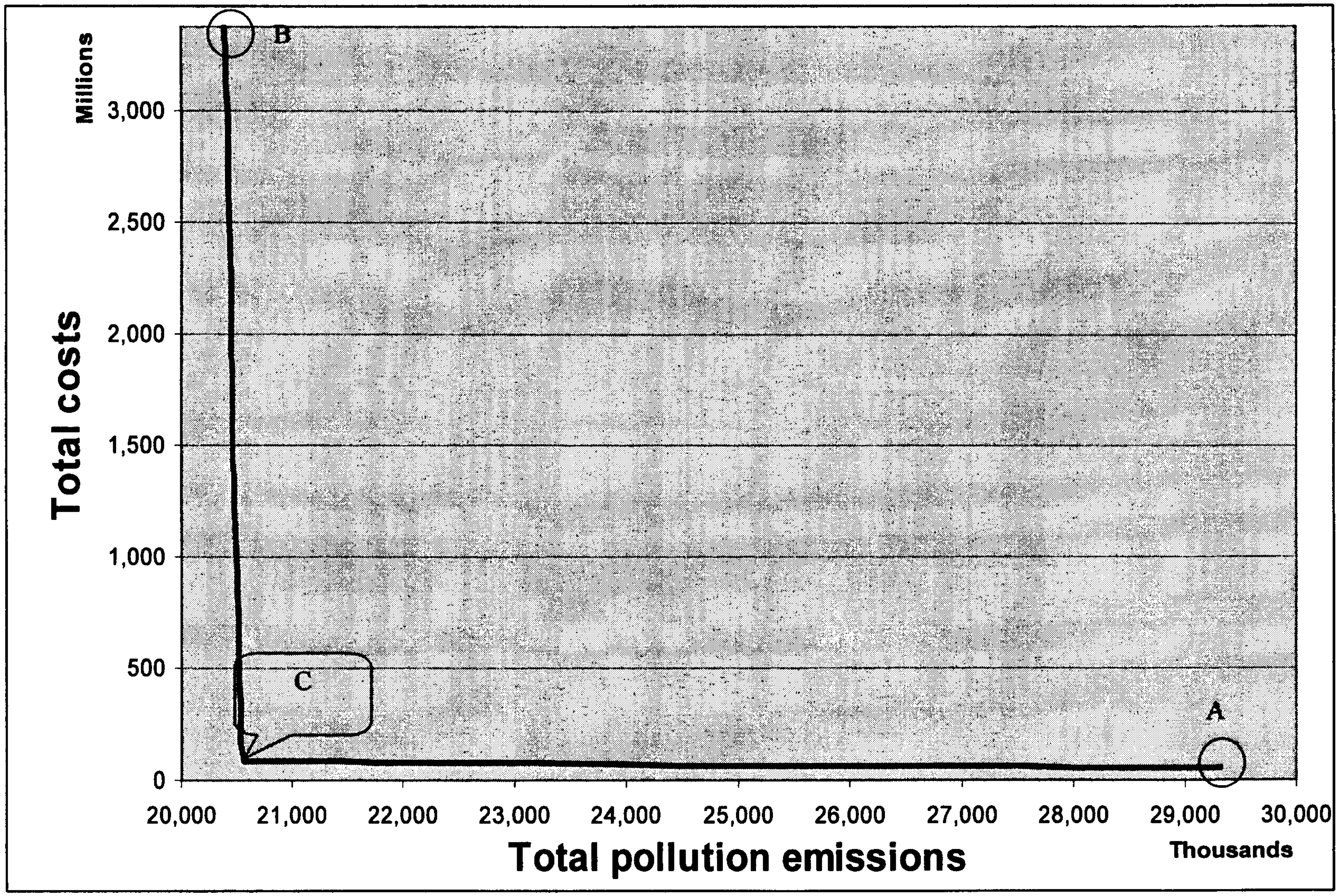

Figure 4.1: Efficient frontier for the planning model

In Figure 4.1, extreme point A represents the lower bound on the total cost and the upper bound on the total pollution emissions; it corresponds to solution scenario 20 in Table 4.28. Extreme point B, on the other hand, represents the upper bound on the total cost and the lower bound on the total pollution emissions; it corresponds to the solution scenario 1. We chose the efficient solution C (corresponding to scenario 10 in Table 4.27) for further study, because it represents the turning point in the efficient frontier. Figure 4.2 provides a bar chart for the cost components corresponding to point C.

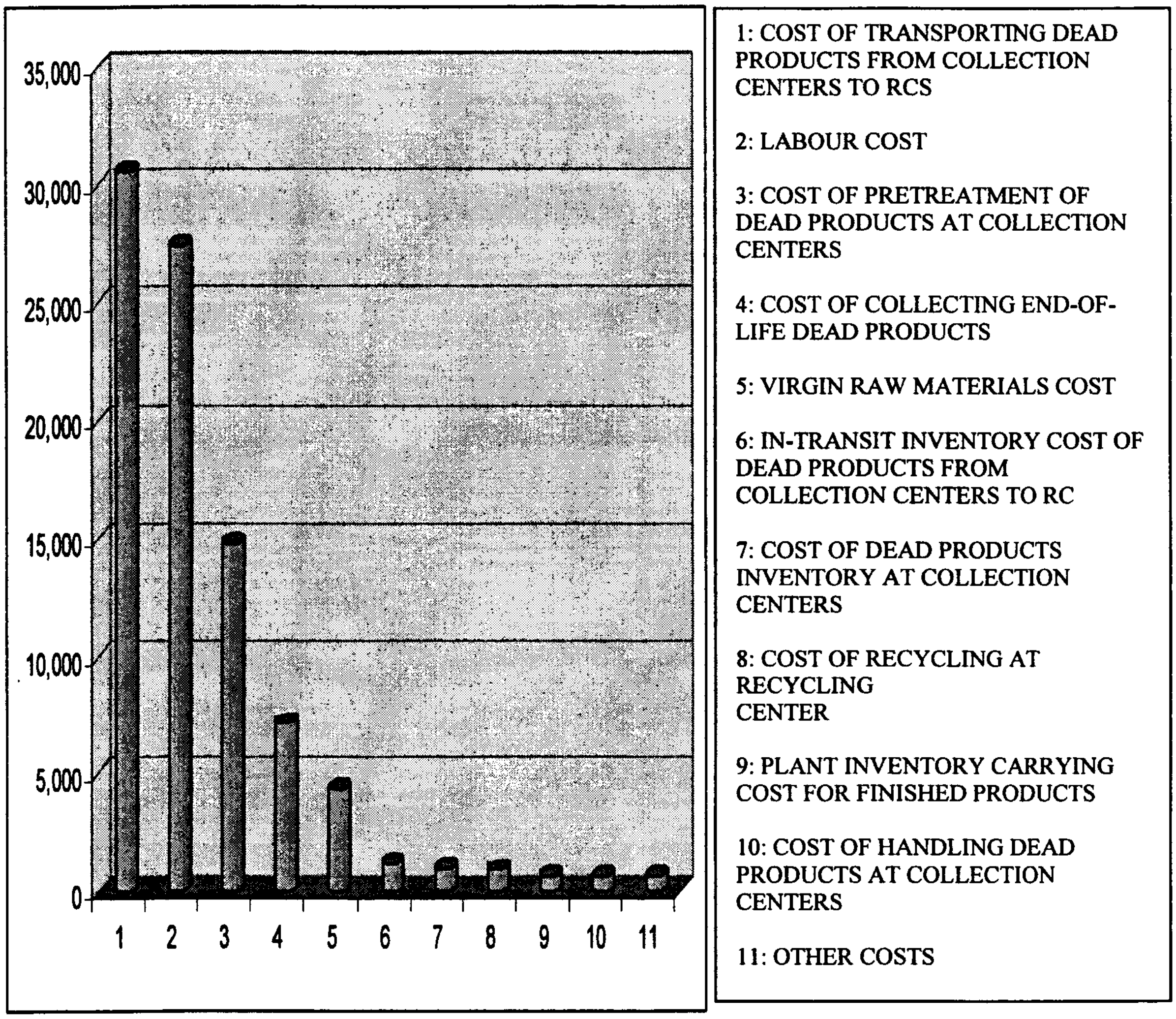

Figure 4.2: Cost components corresponding to efficient point C[*]

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[*] Other costs include virgin raw material inventory costs at the plants, transportation cost of products from plants to DCs, in-transit inventory cost of products between plants and DCs, handling cost of dead productst at the recycling center, cost of buying secondary material sludge

4.3. Detailed results

Table 4.28 displays the various cost components corresponding to the efficient points A, B and C, while Table 4.29 summarizes the corresponding pollution emission indices associated with these points.

Table 4.28: Cost components corresponding to points A, B and C

Cost Components		**Optimizing OBJ1 only (point A)**	**Optimizing OBJ2 only (point B)**	**Efficient Solution (point C)**
TOTAL COST (Thousand Dollars)		**53,431**	**3,382,317**	**89,646**
1	VIRGIN RAW MATERIALS COST	4,423	8,454	4,371
2	VIRGIN RAW MATERIAL INVENTORY COSTS AT THE PLANTS	2	4	2
3	REGULAR TIME AND OVER TIME LABOR HOURS COSTS	27,480	27,799	27,480
4	PLANT INVENTORY CARRYING COST FOR FINISHED PRODUCTS	680	971	706
5	INBOUND TRANSPORTATION COST OF PRODUCTS FROM PLANTS TO DCS	86	71	78
6	IN-TRANSIT INVENTORY COST OF PRODUCTS BETWEEN PLANTS & DCS	42	169	105
7	DC INVENTORY CARRYING COST	1	37	0
8	HANDLING COST AT DCS	0	0	0
9	TRANSSHIPMENT COST OF PRODUCTS BETWEEN DCS	0	0	0
10	IN-TRANSIT INVENTORY COST OF TRANSSHIPMENTS BETWEEN DCS	0	0	0
11	COST OF COLLECTING DEAD PRODUCTS	7,192	7,192	7,192
12	COST OF DEAD PRODUCTS INVENTORY AT COLLECTION CENTERS	911	1,044	973
13	COST OF HANDLING DEAD PRODUCTS AT COLLECTION CENTERS	653	653	653
14	COST OF PRETREATMENT OF DEAD PRODUCTS AT COLLECTION CENTERS	0	14,840	14,835
15	COST OF TRANSPORTING DEAD PRODUCTS FROM COLLECTION CENTERS TO RCS	9,327	3,305,813	30,599
16	IN-TRANSIT INVENTORY COST OF DEAD PRODUCTS FROM COLLECTION CENTERS TO RC	1,153	1,566	1,195
17	COST OF RECYCLING AT RECYCLING CENTER	970	8,229	955
18	INVENTORY CARRYING COST AT RECYCLING CENTER	0	0	0
19	COST OF HANDLING DEAD PRODUCTS AT RECYCLING CENTER	17	6	17
20	COST OF BUYING SECONDARY MATERIAL SLUDGE	496	5,468	486
21	INCOME FROM SALE OF RECYCLED RAW MATERIALS	15	0	14

Table 4.29: Pollution emission index corresponding to points A, B and C

Cost Components		Optimizing OBJ1 only (point A)	Optimizing OBJ2 only (point B)	Efficient Solution (point C)
TOTAL POLLUTION EMISSION		**29,326,830**	**20,396,610**	**20,579,000**
1	POLLUTION INDEX DURING TRANSPORTATION FROM PLANTS TO DCS	373,490	310,286	339,431
2	POLLUTION INDEX DURING TRANSPORTATION FROM DCS TO RCS	28,953,340	20,086,320	20,239,569

We now describe the production plan corresponding to point C. Table 4.30 shows the amount of raw material used in the production processes at the manufacturing plants. For example, we note that 67,846 units of raw material i=1 are used in the production of the product families, of which 100% are recycled from the dead products. Similarly, of the 7,118 units of raw material i=5 used in the production processes, 100% are recycled raw material. The surplus of the recycled raw material is to be sold to the outside market.

Table 4.30: Raw material content used in production processes

	Raw material content	i=1	i=2	i=3	i=4	i=5	i=6	i=7
$\sum_{p=1}^{P}\sum_{t=1}^{T} XRM_{ipt}$	Total raw material used for production	67,846	30,921	1,081	20	7,118	1,081	20
$\sum_{r=1}^{R}\sum_{p=1}^{P}\sum_{t=1}^{T} XRTP_{irpt}$	Recycled raw material from the recycling center	110,809	0	0	0	7,642	0	0

In Table 4.31 we display the aggregated demand, the number of units produced, and the safety stock levels at the end of each time period. For example, the total production of product family q=1 (at all the plants) is 996,596 units, of which 969,563 units (or, 97%) are delivered to the distribution centers to satisfy the customer demands, and 31,033 units are kept at the plant warehouses as safety stock.

Table 4.31: Aggregated demand, production, safety stock levels

	Finished goods	q=1	q=2	q=3
$\sum_{p=}^{P}\sum_{t=1}^{T} XP_{pqt}$	Finished goods produced from all five plants for the entire planning level	996,596	211,382	2,864
$\sum_{p=1}^{Q} PS_{pq}$	Finished goods stored in plants warehouses as safety stock	6,207	2,600	51
$\sum_{d=1}^{D}\sum_{t=1}^{T} D_{qdt}$	Aggregated customer demand	965,563	198,381	2,613

As far as the reverse part of the supply chain is concerned, the collection centers collect the dead products, and transport them to the recycling center to be processed into recycled raw material. Table 4.32 displays the relevant data. For example, for product family q=1, 6714,453 units of end-of-life batteries come into the collection centers, and are subsequently shipped to the recycling center. No inventory of this product family is kept at the collection centers. However, for product family q=2, 308,512 units of end-of-life batteries are collected, 190,706 (or, 62%) are subsequently shipped to the recycling center, and the remaining 117,806 units (or, 38%) are kept at the collection centers as inventory.

Table 4.32: Relevant data for reversed part of supply chain

	End-of-life product	q=1	q=2	q=3
$\sum_{d=1}^{D}\sum_{t=1}^{T} FC_{qdt}$	Aggregated forecasted collection	671,453	308,512	6,269
$\sum_{d=1}^{D}\sum_{r=1}^{R}\sum_{l=1}^{K}\sum_{t=1}^{T} XCNCR_{qdrkt}$	Units of end-of-life batteries transported to the recycling center	324	0	0
$\sum_{d=1}^{D}\sum_{r=1}^{R}\sum_{l=1}^{K}\sum_{t=1}^{T} XCNCR'_{qdrkt}$	Units of pretreated end-of-life batteries transported to the recycling center	671,129	190,706	0
$\sum_{d=1}^{D} XCIL_{qdt}$	Inventory of end-of-life batteries in time period t=5	0	117,806	6,269

4.4: Computational experience

The model was solved using Lingo 9.0 on a PC (1.00 GB RAM, 2.8 GHz Pentium®-4 processor). To reduce the complexity of this large-scale MILP model and obtain global optimal solutions more efficiently, we solve the model allowing only continuous and binary variables. There were 10280 constraints and 22396 variables—including 125 binary integers after relaxation. It took 0.2 million iterations and—on average—2 minutes to reach the optimal solutions.

CHAPTER 5 – SENSITIVITY ANALYSIS

The objective of applying sensitivity analysis to our model is to test the robustness of various key parameters, as well as to evaluate their impact on the system with respect to uncertainties and variations in their values in real-life circumstances.

This chapter is divided into three sections. In the first section, the analysis has been carried out with respect to the effect of outsourcing the transportation operations to a third party logistics (3PL) service.

The second part of the analysis examines the effect of parameter changes on the total cost, the total pollution emission index and the configuration of the network by varying a particular parameter while keeping all others constant. This allows us to test the impact these changes have on the optimal solution of the model. The key parameters considered for sensitivity analysis are the virgin raw material cost, the transportation lead time between suppliers and plants, the transportation lead time between plants and distribution centers, the standard deviation of the demand, the forecasted volume of the end-of-life dead products collected, the transportation lead time between the collection centers and the recycling center, the recycling process cost, and the pollution emission index corresponding to the dead product transportation.

The third part of the analysis is to explore the effect of changes in network design options such as expanding the storage capacity at the collection centers/distribution centers and closing an existing manufacturing plant within the network.

In the discussions that follow, the model results corresponding to the efficient solution C (Figure 4.1) are used as the current solution which serves as a reference point for the sensitivity analyses that were carried out.

5.1. Impact of introducing 3PL into the model

Third party logistics services are widely applied nowadays. The so-called 3PL company provides special transportation services to their customers at a lower cost than the manufacturer can provide. In logistics operations, the transportation costs constitute a significant part of the total costs. In our case, the transportation costs account for 33% of the total costs, as shown in Figure 4.2. Outsourcing the transportation operations, therefore, is ideal under current condition. In this section, the impact of integrating a 3PL service into the network has been evaluated, especially for the transportation of the dead products. The 3PL waste management company transports the dead products from the collection centers to the recycling center, subject to the following constraints and cost structure:

- Maximum 55 gallons per drum
- Maximum 500 pounds per drum
- $30 per drum for transportation—regardless of the distance—with a one-time loading fee of $150
- Fuel surcharge of 21% billed to each customer

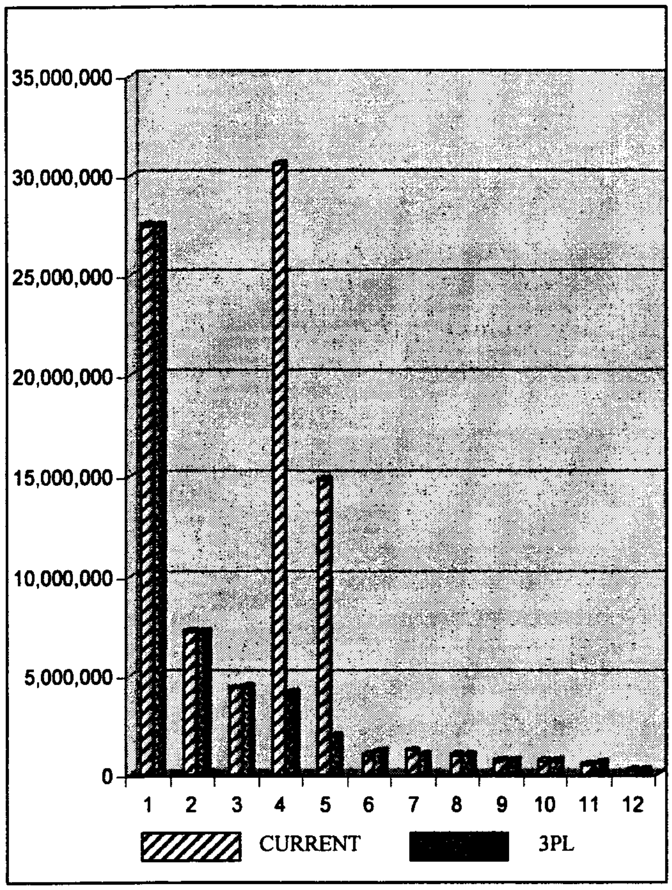
Table 5.1: Comparison of cost components

	TOTAL COST	Current Solution	3PL Application
		89,646,430	**50,439,903**
1	**VIRGIN RAW MATERIALS COST**	4,370,811	4,420,292
2	**PLANT INVENTORY CARRYING COST FOR FINISHED PRODUCTS**	706,364	680,352
3	**INBOUND TRANSPORTATION COST OF PRODUCTS FROM PLANTS TO DCS**	77,732	85,532
4	**IN-TRANSIT INVENTORY COST OF PRODUCTS BETWEEN PLANTS & DCS**	105,125	41,750
5	**DC INVENTORY CARRYING COST**	0	1,049
6	**COST OF DEAD PRODUCTS INVENTORY AT COLLECTION CENTERS**	972,831	1,190,495
7	**COST OF PRETREATMENT**	14,834,630	1,943,052
8	**COST OF TRANSPORTING DEAD PRODUCTS FROM COLLECTION CENTERS TO RCS**	30,599,340	4,150,707
9	**IN-TRANSIT INVENTORY COST OF DEAD PRODUCTS FROM COLLECTION CENTERS TO RCS**	1,194,561	999,296
10	**COST OF RECYCLING AT RECYCLING CENTER**	955,247	979,979
11	**INVENTORY CARRYING COST AT RECYCLING CENTER**	0	1,337
12	**COST OF HANDLING DEAD PRODUCTS AT RECYCLING CENTER**	16,659	16,924
13	**COST OF BUYING SECONARY**	486,014	602,022
...	**OTHER COSTS**	**35,327,116**	**35,327,116**

Table 5.1 compares the current solution, in terms of costs, with the 3PL

application mentioned above. It is noted that the 3PL application has a much lower dead product transportation-related costs. This leads to a significant change in the overall total costs. The overall changes in the cost structure are in favour of the 3PL option, which represents a cost savings in excess of $40 million, or about 40%.

Figure 5.1 displays the cost components comparison corresponding to the current solution to the 3PL application. As can be seen, the dramatic reduction in the transportation cost is based on the fact that, in this case the dead products are pretreated, and the products that could not be recycled are sent to a landfill at the collection center, which reduces the volume of the dead products by at least 50%, thus reducing transportation requirements.



1: LABOUR COST
2: COST OF COLLECTING END-OF-LIFE DEAD PRODUCTS
3: VIRGIN RAW MATEIRAL COST
4: COST OF TRANSPORTING DEAD PRODUCTS FROM COLLECTION CENTERS TO RCS
5: COST OF PRETREATMENT
6: COST OF DEAD PRODUCTS INVENTORY AT COLLECTION CENTERS
7: IN-TRANSIT INVENTORY COST OF DEAD PRODUCTS FROM COLLECTION CENTERS TO RCS
8: PLANT INVENTORY CARRYING COST FOR FINISHED PRODUCTS
9: COST OF HANDLING DAD PRODUCTS AT COLLECTION CENTERS
10: COST OF HANDLING DEAD PRODUCTS AT COLLECTION CENTERS
11: COST OF BUYING SECONDARY MATERIAL SLUDGE
12: OTHER COSTS

Figure 5.1: Cost components comparison of 3PL application to the current solution[*]

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[*] Other costs include cost of virgin raw material inventory cost at the plants, inbound transportation cost of products from plants to DCs, in-transit inventory cost between plants and DCs, DC inventory cost, recycling center inventory cost, handling cost at recycling center

5.2. Sensitivity of the model to changes in key parameters

In this section, the impact of varying certain parameters on the model performance is examined. The parameters to be investigated are the virgin raw materials cost, the standard deviation of the demand, the transportation lead times, the recycling process cost, and the pollution emission related parameters.

5.2.1. Effect of changes in virgin raw material cost

Figure 5.2 illustrates how changing the virgin raw material cost affects the total cost in the case of the current solution. The curve shows a linear behavior in the neighborhood of the initial data values. For every percentage increase/decrease in the cost of all the seven different virgin raw materials, there is a $48,799 increase/decrease in the total cost.

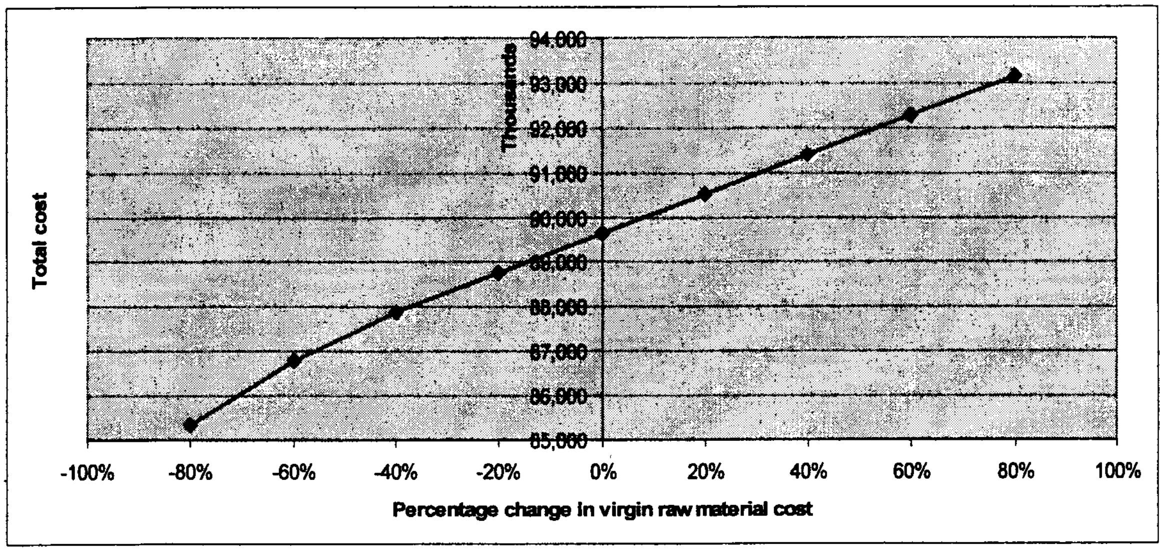

Figure 5.2: Effect of changes in virgin raw materials cost on total cost

5.2.2. Effect of changes in standard deviation of demand

Figure 5.3 illustrates how changes in the standard deviation of the demand affect the total costs of the current solution. The curve shows a linear behavior in the neighborhood of the initial data values. For every percentage increase/decrease in the standard deviation of the demand, there is $368,038 increase/ decrease in the total cost.

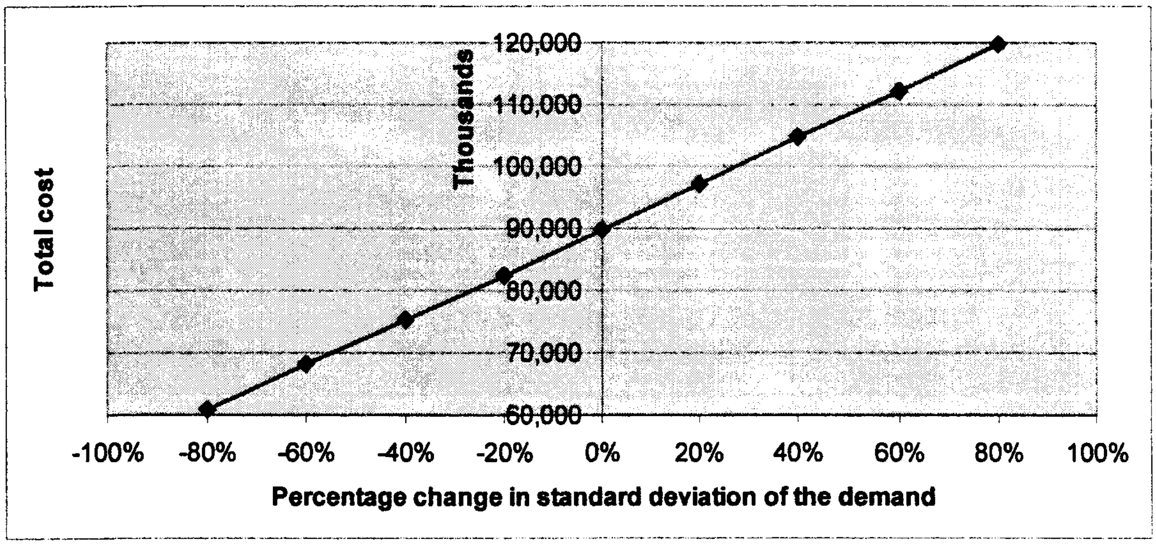

Figure 5.3: Effect of changes in standard deviation of the demand on total cost

5.2.3. Effect of changes in transportation lead time between suppliers and plants

Figure 5.4 illustrates how changes in the transportation lead times between the suppliers and the plants affect the total costs of the current solution. The curve shows a non-linear behavior as the lead time varies in the range of -80% to +80% of the initial

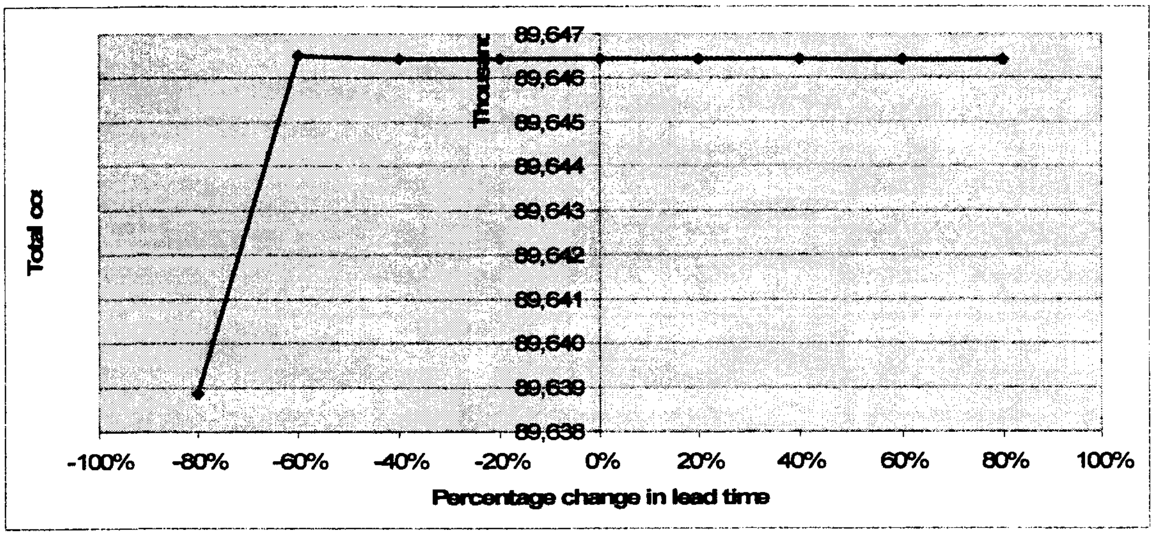

Figure 5.4: Effect of changes in lead time between suppliers and plants on total cost

value. As the lead time varies from -80% to -60%, there is a linear increase in the total cost; however, in the range of -60% to 80% the total cost remains unchanged. An examination of the model results indicate that when the transportation lead times between the suppliers and the plants decrease in the range of -80% and -60%, with shorter lead time the manufacturer purchases less virgin raw material to meet the raw material requirement at manufacturing plants, which leads to a decrease in virgin raw materials cost and a decrease in virgin raw material inventory costs at the plants, as illustrated in Table 5.2. In the range of -60% to 80%, the changes in the transportation lead times have almost no effect on the total cost, due to the fact that when the transportation lead times are too long, the system switches to use the recycled raw material instead.

Table 5.2: Sensitivity of cost components of the current solution to changes in transportation lead time between suppliers and plants

	TOTAL COST	**Lead Time Decreased by 80%**	**Lead Time Decreased by 60%**	**Current Solution**	**Lead Time Increased by 60%**
		89,638,840	**89,646,500**	**89,646,440**	**89,646,410**
1	**VIRGIN RAW MATERIALS COST**	4,363,151	4,370,811	4,370,811	4,370,811
2	**VIRGIN RAW MATERIAL INVENTORY COSTS AT THE PLANTS**	1,569	1,569	1,509	1,479
...	**ALL OTHER COSTS**	**85,274,120**	**85,274,120**	**85,274,120**	**85,274,120**

5.2.4. Effect of changes in transportation lead time between plants and distribution centers

Figure 5.5 illustrates how changes in the transportation lead time between the plants and the distribution centers affect the total costs of the current solution. The curve shows a non-linear behavior as the initial lead time changes in the range of -80% and 80%. Even though the changes in the total cost are fairly small, they result from changes in finished goods inventory carrying cost at the plants, the transportation cost from the

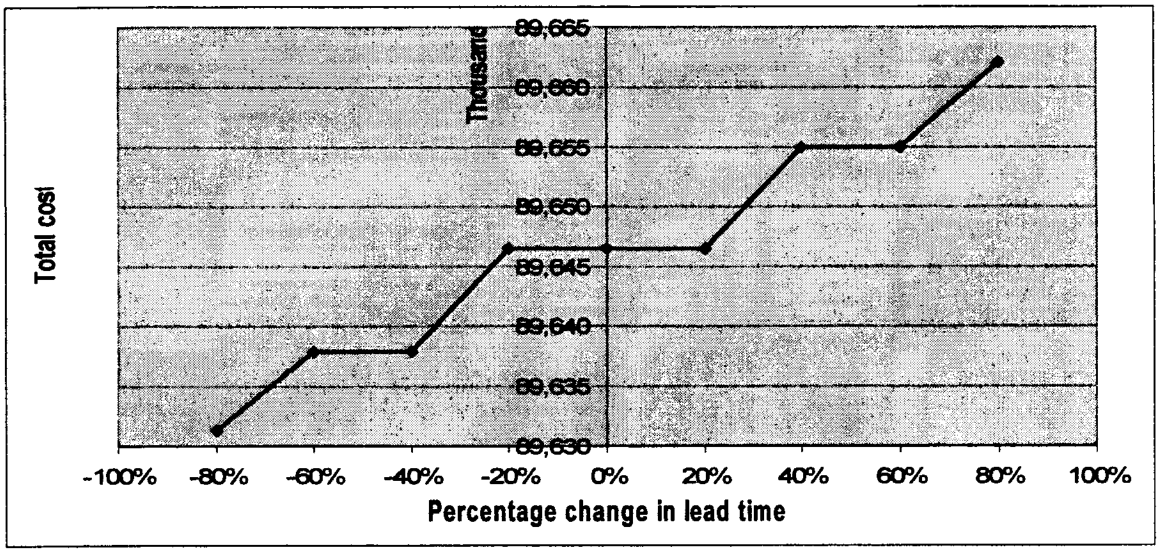

Figure 5.5: Effect of changes in lead time between plants and DCs on total cost

plants to the DCs, the in-transit inventory cost between the plants and the DCs, and the finished goods inventory carrying cost at the DCs, as shown in Table 5.3.

5.2.5. Effect of changes in transportation lead time between distribution centers and the recycling center

Figure 5.6 illustrates how changes in the transportation lead times between the distribution centers (that is, the dead product collection centers) and the recycling center

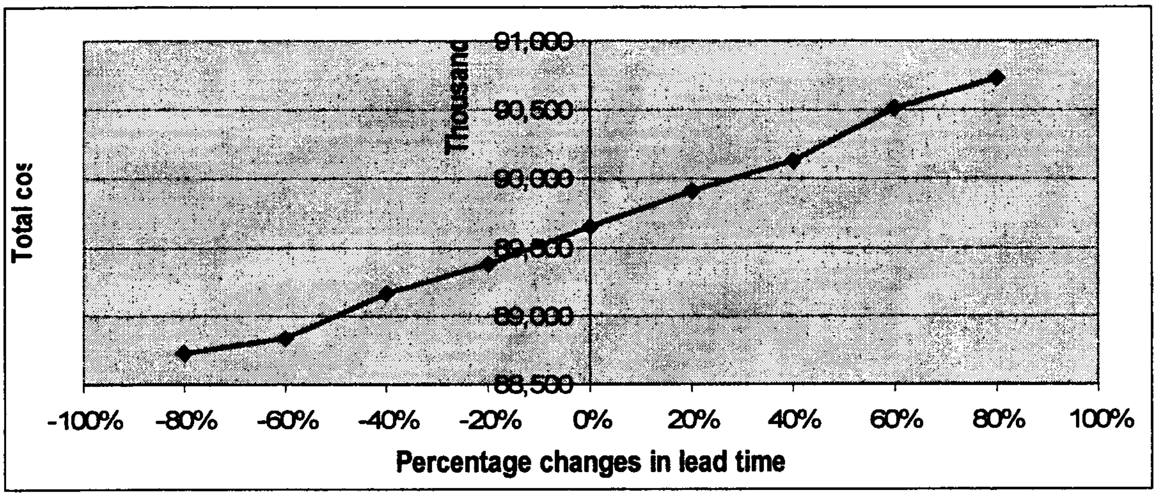

Figure 5.6: Effect of changes in lead time between DCs and recycling center on total cost

Table 5.3: Sensitivity of cost components of the current solution to changes in transportation lead time between plants and DCs

	TOTAL COST	**Percentage changes in lead time relative to current solution**						
		-80%	**-60%**	**-40%**	**Current Solution**	**40%**	**60%**	**80%**
		89,631,290	**89,637,920**	**89,637,920**	**89,646,440**	**89,654,950**	**89,654,950**	**89,662,100**
1	**PLANT INVENTORY CARRYING COST FOR FINISHED PRODUCTS**	727,139	727,139	727,139	706,364	685,588	685,588	704,220
2	**INBOUND TRANSPORTATION COST OF PRODUCTS FROM PLANTS TO DCs**	77,732	77,732	77,732	77,732	77,732	77,732	104,969
3	**IN-TRANSIT INVENTORY COST OF PRODUCTS BETWEEN PLANTS & DCs**	46,537	75,831	75,831	105,126	134,412	134,412	74,914
4	**DC INVENTORY CARRYING COST**	22,664	0	0	0	0	0	20,779
…	**ALL OTHER COSTS**	**88,757,218**	**88,757,218**	**88,757,218**	**88,757,218**	**88,757,218**	**88,757,218**	**88,757,218**

Table 5.4: Sensitivity of cost components of the current solution to changes in transportation lead time between DCs and the recycling center

	TOTAL COST	**Percentage changes in lead time relative to current solution**								
		-80%	**-60%**	**-40%**	**-20%**	**Current Solution**	**20%**	**40%**	**60%**	**80%**
		88,725,830	**88,835,930**	**89,158,440**	**89,381,060**	**89,646,440**	**89,911,810**	**90,134,430**	**90,508,920**	**90,731,530**
1	**VIRGIN RAW MATERIALS COST**	4,370,811	4,370,811	4,370,811	4,370,811	4,370,811	4,370,811	4,370,811	4,370,811	4,370,811
2	**VIRGIN RAW MATERIAL INVENTORY COSTS AT THE PLANTS**	1,509	1,509	1,509	1,509	1,509	1,509	1,509	1,509	1,509
3	**COST OF DEAD PRODUCTS INVENTORY AT COLLECTION CENTERS**	1,085,352	972,831	972,831	972,831	972,831	972,831	972,831	972,831	972,831
4	**COST OF PRETREATMENT**	14,834,630	14,834,630	14,834,630	14,834,630	14,834,630	14,834,620	14,834,630	14,834,630	14,834,630
5	**COST OF TRANSPORTING DEAD PRODUCTS FROM COLLECTION CENTERS TO RCS**	30,599,337	30,599,340	30,599,334	30,599,335	30,599,340	30,599,345	30,599,336	30,599,341	30,599,332
6	**IN-TRANSIT INVENTORY COST OF DEAD PRODUCTS FROM COLLECTION CENTERS TO RCS**	213,404	436,022	758,538	981,157	1,194,561	1,407,965	1,630,584	1,953,099	2,175,718
7	**COST OF RECYCLING AT RECYCLING CENTER**	955,247	955,247	955,247	955,247	955,247	955,247	955,247	955,247	955,247
8	**COST OF BUYING SECONARY**	434,043	434,043	434,043	434,043	486,014	537,985	537,985	589,955	589,955
...	**ALL OTHER COSTS**	**36,231,497**	**36,231,497**	**36,231,497**	**36,231,497**	**36,231,497**	**36,231,497**	**36,231,497**	**36,231,497**	**36,231,497**

affect the total costs. Again, the changes in the total cost are fairly small, and are caused by changes such as the cost of dead product inventory at the collection centers, the cost of dead product transportation, the in-transit inventory cost of dead products from DCs to the recycling center, and the costs related to the recycling center, the cost of purchasing secondary dead product sludge, as illustrated in Table 5.4.

*5.2.6. **Effect of changes in end-of-life dead product collection cost***

In this section, it is assumed that for each 10% increase/decrease in the dead product collection fee for each of the three product families, there is, respectively, a 5%, 3% and 0% increase/decrease in forecasted volume of the dead product collected. Figure 5.7 illustrates how changes in the collection fee affect the total cost of the current solution. The curve shows an almost "linear" behavior as the collection fee varies in the range of -40% to +40% of the initial value. For every percentage increase/decrease in the end-of-life collection fee, there is a $169,081 increase/decrease in the total cost.

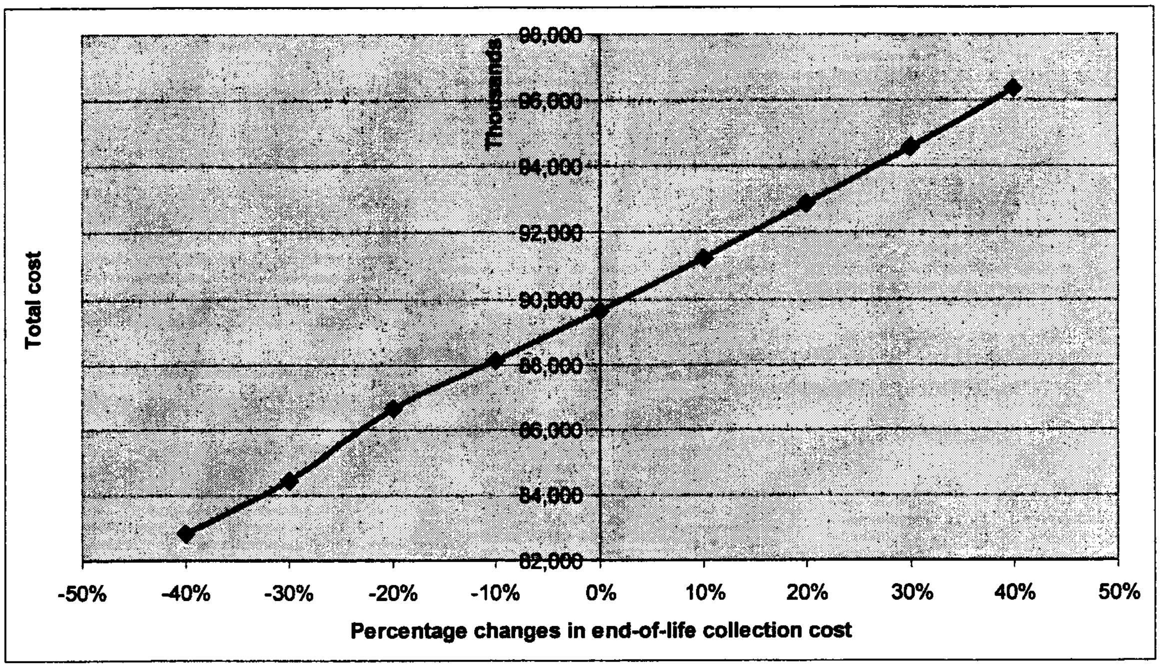

Figure 5.7: Effect of changes in cost of dead product collection on total cost

5.2.7. Effect of changes in recycling process cost

Figure 5.8 illustrates how changing the recycling process cost affects the total cost in the case of the current solution. The curve shows a linear behaviour in the neighborhood of the initial data values. For every percentage increase/decrease in the cost of all the seven different virgin raw materials, there is a $9,615 increase/decrease in the total cost.

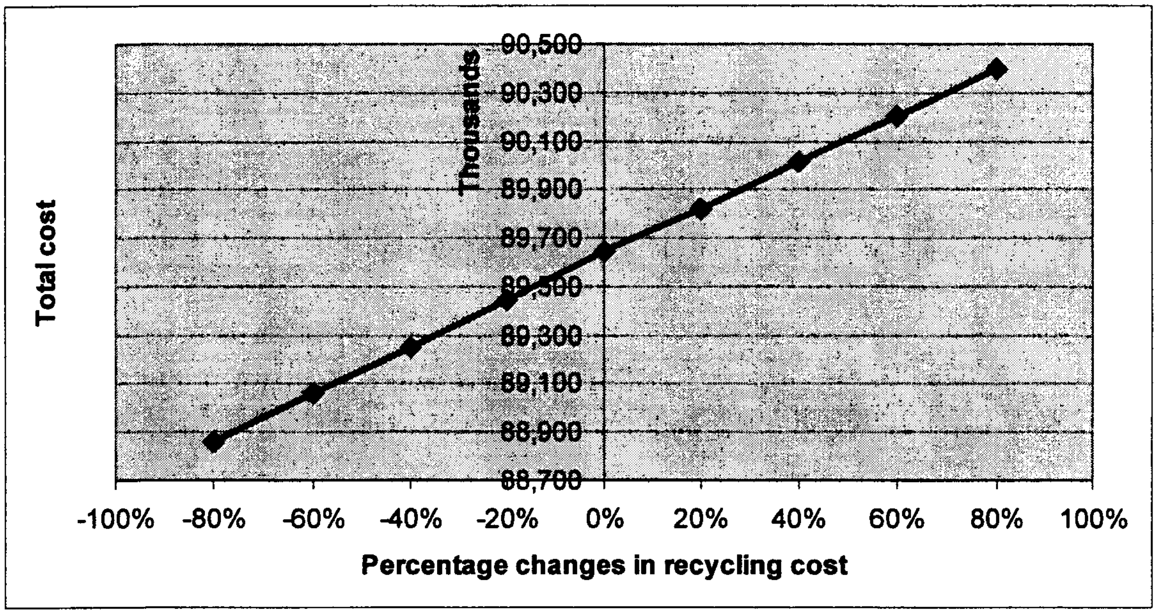

Figure 5.8: Effect of changes in recycling process cost on total cost

5.2.8. Effect of changes in pollution emissions during transportation

Environmental Protection Agency of United States (EPA) categorized the pollution emission into the following four components: Hydrocarbons, Carbon Monoxide, Oxides of Nitrogen and Carbon Dioxide. In this study, the pollution emissions during transportation are limited to carbon dioxide resulting from fuel consumption. The emission level is dependent on the transportation distance, fuel type and the transportation carrier type. It is assumed that the level of carbon dioxide emissions during transportation may be reduced by 30% at most, using the current technological improvement.

Figure 5.9 illustrates how changes in pollution emissions during transportation affect the total cost of the current solution. As can be seen, as the pollution emissions during the transportation decrease the current level to -30%, there is a significant, linear effect on the overall total costs. Table 5.5 shows the details of the corresponding changes in the total cost with respect to the variations in the level of pollution emissions during the transportation. It is evident that the major factors affecting the overall total cost variations are the changes in the cost of transporting dead products from collection centers to the recycling center, and the cost of pretreatment. The other cost components change as well; however, the variations are minor and do not affect the total cost.

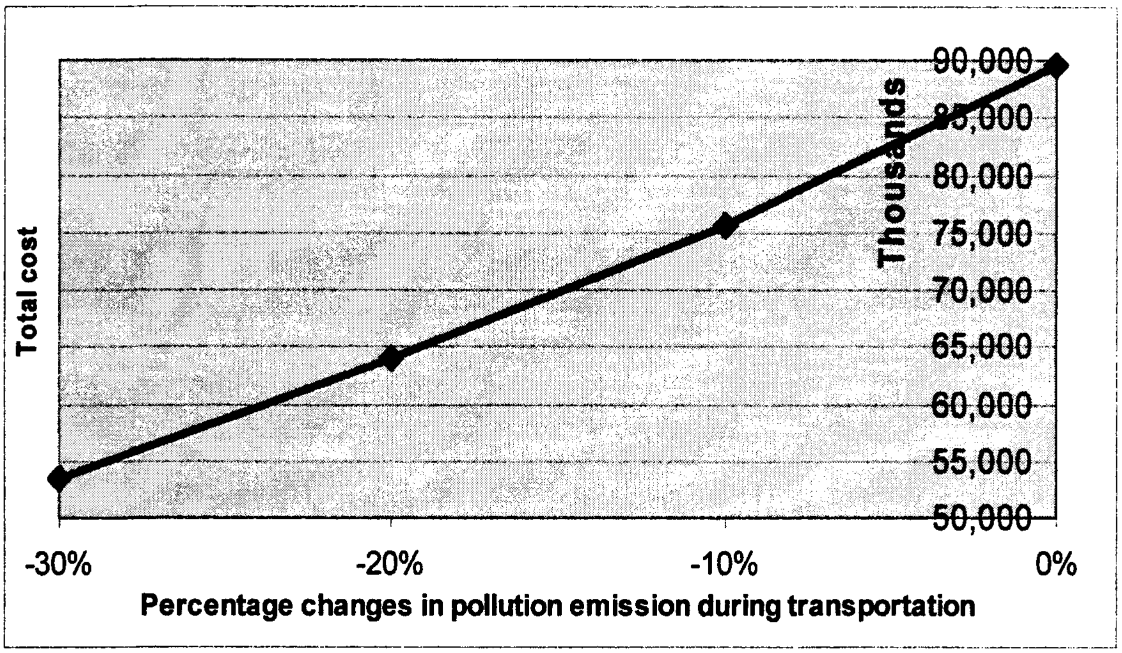

Figure 5.9: Effect of changes in pollution emission during transportation on total cost

Table 5.5: Sensitivity of cost components of the current solution to changes in pollution emissions during recycling

TOTAL COST		Pollution Emission Decreased by 30%	Pollution Emission Decreased by 20%	Pollution Emission Decreased by 10%	Current Solution
		53,434,860	**63,943,139**	**75,588,689**	**89,646,430**
1	VIRGIN RAW MATERIALS COST	4,422,696	4,370,811	4,370,811	4,370,811
2	PLANT INVENTORY CARRYING COST FOR FINISHED PRODUCTS	680,352	706,364	706,364	706,364
3	INBOUND TRANSPORTATION COST OF PRODUCTS FROM PLANTS TO DCS	85,532	77,732	77,732	77,732
4	IN-TRANSIT INVENTORY COST OF PRODUCTS BETWEEN PLANTS & DCS	41,750	105,125	105,125	105,125
5	DC INVENTORY CARRYING COST	1,049	0	0	0
6	COST OF DEAD PRODUCTS INVENTORY AT COLLECTION CENTERS	964,993	972,831	972,831	972,831
7	COST OF PRETREATMENT	0	3,916,757	8,703,297	14,834,630
8	COST OF TRANSPORTING DEAD PRODUCTS FROM COLLECTION CENTERS TO RCS	9,297,068	15,791,830	22,650,840	30,599,340
9	IN-TRANSIT INVENTORY COST OF DEAD PRODUCTS FROM COLLECTION CENTERS TO RCS	1,131,947	1,216,653	1,216,653	1,194,561
10	COST OF RECYCLING AT RECYCLING CENTER	969,711	955,247	955,247	955,247
11	COST OF HANDLING DEAD PRODUCTS AT RECYCLING CENTER	16,911	16,659	16,659	16,659
12	COST OF BUYING SECONARY MATERIAL	495,734	486,014	486,014	486,014
...	ALL OTHER COSTS	**35,327,117**	**35,327,116**	**35,327,116**	**35,327,116**

5.2.9. Summary of the sensitivity analysis in key parameters

It is noted that the model is not very sensitive to changes in the selected key parameters; in most cases the total cost changes are within ±1%, expect for the cost impact in changes in pollution emission index during transportation. Therefore, the model displays a degree of robustness even when the parameters vary widely. However, within the range of the variations displayed by the total cost function, the sensitivity analyses of the planning model with respect to the selected key parameters may be summarized as follows:

(1) The highest impact on the total cost is due to changes in the standard deviation of the demand, followed by changes in the end-of-life collection cost, changes in virgin raw material cost and the recycling process cost. Figure 5.10 compares the effects of these changes on the total cost.

(2) Changes in the transportation lead times between the suppliers and the plants show a non-linear effect on the total cost. They slightly impact the total cost from -80% to -60%, and their impact is negligible between -60% and +80%.

(3) Changes in the transportation lead times between plants and distribution centers impact the total cost in a non-linear fashion. They impact the total cost from -80% to -60%, from -40% to -20%, from 20% to 40% and from 60% to 80%; however, outside these ranges their impact is negligible.

(4) Changes in the transportation lead times between the distribution centers and the recycling center show an almost non-linear effect on the total cost, however, the nonlinearity effect is insignificant.

(5) Changes in the pollution emission during the transportation show a significant, linear effect on the total cost. The impact on the total cost is dramatic in the range of -30% to current solution.

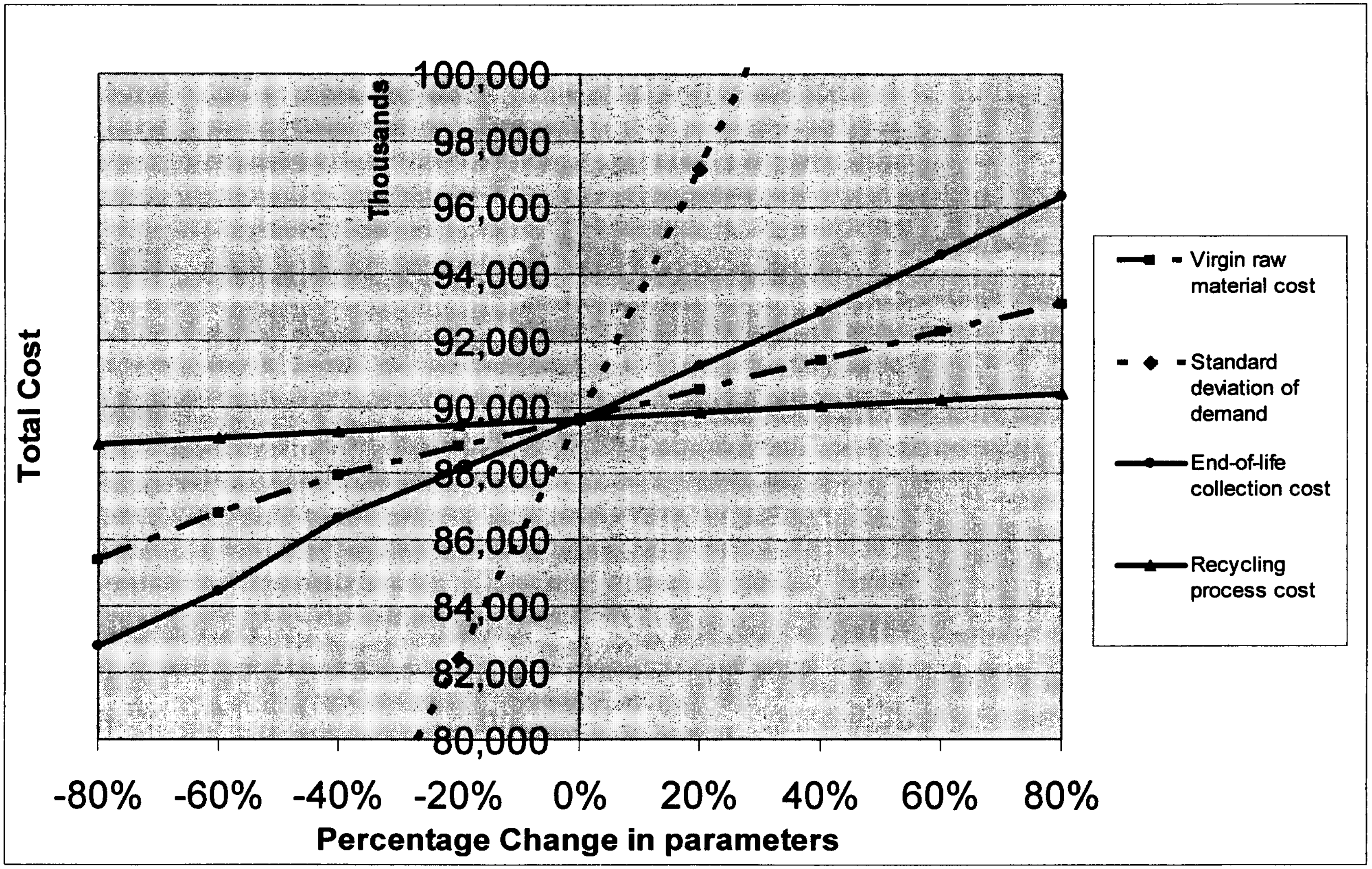

Figure 5.10: Effect of changes in various parameters on total cost

5.3. Sensitivity of the model to changes in network design options

In this section, the impact of the possible expansion of the collection center storage capacities (e.g., through third-party warehouse leasing) on the total cost is evaluated. Subsequently, a sensitivity analysis is carried out to evaluate the impact on the total cost of closing some manufacturing plants.

5.3.1. Effect of expanding collection center storage capacities

The numerical example solution indicated that the model allocated material flow from the distribution centers to the recycling center, and used the recycling center to store inventory. The reason behind this is the insufficiency of storage space for dead products at the collection centers. To examine the impact of expanding the collection center storage capacities, it is assumed that the storage capacity at the existing collection centers may be expanded under the following options*:

- Warehouse lease, one year term, $4 per square-foot
- Warehouse operating expenses (taxes, insurance, etc.), $1.50 per square-foot
- Extra labor cost for warehouse loading/unloading, $10 per square-foot

Figure 5.11 shows the changes in the total cost with respect to various options to expand the collection center storage capacities. It is observed that capacity expansions at any of the collection centers 1, 2 and 3 will lead to an increase in the total costs, while a 20% capacity expansion at any of the collection centers 4 and 5 will minimize the total cost relative to the current solution. The decrease in the total cost is mainly due to a decrease in the number of the transportation consignments sent from the collection centers to the recycling center. As can be observed in Table 5.6, by expanding the storage capacities of collection centers 4 and 5 only, the inventory level of product family q=2 at collection centers 4 and 5 increases. As shown in Table 5.7 and Table 5.8, with the expansion, the number of transportation consignments by mode 3 for non-pretreated dead products increases from 1 (at current capacity) to 1,580 (at 20% expansion), while in the case of pretreated dead products, the number of transportation consignments by mode 1 decreases from 13,231 (at current capacity) to 10,982 (at 20% expansion).

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*The data in this section is extracted from HW Associates Inc (Management Consultant) available at: www.hwassociates.com

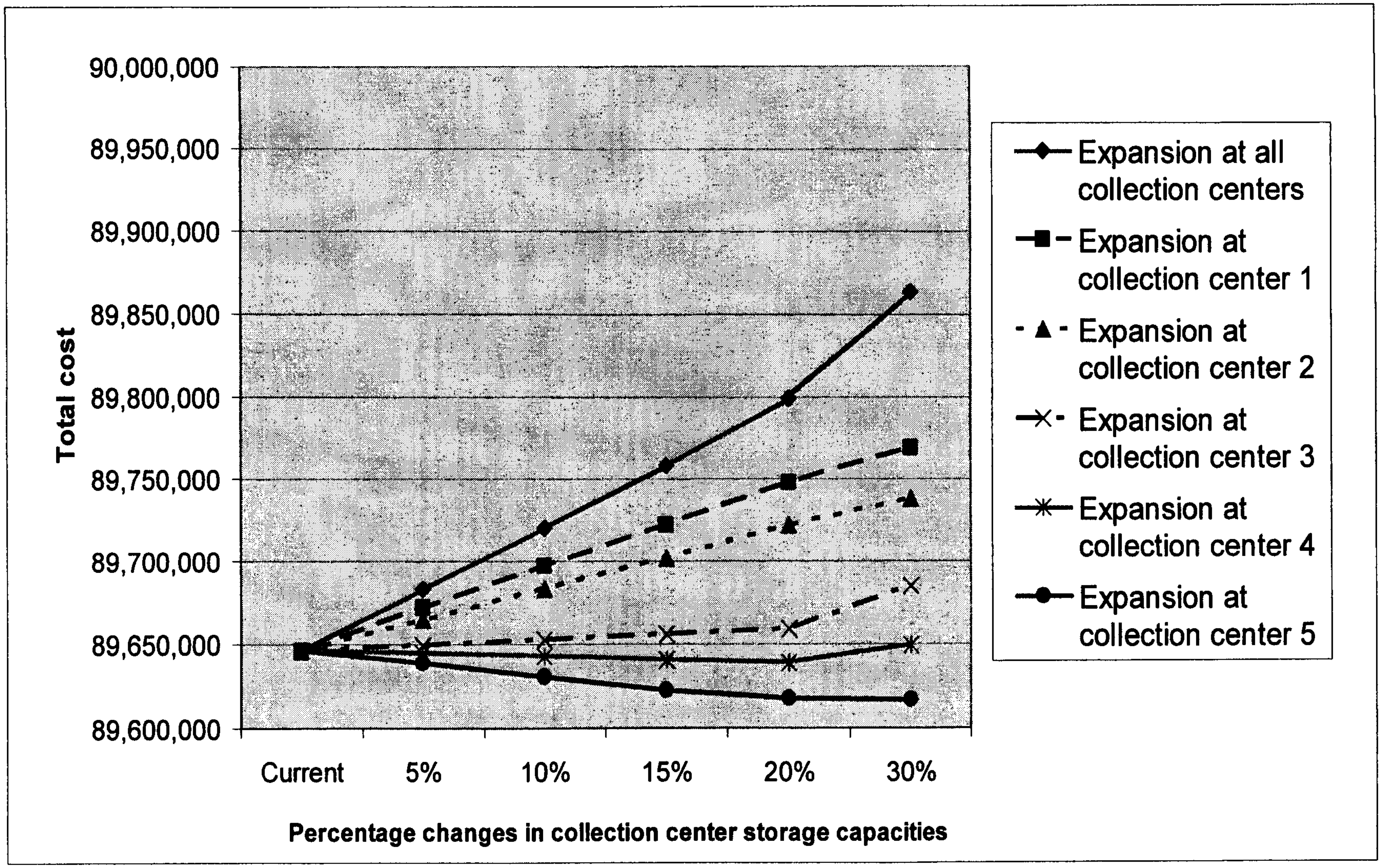

Figure 5.11: Effect of expanding collection center capacities on total cost

Table 5.6: Dead product inventory levels at DCs when expanding the storage capacities of collection centers 4 and 5 only

DC, *d*	**Period, *t***	$XCIL_{qt}$											
		Product Family, *q*=1				**Product Family, *q*=2**				**Product Family, *q*=3**			
		current	**10%**	**15%**	**20%**	**current**	**10%**	**15%**	**20%**	**current**	**10%**	**15%**	**20%**
1	1	0	0	0	0	0	0	0	0	266	266	266	266
	2	0	0	0	0	0	0	0	0	495	495	495	495
	3	0	0	0	0	0	0	0	0	715	715	715	715
	4	0	0	0	0	11,557	11,557	11,557	11,557	992	992	992	992
	5	0	0	0	0	24,056	24,056	24,056	24,056	1,272	1,272	1,272	1,272
2	1	0	0	0	0	0	0	0	0	452	452	452	452
	2	0	0	0	0	0	0	0	0	841	841	841	841
	3	0	0	0	0	0	0	0	0	1,215	1,215	1,215	1,215
	4	0	0	0	0	18,261	18,261	18,261	18,261	1,686	1,686	1,686	1,686
	5	0	0	0	0	33,682	33,682	33,682	33,682	2,162	2,162	2,162	2,162
3	1	0	0	0	0	0	0	0	0	181	181	181	181
	2	0	0	0	0	0	0	0	0	337	337	337	337
	3	0	0	0	0	719	719	719	719	487	487	487	487
	4	0	0	0	0	7,717	7,717	7,717	7,717	675	675	675	675
	5	0	0	0	0	12,370	12,370	12,370	12,370	866	866	866	866
4	1	0	0	0	0	0	0	0	0	49	49	49	49
	2	0	0	0	0	0	0	0	53	91	91	91	91
	3	0	0	0	0	1,247	2,178	2,643	3,108	131	131	131	131
	4	0	0	0	0	5,479	6,410	6,875	7,340	181	181	181	181
	5	0	0	0	0	8,293	9,224	9,689	10,154	232	232	232	232
5	1	0	0	0	0	0	0	0	0	363	363	363	363
	2	0	0	0	0	0	0	0	0	676	676	676	676
	3	0	0	0	0	0	0	0	1,916	976	976	976	976
	4	0	0	0	0	20,678	25,376	27,724	30,073	1,354	1,354	1,354	1,354
	5	0	0	0	0	39,400	44,098	46,446	48,795	1,737	1,737	1,737	1,737
...	**SUM**	**0**	**0**	**0**	**0**	**117,801**	**123,430**	**126,243**	**129,057**	**6,269**	**6,269**	**6,269**	**6,269**

Table 5.7: Number of transportation consignments for non-pretreated dead products from DCs (CRC) to RC when expanding the storage capacities of collection centers 4 and 5 only

DC, *d*	**PERIOD, *t***	$XCCR_{dkt}$											
		MODE, k=1 (Regular Truck)				**MODE, k=2 (Expedited Truck)**				**MODE, k=3 (Rail)**			
		current	**10%**	**15%**	**20%**	**current**	**10%**	**15%**	**20%**	**current**	**10%**	**15%**	**20%**
1	1	0	0	0	0	0	0	0	0	0	101	101	101
	2	0	0	0	0	0	0	0	0	0	104	104	104
	3	0	0	0	0	0	0	0	0	0	105	105	105
	4	0	0	0	0	0	0	0	0	0	133	133	133
	5	0	0	0	0	0	0	0	0	1	105	105	105
2	1	0	0	0	0	0	0	0	0	0	0	188	188
	2	0	0	0	0	0	0	0	0	0	0	194	194
	3	0	0	0	0	0	0	0	0	0	197	197	197
	4	0	0	0	0	0	0	0	0	0	0	96	248
	5	0	0	0	0	0	0	0	0	0	122	0	195
3	1	0	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0	0	0	10
	4	0	0	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	0	0	0
4	1	0	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	0	0	0
5	1	0	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	0	0	0
…	**TOTAL**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**867**	**1,223**	**1,580**

Table 5.8: Number of transportation consignments for pretreated dead products from DCs (CRC) to RC when expanding the storage capacities of collection centers 4 and 5 only

DC, *d*	PERIOD, *t*	$XCCR1_{dkt}$											
		MODE, k=1 (Regular Truck)				MODE, k=2 (Expedited Truck)				MODE, k=3 (Rail)			
		current	10%	15%	20%	current	10%	15%	20%	current	10%	15%	20%
1	1	716	609	609	609	0	0	0	0	0	0	0	0
	2	849	739	739	739	0	0	0	0	0	0	0	0
	3	805	693	693	693	0	0	0	0	0	0	0	0
	4	510	369	369	369	0	0	0	0	0	0	0	0
	5	109	0	0	0	0	0	0	0	0	0	0	0
2	1	951	951	752	752	0	0	0	0	0	0	0	0
	2	1117	1117	911	911	0	0	0	0	0	0	0	0
	3	1063	855	855	855	0	0	0	0	0	0	0	0
	4	514	514	412	252	0	0	0	0	0	0	0	0
	5	206	77	206	0	0	0	0	0	0	0	0	0
3	1	319	319	319	319	0	0	0	0	0	0	0	0
	2	370	370	370	370	0	0	0	0	0	0	0	0
	3	318	318	318	304	0	0	0	0	0	0	0	0
	4	122	122	122	122	0	0	0	0	0	0	0	0
	5	96	96	96	96	0	0	0	0	0	0	0	0
4	1	191	191	191	191	0	0	0	0	0	0	0	0
	2	222	222	222	219	0	0	0	0	0	0	0	0
	3	148	101	77	56	0	0	0	0	0	0	0	0
	4	71	71	71	71	0	0	0	0	0	0	0	0
	5	56	56	56	56	0	0	0	0	0	0	0	0
5	1	1104	1104	1104	1104	0	0	0	0	0	0	0	0
	2	1304	1304	1304	1304	0	0	0	0	0	0	0	0
	3	1238	1238	1238	1140	0	0	0	0	0	0	0	0
	4	634	394	274	252	0	0	0	0	0	0	0	0
	5	198	198	198	198	0	0	0	0	0	0	0	0
...	**TOTAL**	**13,231**	**12,028**	**11,506**	**10,982**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

5.3.2. Effect of decreasing manufacturing capacity in the system

Often a manufacturing system faces the problem of adjusting its production capacity in line with the market demand for its products. To test the impact of reducing the production capacity on the total cost in this case, we investigate the following two scenarios in which plants 3 and 5 are, respectively, eliminated. In Table 5.8, we compare the cost component values of the two scenarios with those of the current solution.

Table 5.9: Total cost components values when closing the manufacturing plants 3 and 5

TOTAL COST		CURRENT	CLOSE PLANT p=3	CLOSE PLANT p=5
		89,646,430	**85,973,558**	**94,310,727**
1	**VIRGIN RAW MATERIALS COST**	4,370,811	4,309,756	5,906,841
2	**VIRGIN RAW MATERIAL INVENTORY COSTS AT THE PLANTS**	1,509	1,609	1,856
3	**LABOR COST**	27,480,240	24,588,750	30,056,580
4	**PLANT INVENTORY CARRYING COST FOR FINISHED PRODUCTS**	706,364	650,785	646,781
5	**INBOUND TRANSPORTATION COST OF PRODUCTS FROM PLANTS TO DCS**	77,732	70,931	107,841
6	**IN-TRANSIT INVENTORY COST OF PRODUCTS BETWEEN PLANTS & DCS**	105,125	248,244	237,822
7	**DC INVENTORY CARRYING COST**	0	11,445	0
8	**COST OF PRETREATMENT**	14,834,630	14,700,430	14,839,500
9	**COST OF TRANSPORTING DEAD PRODUCTS FROM COLLECTION CENTERS TO RCS**	30,599,340	29,939,280	30,899,370
10	**IN-TRANSIT INVENTORY COST OF DEAD PRODUCTS FROM COLLECTION CENTERS TO RCS**	1,194,561	1,194,561	1,238,945
11	**COST OF RECYCLING AT RECYCLING CENTER**	955,247	939,056	1,045,217
12	**COST OF HANDLING DEAD PRODUCTS AT RECYCLING CENTER**	16,659	16,377	18,716
13	**COST OF BUYING SECONARY**	486,014	484,136	493,060
...	**ALL OTHER COSTS**	**8,818,198**	**8,818,198**	**8,818,198**

From the Table 5.9, we observe that closing manufacturing plants may impact the total cost in different ways. In this example, closing manufacturing plant p=3 reduces the total costs, whereas closing manufacturing plant p=5 increases the total costs. Considering the elimination of plant 3 as an example, the reduction in the total cost is, to a major extent, due to a reduction in the labour cost, although there are also decreases in the cost of pretreatment, cost of transporting dead products from collection centers to the recycling center, virgin raw material cost, plant inventory carrying cost for finished products, the inbound transportation cost and corresponding minor changes in cost components, shown on the table 5.9.

The changes in the cost component values are due to the resulting changes in the production plans when the overall production capacity is adjusted. In Tables 5.10 and 5.11, the production levels and the corresponding safety stocks at each plant are evaluated under the two scenarios above, and compared with the current solution. We observe that when plant p=3 is eliminated, the production at this plant is shifted to plant 4 only, the overall production of product family q=2 is reduced from 211,382 units to 210,613 units, and correspondingly, the safety stock of product family q=2 is reduced from 2,600 units to 2,442 units, which leads to a reduction in the overall total costs.

5.3.3. Summary of model sensitivity analysis to changes in network design options

Expanding the collection center storage capacities may reduce the total cost to a certain limit. When collection centers 4 and 5 expand by 20%, the total cost decreases and reaches a minimum. On the other hand, any expansion of the storage capacity at the collection centers 1, 2 and 3 increases the total cost.

Closing some manufacturing plants and transferring the production of the product families affected to other plants may impact the total cost in different ways. Closing one plant maybe increase the total cost (for example, plant 3 in our example), while closing another plant may reduce the total cost (for example, plant 5). The overall change in the total cost is a function of the different ways in which material allocations take place when production capacity is adjusted.

Table 5.10: Comparison of production at plants, $\sum_{t=1}^{T} XP_{pqt}$, when closing plants 3 and 5

PLANT, p	CURRENT			CLOSE PLANT 3			CLOSE PLANT 5		
	$q=1$	$q=2$	$q=3$	$q=1$	$q=2$	$q=3$	$q=1$	$q=2$	$q=3$
$p=1$	344,145	0	1,045	344,145	0	1,045	344,145	0	2,942
$p=2$	245,810	73,914	0	245,810	73,914	0	245,810	80,659	0
$p=3$	304,987	58,093	0	0	0	0	304,987	58,093	0
$p=4$	101,654	74,544	0	406,668	140,867	0	101,654	74,544	0
$p=5$	0	4,831	1,819	0	4,831	1,819	0	0	0
SUM	**996,596**	**211,382**	**2,864**	**996,622**	**210,613**	**2,864**	**996,596**	**213,295**	**2,942**

Table 5.11: Comparison of pooled safety stock levels, PS_{pq}, of finished products at plants when closing plant 3 and 5

PLANT, p	CURRENT			CLOSE PLANT 3			CLOSE PLANT 5		
	$q=1$	$q=2$	$q=3$	$q=1$	$q=2$	$q=3$	$q=1$	$q=2$	$q=3$
$p=1$	2,143	0	10	2,143	0	10	2,143	0	56
$p=2$	1,531	779	0	1,531	779	0	1,531	1,373	0
$p=3$	1,899	520	0	0	0	0	1,899	520	0
$p=4$	633	1,039	0	2,532	1,400	0	633	1,039	0
$p=5$	0	263	40	0	263	40	0	0	0
SUM	**6,207**	**2,600**	**50**	**6,207**	**2,442**	**50**	**6,207**	**2,932**	**56**

CHAPTER 6 – SUMMARY AND FUTURE DIRECTION

In this chapter the major contributions of this thesis has been summarized, and then several extensions to the current model formulation was discussed. To conclude the study, some directions for future study were also proposed.

6.1. Summary of the present work

The environmental concerns regarding the reduction of waste, hazardous material and other consumer residuals—together with the economic value of extending the product life cycle—provide industries with new and emerging business opportunities. Both these objectives (environmental and economic) can be achieved with the same system by utilizing a close-loop supply chain model. Most of the existing works in the area of supply chain do not connect the reverse supply chain to the forward supply chain in the same system. In addition, they do not consider the effect of pollution emissions.

The proposed model not only creates a closed-loop supply chain (by extending the forward supply chain to the stage after the service life cycle and setting up the reverse chain so that it connects to the original point), but also considers the effect of pollution emissions as a secondary objective in addition to the total cost.

The planning model was developed to determine the raw material level, production level, inventory level, workforce levels at different manufacturing facilities and transportation modes between the echelons with the primary objective of minimizing the total costs incurred by the manufacturer—the major driver of the whole system. a pollution emission index was also build to evaluate the pollution level during the transportation to address the secondary objective of the model. The forward and reverse network model was integrated through appropriate constraints on the centralized safety stock policy for raw material and the inventory level of the raw material, both virgin raw material and recycled raw material concerned.

The mixed integer programming model developed in this research provides the users with a business decision making tool. The model can be adapted to real-life scenarios by adding/removing any relevant constraints or objective functions. The MIP models can also be used for fast sensitivity analysis based on re-optimization of the system under different scenarios.

The model in this research was tested with some real data extracted from industry sources, and some randomly generated data for sensitivity analysis. Despite the fact that data from a specific company is used as a basis for this research, the modeling process is generalized enough to be relevant to most types of OEMs or hazard material involved manufacturers. The results from the extensive numerical experiments performed prove that the model can be successfully applied as a planning tool for the reconfiguration of supply chain networks.

From a purely computational point of view, the model solves for 10280 constraints, 22396 variables—including 7055 integers (125 binary integers when relaxing the general integer variables into continuous variables). It took, on average, 0.5 million iterations and 3 minutes of CPU time to reach optimum solutions. The time will be increased for larger and more complex problems, but it is expected to remain computationally feasible. Using other algorithms, such as branch-and-cut/Lagrangean relaxation (Chandru and Rao., 1996) as well as a more powerful computer is expected to reduce the computational time.

Sensitivity analyses were performed to examine the impact of the introduction of 3PL services as part of the entire system and to evaluate the effect of changes in key parameters on the total cost. Numerous investigations were made to determine the various design options for the network by removing manufacturing plants or expanding distribution center storage capacities.

Integrating the 3PL services into the network reduces the total cost by about 44% due to the major changes in pretreatment cost, dead product transportation cost collection centers to the recycling center, and the corresponding in-transit inventory cost from collection centers to the recycling center. It is mainly because that the transportation pollution emission restriction was not concerned in outsourcing application.

The study of key parameters with consideration of pollution emission control indicates that the total cost is insignificantly impacted by changes in the standard deviation of the demand, followed by changes in the end-of-life collection cost, the virgin raw material cost and the recycling process cost. Changes in the transportation lead times between suppliers and manufacturing plants, between manufacturing plants and distribution centers, and between collection centers and the recycling center all show a very small, non-linear effect on the total costs. Changes in the pollution emission index during transportation show a significant, linear effect on the total cost. Most of these changes prove the robustness of the planning model.

Changing the network design options by expanding the collection center storage capacities by up to 20% can reduce the total cost to a new minimum value. Reducing production capacity by removing some manufacturing plants is another network design option that has been studied. The model solutions, however, reveal opposing results: a reduction in the total cost when removing plant p=3, and an increase in the total cost when removing plant p=5.

The analysis tool introduced in this thesis can be used to improve the operations of a supply chain network by reducing costs and pollution emissions. The main contribution of this work is the development of a new planning model which extends the supply chain to include an entire product life cycle through the integration of the forward and reverse supply chains, while paying special attention to pollution control.

6.2. Proposed future research direction

Further research may be conducted in the following areas:

1. Reverse logistics activities: in the present model, only the recycling of dead products was concerned. Other possible activities within the reverse logistics can be added to the model, such as product remanufacturing (e.g., disassembly of the battery).
2. Manufacturing plant activities: additional manufacturing plant functions, such as sub-assembly manufacturing or product scrap returns, may be added to the model. The production stages at the plants and the semi-finished product inventories can also be

explicitly modeled at the tactical level.

3. Strategic level planning models: the present model is a tactical level supply chain planning tool, which takes into account the entire circle of manufacturing facilities, distribution centers and recycling centers. The logical next step is to develop a strategic level planning model that is suitable for long-term planning. Using such a model, it can be determined whether and where to open a new facility, expand the capacity of a warehouse or manufacturing plant, open a new distribution center, or develop a new supplier alliance.
4. Operational level planning models: another logical extension to this problem is to develop an operational level planning model for short-term operational planning. This model may be used to plan activities such as scheduling and routing for transportation channels
5. Decision Support System: the model uses the commercial solver Lingo 9.0 as the application program with Microsoft Access as the database. A friendly interface can be developed using Visual Basic to make the model a decision support tool which can be easily applied by users.

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APPENDICES (CD FORMAT)

APPENDIX 1:	LINGO script for the planning model
APPENDIX 2:	Forecasting methodology and calculations
APPENDIX 3:	Complete results for the planning model

The CD attached at the end of this thesis provides the appendices

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